Modelling the efficacy and profitability of mitigation strategies for 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. This modelling exercise explored the cumulative impact of dairy management decisions on GHG emissions and profitability at the farm level. The objective was to maintain production, but reduce GHG emissions per unit of land and product.

A recent survey (Groundwork Associates; Hamilton, New Zealand) collated the views of experts regarding available technologies for GHG mitigation on farm. This, together with performance indicators for dairy farms obtained from DairyBase (DairyNZ), formed the basis for the exercise (Figure 1). A farm scale computer model (DairyNZ's Whole Farm Model) with a mechanistic cow model (Molly) was used to model an average, all-pasture Waikato farm over different climate years. A mitigation strategy based on reduced milker replacement rates was then added to this baseline farm and modelled over the same years. Three more strategies were added, including improved cow efficiency (higher genetic merit), improved pasture management (better pasture quality), and home-grown maize silage (increased total yield and reduced N intake), and modelled to predict milk production, intakes, methane, urinary-N, and operational profit. Profit was calculated from 2006/07 economic data, where milksolids payout was \$4.09/kg. The Overseer® nutrient budget model was used with these scenarios and two more strategies added: standing on loafing pads during wet conditions and nitrification inhibitors. Overseer® predicted total GHG emissions in CO_2 equivalents and included some life cycle analysis of emissions from fertiliser manufacturing, fuel and electricity generation.

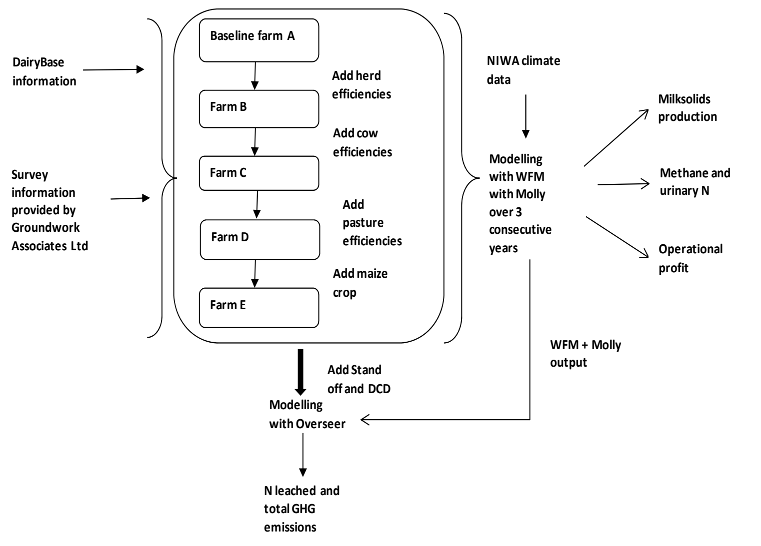

Figure 1. Schematic representation of the modelling process.

The simulations suggest an implementation of these strategies could decrease GHG emissions by 27–32% while increasing profitability by up to \$821/ha/annum on a Waikato dairy farm. Success requires production to be maintained by increasing the efficiency of milk production from forage. This 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, and pasture management to increase average pasture and silage quality by 1 MJ ME/kg Dry Matter. These efficiencies enable stocking rate to be reduced from 3 to 2.3 cows/ha. Nitrogen from fertilisers would be reduced to less than 50 kg/ha/yr and include "best practice" application of nitrification inhibitors. Considerable GHG mitigation may be achieved by applying optimal animal management to maximise efficiency, minimise wastage and target N fertiliser use.

Keywords: *Farm efficiencies, Nitrogen fertiliser, Stocking rate, Enteric methane, Kyoto Protocol*

1 INTRODUCTION

In New Zealand, methane (CH_4) contributes 38% and nitrous oxide (N_2O) 17% (CO_2 equivalents; CO_2-e) of the annual GHG emissions (NZ Climate Change Office, 2003). Agriculture contributes about half of New Zealand GHG emissions, most of it coming from grazed pasture-based livestock production systems. In these systems, ruminal fermentation and urinary nitrogen (urinary-N) are the most important sources of CH_4 and N_2O (Waghorn, 2008). Previous studies have summarised the current and future strategies available to pasture-based farmers for reducing GHG emissions by animal, feed-based, soil and management interventions (Beauchemin et al., 2008; de Klein and Eckard, 2008). There is a need to evaluate the impacts of these strategies when incorporated into the farm system and also the cumulative effects when some of these strategies are combined. Furthermore, variability as influenced by climate and animal-feed dynamics needs to be considered (Beauchemin et al., 2008). Farm-scale models are cost effective ways of exploring the cost/benefits of practical and multi-pronged mitigation over several years.

