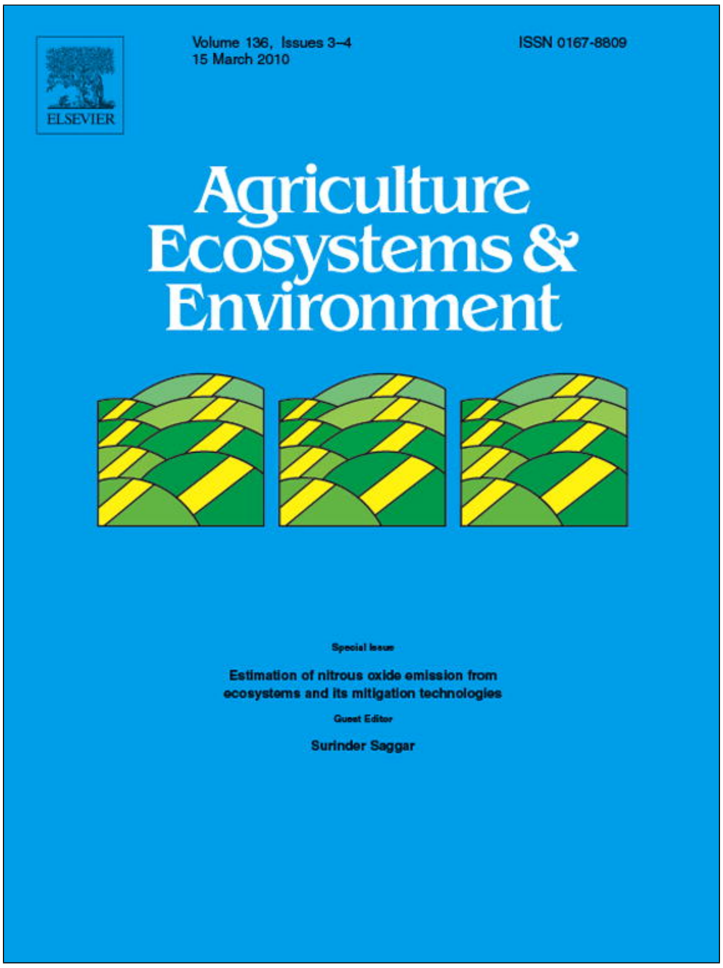

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Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand

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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.

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 emissions (NZ Climate Change Office, 2003). Agriculture contributes about half of New Zealand GHG emissions, most of them coming from grazed pasture-based livestock production systems. In these systems, enteric fermentation and urinary-nitrogen (urinary-N) are the most important sources of CH_4 and N_2O (Waghorn, 2008). Previous studies have summarized 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 multiple mitigation options over several years.

Dairy farming in New Zealand is responsible for about 36% of agricultural GHG emissions (Ministry for the Environment, 2008). Seasonal calving dairy cows are fed ryegrass-dominant pastures. Typically, all cows calve at the end of winter (July–September) and are milked for 8–9 months so feed requirements are largely met

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through fresh pasture. Supplements are typically up to 10% of feed intake, sometimes bought from outside the farm (and overseas), or else grown on farm. Grains are rarely fed but silages are important.

The objective of this modeling exercise was to evaluate the cumulative efficacy of selected mitigation strategies and to calculate their effects on farm profitability. The hypothesis was that improved farm efficiencies may be used to mitigate GHG emissions and increase 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 total feed use (i.e. of the whole herd including replacements) 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 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; protein + fat) per unit of land, and because less feed is required so less CH_4 should be emitted and less urinary-N is deposited (de Klein and Eckard, 2008).
- Increasing pasture quality to achieve a higher average metabolizable energy (ME) content (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. Furthermore, because less feed is required (of better quality) less N-fertilizer is required, resulting in savings in GHG generated during the fertilizer manufacturing process (Wells, 2001).
- Growing a maize 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-fertilizer is required for pasture, with reduced N_2O loss from fertilizer as well as CO_2-e from the fertilizer 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 fertilizer rates (de Klein and Eckard, 2008).
- Standing cows on loafing pads to capture excreta and also reduce pasture damage during wet conditions (standing off). Captured excreta can be re-cycled to pastures for efficient utilization of N by plants (de Klein and Eckard, 2008) and the reduction in N-fertilizer 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 a pasture-based, self-contained (<10% bought-in feed), 'average' dairy farm in the Waikato region of New Zealand. 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 modeled through DairyNZ's Whole Farm Model (WFM; Beukes et al., 2008) with the Molly cow model (Baldwin, 1995), and through Overseer® (Wheeler et al., 2003). The WFM predicted milk production, total feed 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-fertilizer (Fig. 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^{-1}) as more mitigation strategies were included in the farm system.