The objective of this modelling exercise was to evaluate the cumulative efficacy of selected mitigation strategies and to calculate the effects on farm profitability. The hypothesis was that improved farm efficiencies may be used to mitigate GHG emissions and maintain profitability without affecting production. The rationale was that feed intake is the main driver of GHG emissions on the dairy farm, and improved efficiency would reduce feed use for the same level of milk production. The following strategies were included:

- Reduction in the numbers of replacement and other non-productive animals. Non-productive animals produce CH_4 and urinary-N (an important source of N_2O) without contributing to milk production (Waghorn, 2008).
- Increasing the feed conversion efficiency using animals with higher genetic merit. Efficient cows produce more milk from the same energy intake and CH_4 output. Fewer efficient animals are required to produce the same milksolids (MS) per unit of land, and because less feed is required so less CH_4 is emitted and less urinary-N is deposited (de Klein and Eckard, 2008).
- Increasing pasture quality to achieve a higher average ME content in the DM (Beauchemin et al., 2008). With high ME pasture, less feed is required to produce the same output per unit of land, resulting in lower CH_4 emissions and less urinary-N deposited. Because less feed is required (of better quality) less N-fertiliser is required, resulting in savings in GHG generated during the fertiliser manufacturing process (Wells, 2001).
- Growing a maize silage crop on part of the farm will increase ME yield per hectare because the yield from maize is higher than from pasture, and a lower pasture yield from the rest of the farm will be required to produce the required ME, hence less N-fertiliser is required for pasture, with reduced N_2O loss from fertiliser as well as CO_2-e from the fertiliser manufacture. Feeding maize silage to cows will also lower urinary-N excretion and, therefore, N_2O loss from urine patches (Van Vuuren et al., 1993).
- Application of nitrification inhibitors (e.g. DCD) in autumn and winter to slow the process of nitrification and reduce the losses of N_2O. More N remains in the soil for pasture growth allowing lower fertiliser rates (de Klein and Eckard, 2008).
- Standing cows off pasture to capture excreta and also reduce pasture damage during wet conditions. Captured excreta can be recycled to pastures for efficient utilization of N by plants (de Klein and Eckard, 2008) and the reduction in N-fertiliser use lowers GHG emissions associated with its manufacture. By reducing pugging and soil compaction, N_2O emissions from soils can also be reduced.

2 METHODS

2.1 Approach

Information from DairyBase (www.dairybase.co.nz) was used to describe an all-pasture, self-contained (<10% bought-in feed), 'average' dairy farm in the Waikato region. This baseline farm did not implement specific strategies to reduce GHG emissions. Mitigation strategies were then sequentially added to this baseline farm, based on performance indicators from top-performing farms, and modelled through DairyNZ's Whole Farm Model (WFM) with the Molly cow model (Baldwin, 1995), and through the nutrient budgeting model, Overseer® (www.agresearch.co.nz/overseerweb). The WFM predicted annual production, total intake, total CH_4 and urinary-N output from animals and operational profit. Overseer® predicted nitrate leaching and total GHG emissions (in CO_2-e) from animals and other sources like effluent and N fertiliser

(Figure 1). The hypothesis was that mitigation could be achieved with minimal impact on farm profitability. In an attempt to achieve this, farm management and inputs were adapted to maintain constant production (kg MS/ha) as more mitigation strategies were included in the farm system.

2.2 Models

2.2.1 WFM

The WFM was developed to assist with analysis and design of farm systems experiments and to ask “what if” questions, requiring system interactions over multiple years. The model consists of a framework written in VisualAge Smalltalk (IBM), and sub-models that are written in various programming languages. These sub-models are dynamic and mechanistic and simulate both cow metabolism (Molly) and pasture growth (McCall and Bishop-Hurley, 2003), the latter being driven by daily climate. Animals (and paddocks) are represented by a copy (or instance) of the relevant sub-model initialised for each animal (and paddock). For example, the age, breed and other characteristics that are unique to an individual are used for each cow instance, while for each paddock the pasture cover (herbage mass) and soil characteristics are specified. Recently the WFM was upgraded to predict reproductive outcomes for individual cows. This capability allows the model to be used to predict the effects of mating management (anoestrus treatment, oestrus detection efficiency and bull management) and system changes (farm set-up at the start of the year and feeding before and during mating) on the reproductive performance of the herd. Reproductive performance influences management decisions (e.g. culling and replacement) that have an impact on farm profitability within a year, and produce carry-over effects into the next year. Replacement cows can be reared on-farm incurring costs related to calf milk, calf meal and grazing of yearlings, or weaned calves can be grazed off the farm at a cost per week. In both cases replacement cows contribute to GHG emissions associated with the farm. This model capability was important for exploring the costs/benefits of reducing the replacement rate of the herd and the potential benefit for reducing GHG emissions.

Another WFM development important for this exercise was the linking of a climate-driven maize sub-model to the framework. This necessitated the development of a flexible cropping policy that allows the user to specify paddocks to be cropped, specific maize hybrids, sowing dates and fertiliser policy. Predictions of yield and harvest date are driven by soil type and real climate data from the nearest weather station. In the WFM the maize crop is harvested and, after allowing for ensiling losses, is stored for later rationing as determined by the supplement feeding policy. The user defines the quality of the silage (protein, fibre, soluble carbohydrates, ash etc.), which determines how the cows respond in milk production, body condition, CH_4 emission and urinary-N concentration.

Since the objective included farm profitability, it was important that the WFM accurately represented changes in farm costs and operating profit with different management strategies aimed at GHG mitigation. Economic input data were updated with the 06/07 season costs of buying or selling cows of different age and breeding status, health, breeding and herd improvement costs, cropping and harvesting costs, fertiliser costs, bought-in supplements and milk price.

2.2.2 Molly

Molly is the model that simulates cow metabolism in the WFM. It is a mechanistic and dynamic model representing the critical elements of digestion and metabolism of a dairy cow. The cow’s production is influenced by the quantity and quality of feed given to her and by her metabolic capacity to absorb and convert nutrients into milk (i.e. her genotype). Molly’s feed intake is driven by metabolic demand. Feed quality is described in a feed composition table in WFM where the user defines feed fractions for all the feeds used in the farm system. The feed fractions are then processed through Molly’s digestive system and nutrients absorbed into the bloodstream. The metabolic energy content of the feed is therefore not an input, but a product of digestion and absorption. Beukes et al. (2006) described a system whereby the user of the WFM can set the genetic merit of each Molly cow by altering a parameter through the framework that regulates the udder’s capacity to secrete milk. Molly predicts enteric CH_4, urinary-N, faecal-N and milk-N as influenced by feed quality, genetic merit and lactation status. CH_4 is predicted from H (hydrogen) production in the rumen and milk- and urinary-N are driven by protein intake and plasma urea concentrations.

2.2.3 Overseer®

Overseer® is a decision support model to help users develop annual nutrient budgets and evaluate implications of alternative management practices. It is an empirical model that provides estimates of the fate of nutrients in kg/ha on an annual basis. The model does not consider year-to-year variability caused by weather and the user is advised to enter average weather inputs. The GHG inventory in the model is based on algorithms used for New Zealand's GHG national inventory, but with modifications to include on-farm management practices (Wheeler et al., 2003). Methane emissions are based on a metabolisable energy intake model developed by Clark (2001). N_2O emissions are based on the New Zealand IPCC-based inventory, which includes the use of emission factors for direct N_2O losses from excreta, fertiliser and effluent, and indirect losses from leached N and volatilised ammonia (de Klein et al., 2001). The amounts of effluent, leached N and volatilised ammonia are estimated from the associated N budget model. CO_2 emissions from fuel and electricity, processing and some indirect contributions (e.g. fertiliser manufacturing) are largely based on the data of Wells (2001).