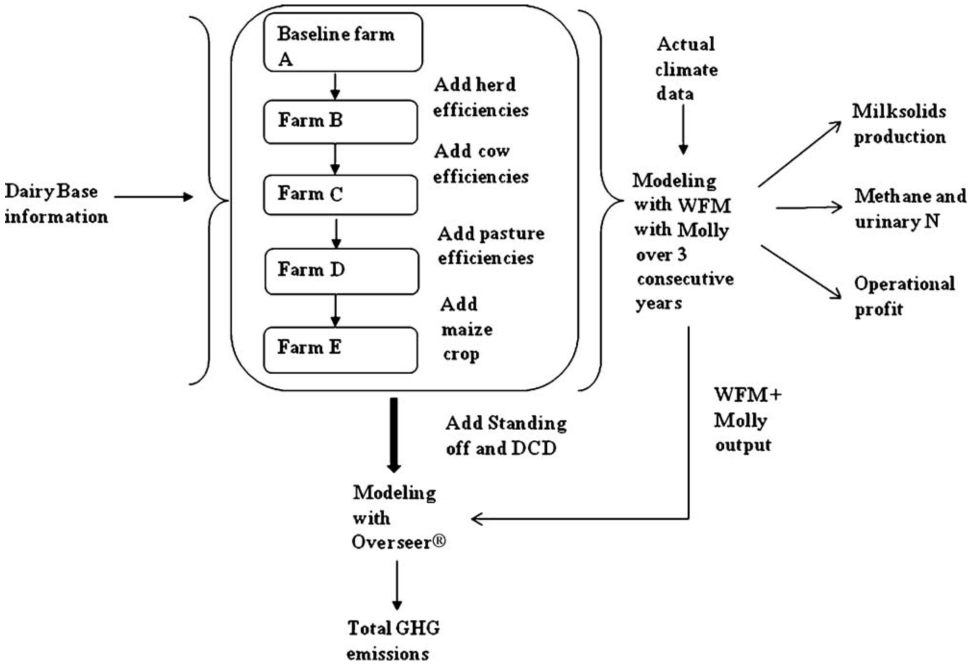

Fig. 1. Schematic representation of the modeling process. Mitigation strategies were sequentially added to Farm A (baseline) to develop Farm B (improved herd efficiency), Farm C (improved animal efficiency), Farm D (improved pasture management) and Farm E (home-grown maize silage). Extra mitigation measures, i.e. standing off and nitrification inhibitors (DCD), were added to each of these farms.

2.2. Models

2.2.1. Whole Farm Model

The WFM was developed to assist with analysis and design of dairy 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 initialized for each. For example, the age, breed and other characteristics that are unique to an individual are used to initialize each cow instance, while for each paddock the 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 rates) 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. 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 necessary for this exercise was the linking of a climate-driven maize sub-model to the framework (Li et al., 2007). 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 fertilizer 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 (i.e. fiber, starch, protein), 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 2006/2007 season costs of buying or selling cows of different age and breeding status, health, breeding and herd improvement costs, cropping and harvesting costs, fertilizer 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. For accurate prediction of production and environmental impacts on a farm-scale, it is important that the cow's production is influenced by the quantity and quality of feed given to it and by its metabolic capacity to absorb and convert nutrients into milk (i.e. its 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, nutrients absorbed into the bloodstream, and metabolized into tissue products (i.e. milk). 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, fecal-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 farm 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^{-1} 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 ME 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, fertilizer and effluent, and indirect losses from leached N and volatilized ammonia (de Klein et al., 2001). The amounts of effluent, leached N and volatilized ammonia are estimated from the associated N budget model. CO_2 emissions from fuel and electricity, processing and some indirect contributions (e.g. fertilizer manufacturing) are largely based on the data of Wells (2001).