2.3 Development of the farm scenarios

In phase 1 of the exercise the WFM was used with Molly. Starting with the average Waikato dairy farm as the baseline (Farm A), four mitigation strategies were added. Incremental gains were introduced sequentially (Farms B, C, D and E) (Table 1). Nitrogen fertiliser application to pasture and stocking rate were adjusted to maintain a constant MS production/ha across the five farms (Table 1).

Table **1**. Comparative description of the baseline farm (A), and farms with mitigation strategies (B, C, D and E). Shaded rows indicate management strategies where farms differ from the ones they were developed from.

	Farm A	**Farm B**	**Farm C**	**Farm D**	**Farm E**
Rear own young stock on support block	Yes	Yes	Yes	Yes	Yes
Bought-in feed	<10%	<10%	<10%	<10%	<10%
Milk (kg MS/milking ha)	1090	1090	1090	1090	1090
Replacement rate	>20%	±15%	±15%	±15%	±15%
Reproduction	Average	Above average	Above average	Above average	Above average
Cow genetic merit	Average	Average	High	High	High
Pasture/Silage quality (MJ ME/kg DM)	11/10	11/10	11/10	12/11	12/11
Cropping	No	No	No	No	Maize on 6% of milking area
Fertiliser on pasture (kg N /ha)	180	115	15	0	0
Stocking rate (cows/ha)	3.0	3.0	2.6	2.3	2.3

In phase 2 of the exercise two more strategies, nitrification inhibitors (DCD) and standing cows on loafing pads during wet conditions (stand-off), were explored using the Overseer® model. In this phase the set-up and results of each of the five simulated farms (Farms A-E) were entered into Overseer® with inhibitors, then with stand-off, then with both, to quantify any further potential mitigation impacts of these two strategies.

2.4 Simulations and measurements

Each WFM farm scenario was run 3 times. Each run consisted of a 3-year simulation using actual weather data from the Ruakura Weather Station (1998-2001; 2001-2004 and 2004-2007). Results were recorded on a "farm season" basis (e.g. 98/99) where each season was from 1 June to 31 May. Results included production (MS/cow, MS/ha), and total CH_4 emitted, urinary-N deposited, total DM intake, and operational profit. Profit was expressed as $/ha using 06/07 economic input data, with a payout of $4.09/kg MS. Results were analysed with ANOVA as a randomised block design, where blocks were 3-year simulations.

The results from the WFM simulations were averaged from 3 x 3 = 9 climate years for the five farms and entered into Overseer®. Overseer® calculated GHG emissions expressed as CO_2-e from enteric CH_4, N_2O emissions from excreta and fertiliser, and from other sources including lime, fertiliser manufacturing, electricity and fuel. The inclusion of the "other sources" was not an attempt to represent a full life cycle analysis for the farm, but covered some of the principal CO_2 emission sources that could be affected by the mitigation strategies.

2.5 Assumptions

Apart from assumptions inherent in the WFM, Molly and Overseer®, some further simplifications were made.

- Mitigation strategies simulated by the WFM were added to the previous system without fine-tuning or optimising for maximum benefit, in terms of GHG mitigation or profitability.
- Total urinary-N output from WFM simulations was regarded as an index of N_2O emissions from all excreta (faeces and urine deposited in the paddocks and from effluent ponds) so actual losses from faeces were ignored. This assumption is supported by the fact that urine is the major source of N_2O because of the relatively rapid hydrolysis of urea in urine compared with the slow release of NH_4^+ from the organic N in dung (de Klein and Eckard, 2008).
- Direct N_2O emissions from N fertiliser applications on the land were not calculated in WFM simulations, but were included in the Overseer® calculations.
- The maize crop in farm E was assumed to be cultivated from pasture on well-fertilised paddocks, therefore not requiring any N-fertiliser.
- In Overseer® simulations, a partial life cycle analysis was used to account for the CO_2 emissions from the fertiliser manufacturing process, assumed to be 3 kg CO_2/kg N fertiliser applied (Wells, 2001).
- In Overseer®, the soil type was assumed to be a deep volcanic soil with macronutrient status within the biologically optimum range.
- The implementation of stand-off and DCD in Overseer® assumed "best practice". The number of stand-off days per month varied according to wet conditions in autumn and winter/spring, and excreta captured on the stand-off pad was re-cycled onto the paddocks. DCD applications followed the recommendations outlined in Overseer®.