2.3. Development of the farm scenarios

The DairyBase database was queried for all owner-operated farms with financial and detailed physical data entered for the Waikato Region of New Zealand for the 2006/2007 season. This group of 31 farms covered the whole range of levels of imported feed. Imported feed creates complexities when investigating the effects of farm system changes on GHG emissions because the imported feed has GHG repercussions beyond the farm gate. There were too few farms with no imported feed to use as a base for developing realistic performance indicators of self-contained, pasture-based Waikato dairy farms. It was decided that less than 10% imported feed was low enough to be considered "self-contained" and, from the 31 farms, 17 that met this criterion were selected. The key performance indicators, policies and economic inputs from this low-input group of farms were used to develop the farm scenarios.

In phase 1 of the exercise the WFM was used. Starting with the average Waikato dairy farm as the baseline (Farm A), four mitigation strategies were added. Incremental gains were introduced sequentially (Farms B–E) (Table 1).

Farm A was simulated in the WFM as a scaled-down 25 ha farm (milking area) starting with 75 mixed-age cows and a further 2.5 ha for rearing young stock (support area). The simulation started on 1 June (mid-winter) with 22 yearlings on the support area and a silage feed store sufficient to fill any pasture deficits. Using information from DairyBase for the "average" pasture-based farm the production target for Farm A was set at 1090 kg MS ha^{-1} and cow replacement rate was 22% per year. Reproduction targets included planned-start-of-calving on 27 July, body condition score (BCS) at calving of 4.4, pregnancy rate after 6 weeks of mating less than 70%, and non-pregnant rate after 12 weeks of mating 12%. The genetic merit of the crossbred cows (average liveweight 430 kg) was average, resulting in production of 390 kg MS cow^{-1} over 262

Table 1

Comparative description of the baseline (Farm A), and farms with mitigation strategies i.e. with improved herd efficiency (Farm B), with improved animal efficiency (Farm C), with improved pasture management (Farm D) and home-grown maize silage (Farm E).

	Farm A	Farm B	Farm C	Farm D	Farm E
Replacement rate	~22%	~15%	~15%	~15%	~15%
Reproduction	Average	Above average	Above average	Above average	Above average
Cow genetic merit	Average	Average	High	High	High
Pasture/silage (MJ ME kg DM^{-1})	11/10	11/10	11/10	12/11	12/11
Cropping	No	No	No	No	Maize on 6% of milking area
Fertilizer on pasture (kg N ha^{-1})	180	115	15	0	0
Stocking rate (cows ha^{-1})	3.0	3.0	2.6	2.3	2.3

days in milk. Average pasture quality (MJ ME kg DM^{-1}) over the year was 11.0 and grass silage quality 10.0 (CP of 21.7% and 14.8%, respectively). N-fertilizer at 180 kg N ha^{-1} was applied (Table 1). The baseline farm was then stepwise improved using information from DairyBase for the top-performing pasture-based farms.

In *Farm B*, planned-start-of-calving was brought forward to 22 July, BCS at calving improved to 5.0, and mating management improved to achieve a pregnancy rate of 75% after 6 weeks of mating and a non-pregnant rate of 7% after 12 weeks of mating. The overall improvement in herd efficiencies resulted in a replacement rate of 16%.

In *Farm C*, the genetic merit of the cows was improved resulting in production of 430 kg MS cow^{-1}.

In *Farm D*, pasture management was assumed to have improved to achieve an average pasture quality of 12.0 MJ ME kg DM^{-1} (CP of 24.2%) over the year and silage with an average quality of 11.0 MJ ME kg DM^{-1} (CP 14.8%).

In *Farm E*, maize was grown for silage production on 6% of the milking area.

Nitrogen fertilizer application to pasture and stocking rate was adjusted to achieve a constant MS production per hectare across the five farms (Table 1).

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

2.4. Simulations and measurements

Each WFM farm scenario was run three times (each run was considered a replicate for statistical analysis). Each replicate consisted of a 3-year simulation using actual weather data from the Ruakura Weather Station (37.8°S 175.3°E) (1998–2001; 2001–2004 and 2004–2007). Results were recorded on a "farm season" basis (e.g. 1998/1999) where each season was from 1 June to 31 May. Results included production (MS cow^{-1}, MS ha^{-1}), and total CH_4 emitted, urinary-N deposited, total DM intake, and operational profit. Profit was expressed as NZ\$ ha^{-1} using 2006/2007 economic input data, with a payout of NZ\$ 4.09 kg MS^{-1}. In calculating operational profit income from milk and livestock sales were considered. Working expenses included wages, animal health, breeding and herd improvement, farm dairy, electricity, supplements made on farm or purchased, lease of the support area, fertilizer, re-grassing, weed and pests, vehicle and fuel, repairs and maintenance, freight and general, administration, insurance, accident compensation, and rates. Sustainability adjustments were made to the operational profit by considering changes in cow condition, average farm herbage mass, and feed inventory from start to end of the simulation.

The results from the WFM simulations were averaged from 3 × 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 fertilizer, and from other sources including lime, fertilizer 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. Statistical analyses

The following statistical model was used for phase 1 results:

$$y_{ij} = \mu + F_i + R_j + e_{ij} \quad \begin{cases} i = \text{A, B, C, D or E} \\ j = 1, 2 \text{ or } 3 \end{cases}$$

where y_{ij} = *ij*th observation (the mean or standard deviation of some output variable over the *ij*th 3-year simulation run), μ = general mean, F_i = *i*th farm effect, R_j = *j*th replicate (i.e. 3-year weather sequence effect), e_{ij} = error corresponding to the *ij*th observation. The significance level was set at α = 0.05 and the mean comparison between farm effects was established by Duncan's multiple range test using the statistical package GenStat 11.1 (Payne et al., 2008).

2.6. 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 optimizing for maximum benefit, in terms of GHG mitigation or profitability.
- Mitigation strategies were added without considering the transition period between the baseline and the improved situation. The time and costs that may be involved, particularly in improving the genetic merit of the herd, were not included in the economic analysis.
- 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 fertilizer 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-fertilized paddocks, therefore not requiring any N-fertilizer.
- In Overseer® simulations, a partial life cycle analysis was used to account for the CO_2 emissions from the fertilizer manufacturing process, assumed to be 3 kg CO_2 kg N $fertilizer^{-1}$ applied (Wells, 2001).

Table 2
Number of cows and yearlings at the start of the season on a 25 ha platform and 2.5 ha support block, intake, milk production and feed conversion efficiency for farm A (baseline), B (improved herd efficiency), C (improved animal efficiency), D (improved pasture management) and E (home-grown maize silage).

Farm	Cows	Yearlings	Total intake (kg DM total ha^{-1})	Milk production (kg MS total ha^{-1})	Feed conversion efficiency (g MS kg DM eaten^{-1})
A	75	22	13600 ± 239a	965 ± 14b	71.0 ± 0.5d
B	75	15	13250 ± 78b	1008 ± 17a	76.1 ± 1.5c
C	66	13	11930 ± 138c	995 ± 15a	83.4 ± 1.7b
D	58	11	11390 ± 282d	1010 ± 25a	88.7 ± 0.6a
E	58	11	11410 ± 263d	1008 ± 21a	88.4 ± 0.6a

In a column, means followed by a different letters are statistically different (Duncan's Multiple Range Test, $P < 0.05$).

Table 3
CH_4 emissions 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 (kg CH_4 ha^{-1})	Per unit of product (g CH_4 kg MS^{-1})	Per unit of DM eaten (g CH_4 kg DM^{-1})
A	336 ± 4a	348 ± 2a	24.7 ± 0.2b
B	321 ± 3b	319 ± 4b	24.2 ± 0.2c
C	287 ± 2c	289 ± 3c	24.1 ± 0.3c
D	285 ± 7c	282 ± 2d	25.0 ± 0.1a
E	287 ± 7c	284 ± 2d	25.1 ± 0.1a

In a column, means followed by a different letters are statistically different (Duncan's Multiple Range Test, $P < 0.05$)

Table 4
Urinary-nitrogen per unit of land (including land for rearing replacements), per unit of product and per unit of DM eaten, for Farms 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 (kg N ha^{-1})	Per unit of product (g N kg MS^{-1})	Per unit of DM eaten (g N kg DM^{-1})
A	235 ± 1a	243 ± 4a	17.3 ± 0.4c
B	229 ± 4b	228 ± 2b	17.3 ± 0.3c
C	201 ± 2e	202 ± 2e	16.8 ± 0.3d
D	212 ± 8c	210 ± 4c	18.6 ± 0.3a
E	207 ± 8d	206 ± 4d	18.2 ± 0.4b

In a column, means followed by a different letters are statistically different (Duncan's Multiple Range Test, $P < 0.05$).