3 RESULTS

The WFM simulations showed that the cumulative effect of the improved herd efficiencies and animal genetics in Farms C, D and E resulted in a significant 15% reduction in CH_4/ha compared with Farm A, based on conventional (baseline) management (Fig 2a). Cows had lower DM intakes/ha but with similar or higher MS production, resulting in up to 25% higher conversion of feed into MS relative to the baseline farm (Fig 2b). Farms D and E had higher quality pasture and maize silage compared with Farm C, which resulted in a higher feed conversion efficiency but feed quality did not affect a significant reduction in CH_4 (Fig 2).

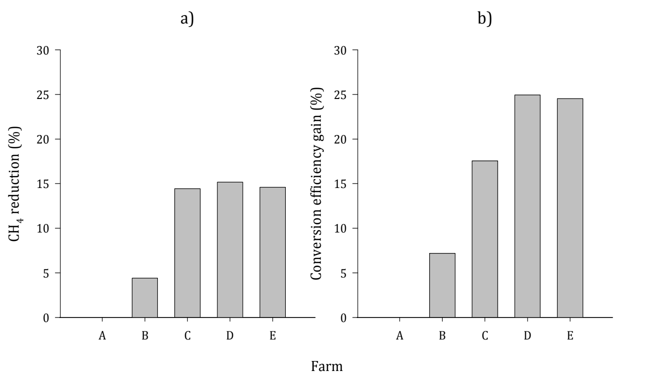

Figure 2. a) Percentage reduction in CH_4 enteric emission per unit of area and b) increase in conversion of feed into MS. Farm A (baseline), B (improved herd efficiency), C (improved animal efficiency), D (improved pasture management) and E (home-grown maize silage).

The cumulative effects of improved herd and animal efficiencies in Farm C resulted in the lowest deposition of urinary-N per unit of land, MS, and DM eaten of the five systems (Table 2). Improved herd and animal efficiencies could reduce N_2O by 14% per hectare of land, compared with the baseline farm. Maize silage in Farm E reduced urinary-N compared with Farm D (no maize silage), but the high quality pasture (12 MJ ME, 24.2% CP) fed in both farms D and E resulted in significantly higher urinary-N compared with Farm C with average pasture quality (11 MJ ME, 21.7% CP) (Table 2).

Table **2.** Urinary nitrogen per unit of land (including land for rearing replacements), per unit of product and per unit of DM eaten, for farm A (baseline), B (improved herd efficiency), C (improved animal efficiency), D (improved pasture management) and E (home-grown maize silage).

Farm	per unit of land	per unit of product	per unit of DM eaten

	kg N/ha	g N/kg MS	g N/kg DM
A	235	243	17.3
B	229	228	17.3
C	201	202	16.8
D	212	210	18.6
E	207	206	18.2
LSD*	3.51	3.12	0.256

* Least Significant Difference ($P < 0.05$)

The average (±stdev) operating profit ($/ha/year) for the five farms was estimated by the WFM (using 06/07 economic input with MS payout of $4.09/kg MS) as 1306±52, 1406±289, 1612±289, 2127±173 and 2009±189 for Farms A, B, C, D and E, respectively. The increase in operating profit from Farms A to D was mainly the result of a decrease in stocking rate (costs: $422/cow) and decrease in nitrogen fertiliser used (priced: $685/t urea).

The Overseer® results demonstrated incremental reductions in GHG emissions (27%) as more mitigation strategies were introduced from Farms A to D, but that the introduction of home-grown maize silage in Farm E resulted in no further gains (Fig 3). The use of nitrification inhibitors reduced emissions by a further 5% on average. Standing cows off during wet conditions had no significant impact on emissions (Fig 3).