- In Overseer®, the soil type was assumed to be a deep volcanic soil with macronutrient status within the biologically optimum range.
- The implementation of standing off and nitrification inhibitors (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 loafing pad was re-cycled onto the paddocks. DCD applications followed the recommendations outlined in Overseer®.

3. Results

When the farm scenarios were developed, the intention was to maintain milk production constant (within acceptable limits) across the five farms. However, since milk production is an output, in the simulations of the five scenarios over consecutive years, it was influenced by herd reproductive performance of the previous year, dry-off decisions, and climate-driven feed dynamics. This resulted in the average milk production for Farm A being slightly lower compared to the four other farms (Table 2). This should not detract from the fact that feed conversion efficiency increased significantly from Farms A to D as mitigation strategies were added. The strategy of growing maize on-farm in E did not further improve conversion efficiency (Table 2).

The WFM simulations showed that the cumulative effect of the improved herd efficiencies and animal genetics in Farms C–E resulted in a significant 15% reduction in CH_4 ha^{-1} compared with Farm A, based on conventional (baseline) management (Table 3; Fig. 2a). Cows had lower DM intakes per hectare 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 (Table 2), but because of higher g CH_4 kg DM^{-1} eaten (Table 3), quality did not affect a significant reduction in CH_4 ha^{-1} (Table 3; Fig. 2).

The cumulative effects of improved herd and animal efficiencies in Farm C resulted in the lowest deposition of urinary-N, therefore resulting in the lowest emissions of N_2O per unit of land, MS, and DM eaten of the five systems (Table 4). Improved herd and animal

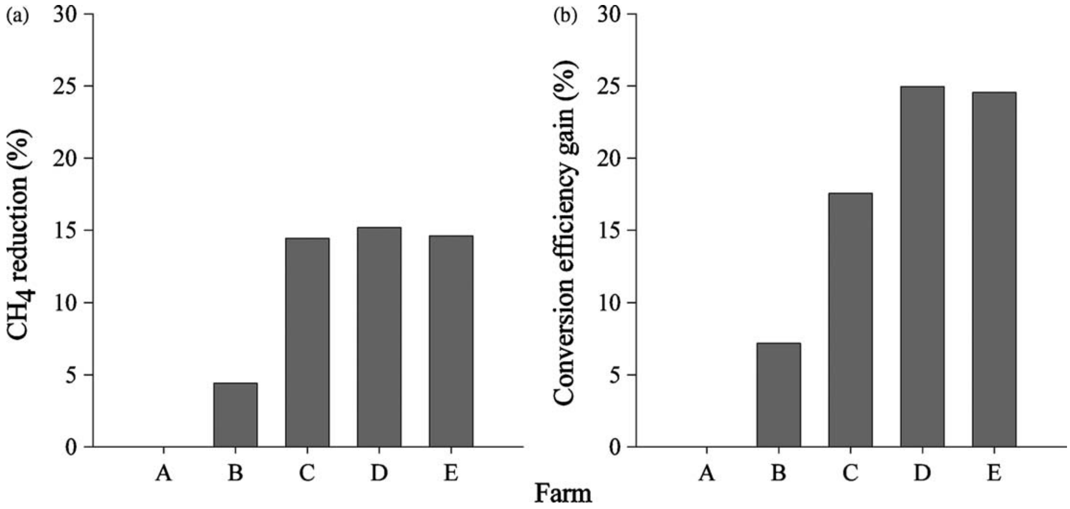

Fig. 2. (a) Percent reduction in CH_4 enteric emission per unit of area and (b) percent increase in conversion of feed into milksolids. Farms A (baseline), B (improved herd efficiency), C (improved animal efficiency), D (improved pasture management) and E (home-grown maize silage).

Table 5
Overseer® results for farm A (baseline), B (improved herd efficiency), C (improved animal efficiency), D (improved pasture management) and E (home-grown maize silage), and added mitigation strategies: standing off (+SO), nitrification inhibitors (+DCD) and the combination (+SO + DCD).

Farm	N applied ($kg\ ha^{-1}\ yr^{-1}$)	CH_4 from animals[a] ($kg\ CO_2$-$e\ ha^{-1}\ yr^{-1}$)	N_2O emissions[b] ($kg\ CO_2$-$e\ ha^{-1}\ yr^{-1}$)	Other sources[c] ($kg\ CO_2$-$e\ ha^{-1}\ yr^{-1}$)	N fertilizer manufacturing ($kg\ CO_2$-$e\ ha^{-1}\ yr^{-1}$)	Total[d] ($kg\ CO_2$-$e\ ha^{-1}\ yr^{-1}$)	$kg\ CO_2$-$e\ kg\ MS^{-1}$
A	180	6295	3508	263	540	10913	11.5
B	115	6087	3235	271	345	10245	10.3
C	15	5706	2494	269	45	8821	9.0
D	0	5122	2201	272	0	7902	8.0
E	0	5487	2412	282	0	8488	8.6
A + SO	180	6335	3508	263	540	10953	11.6
B + SO	115	6127	3235	271	345	10285	10.4
C + SO	15	5743	2494	269	45	8858	9.1
D + SO	0	5149	2201	272	0	7929	8.0
E + SO	0	5526	2412	282	0	8527	8.6
A + DCD	180	6295	2892	263	540	10297	10.9
B + DCD	115	6087	2651	271	345	9661	9.8
C + DCD	15	5706	2055	269	45	8382	8.6
D + DCD	0	5122	1812	272	0	7513	7.6
E + DCD	0	5487	1986	282	0	8062	8.1
A + SO + DCD	180	6335	3002	263	540	10447	11
B + SO + DCD	115	6127	2769	271	345	9819	9.9
C + SO + DCD	15	5743	2166	269	45	8530	8.7
D + SO + DCD	0	5149	1913	272	0	7641	7.7
E + SO + DCD	0	5526	2096	282	0	8211	8.3

[a] 1 kg CH_4 = 21 kg CO_2-e.
[b] 1 kg N_2O = 310 kg CO_2-e.
[c] From lime, fuel, electricity and cultivation.
[d] Includes CO_2-e from capital items of 307 $kg\ ha^{-1}\ yr^{-1}$.

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 4).

The average operating profit (NZ\$ ha^{-1} $year^{-1}$) for the five farms was estimated by the WFM as 1306 ± 52, 1406 ± 289, 1612 ± 289, 2127 ± 173 and 2009 ± 189 for Farms A–E, respectively. The increase in operating profit from Farms A to D was mainly the result of a decrease in stocking rate (overhead costs: NZ\$ 422 cow^{-1}) and a decrease in N-fertilizer used (priced: NZ\$ 685 t $urea^{-1}$), both of which were achieved by increases in efficiencies at herd, cow and pasture level.

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

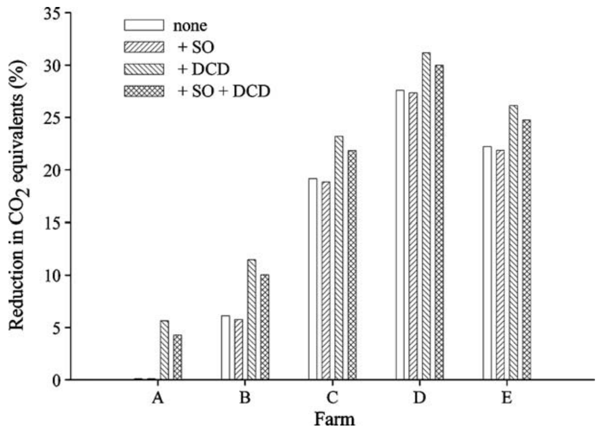

Fig. 3. Percent reduction in total farm emissions (CO_2-e ha^{-1} $year^{-1}$) according to Overseer®, for Farms A (baseline), B (improved herd efficiency), C (improved animal efficiency), D (improved pasture management) and E (home-grown maize silage), and extra mitigation measures: standing off (+SO), nitrification inhibitors (+DCD) and the combination (+SO + DCD).