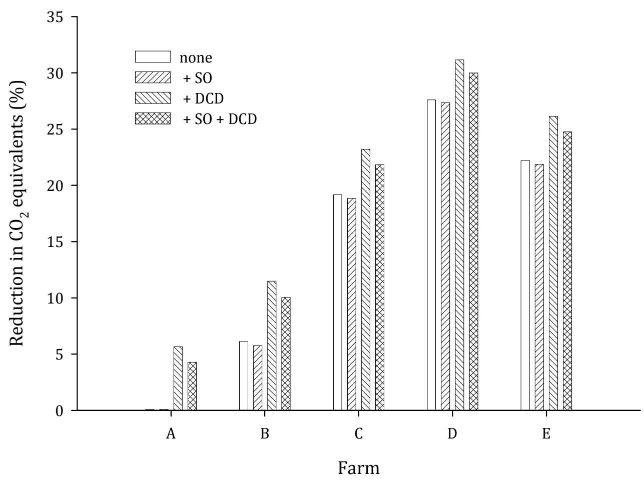

Figure 3. Percentage reduction in total farm emissions (CO_2-e/ha/year) according to Overseer®, for Farm A (baseline), B (improved herd efficiency), C (improved animal efficiency), D (improved pasture management) and E (home-grown maize silage), and extra mitigation measures: stand-off (+SO), nitrification inhibitors (+DCD) and the combination (+SO+DCD).

4 DISCUSSION AND CONCLUSIONS

Improvements in herd and animal efficiencies could mitigate GHG emissions, primarily by reducing total DM intake while maintaining production. Enteric CH_4 is the largest contributor to GHG emissions from pasture-based dairy farms, and DM intake is the main driver of enteric CH_4 emissions in these systems. Improved efficiencies also reduced urinary-N deposition, indicating a potential decrease in N_2O emissions (de Klein and Eckard, 2008). Production was maintained in the mitigated systems because fewer cows, with higher feed conversion efficiency, were stocked, and this resulted in cost savings and increased profitability. This is clearly a win-win situation where dairy farmers can reduce GHG emissions whilst maintaining, or even increasing, profitability.

WFM simulations showed that Farm C, with improved herd and cow efficiencies, had the lowest GHG emissions per hectare of land (compared with the baseline Farm A), and this reduction was attributed to a 15% reduction in CH_4 and 14% reduction in N_2O emissions. Overseer® indicated potential GHG reductions of up to 27% (CO_2 equivalents/ha) by a combination of improved herd, animal and pasture efficiencies (Farm D). Nitrification inhibitors showed the potential to reduce emissions by a further 5%.

These simulations have important implications for agricultural GHG mitigation. A Memorandum of Understanding between the New Zealand government and the agricultural sector is focusing on delivery of technologies that would mitigate N_2O and CH_4 emissions by 20% relative to “business as usual” (baseline farm in this study) by the end of the first Kyoto commitment period (2012) (Ministry for the Environment, 2008). The potential reduction of 15% in CH_4 emissions/ha are encouraging, given predictions by O'Hara *et al.* (2003) that ruminant CH_4 emissions will exceed the 1990 levels (the target) by 16% in 2010.

If the assumptions used in the simulations could be implemented on a Waikato dairy farm there is potential to decrease GHG emissions by 27–32% while increasing profitability by up to $821/ha/annum. The key lies in maintaining production and lowering total DM intake. This can be achieved by a combination of high (but realistic) reproductive performance leading to low involuntary culling, using crossbred cows with high genetic merit and able to produce 430 kg MS/yr, and pasture managed to increase quality by 1 MJ ME/kg DM relative to an average farm. With these improved efficiencies, stocking rate can be reduced from 3 to 2.3 cows/ha. Nitrogen fertiliser rates can be reduced to less than 50 kg/ha/yr and this will include "best practice" application of DCD to maintain DM yield. Considerable GHG mitigation can be achieved by farming with high precision, maximising efficiency, minimising wastage, and better targeting fertiliser application. The results of this study suggest that, by adopting available technologies, it could be possible to meet Kyoto commitment and at the same time improve the profitability of pasture-based dairy farms.

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