4. Discussion

Both production (products per hectare) and GHG emissions from grazed pastoral systems are mainly driven by stocking rate and, therefore, total DM intake (de Klein et al., 2008). An increase in production efficiency can either result in more production for the same DM intake, but not necessarily with any net reduction in emissions, or less intake (and emissions) for the same production. These differences are important when evaluating management strategies that can have the largest reduction in environmental emissions for a given level of production. The results presented here indicate that improvements in herd and animal efficiencies could result in a net reduction in total 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 (de Klein et al., 2008). Improved efficiencies also reduce 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 were stocked, with higher feed conversion efficiency, and this resulted in cost savings and a potential increase in profitability. However, the potential increase in profitability has to be placed in context. In the model the mitigated farms were achieved instantaneously whereas in reality it will take time and costs to implement the mitigation strategies, especially the increase in the average genetic merit of the herd. This transition time and costs were not part of the economic analysis. Also, in the time taken to implement the mitigation strategies the baseline farm (Farm A) may have improved in terms of herd genetics and management, which could alter the outcome of profitability comparisons between the baseline and mitigated systems.

The reduction of 5% in CH_4 as a result of improved herd efficiencies in Farm B compared to Farm A, seems conservative when compared with the results of Garnsworthy (2004) who predicted that improving fertility levels in dairy cows, and therefore reducing the number of heifer replacements (≈herd efficiency), could reduce CH_4 emissions on a herd level by 10–11%, and ammonia emissions by about 9%. The WFM simulations showed that the farm with a stocking rate of 2.6 cows ha^{-1} (Farm C) had 15% lower CH_4 emissions per hectare of land compared with the baseline with a stocking rate of 3 cows ha^{-1} (Farm A). In another modeling exercise, Yates et al. (2001) predicted that feeding fewer cows to produce the same milk for the whole herd may result in a 20% reduction in CH_4 emissions. Much of the knowledge and technology for improving reproductive performance, and therefore herd efficiency, is already available (Burke et al., 2008). Similarly, there are opportunities for every dairy farmer to improve the average genetic merit of the herd. It is, therefore, possible and feasible for the average, pasture-based, dairy farmer to reduce CH_4 emissions by at least 10–20% while maintaining production and profitability. The most efficient farms could achieve GHG reductions of up to 27% (CO_2 equivalents per hectare) by a combination of improved herd, animal and pasture efficiencies (Farm D). Nitrification inhibitors showed the potential to reduce emissions by a further 5%, giving a total of 32%. However, it will be a challenge to improve the average pasture quality to >12 MJ ME kg DM^{-1} throughout the year. This has been shown to be possible for the Lincoln University Dairy Farm (Christchurch, New Zealand), where management achieved an average of 12.0 MJ ME kg DM^{-1} for the pasture over the 2003/2004 farming season, an increase of 1 MJ ME over the previous season (Van Bysterveldt, 2005). This was achieved using pasture management policies available to most farmers. However, it was also achieved under different climatic conditions to the rest of the country, with 200 kg N ha^{-1}, irrigation available, and with a stocking rate substantially higher than the 2.3 cows ha^{-1} recommended in this study. It has to be demonstrated that an increase in pasture quality of this magnitude over the whole farming season is feasible with low N-fertilizer inputs, with low stocking rates and under a variety of climatic conditions.

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 per hectare is 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.

The literature indicates that strategies focusing on reduction of g CH_4 kg DM^{-1} eaten by altering components or combinations of components of forage-based diets do not show any clear trends (Waghorn and Woodward, 2006). Unless technologies like monensin, lipid or other feed additives can be shown to significantly reduce g CH_4 kg DM^{-1} eaten, the industry drive to produce more DM ha^{-1}, and, therefore, increase total feed intake of the national herd, will result in an increase in GHG emissions.

Modeling with Overseer® showed that the strategy of standing cows off during wet soil conditions had no impact on GHG mitigation. According to D.M. Wheeler (pers. comm., AgResearch, 2008) there are not enough data to support the hypothesis that removing urinary-N from wet paddocks will reduce denitrification rates. Instead, the urinary-N from the stand-off area ends up in the effluent ponds anyway, from where some N escapes as N_2O, thereby cancelling the hypothetical gains from lower deposits in the paddocks. On the contrary, the increased load of excreta from the stand-off area ends up in the effluent ponds where anaerobic conditions favour higher CH_4 emissions. Insam and Wett (2008) present options to farmers to utilize this effluent for biogas production that reduces GHG emissions by replacing fossil fuels. A negative aspect of standing off is the possibility that cows eat faster and chew less in the shorter grazing times available to them under stand-off conditions (Chilibroste et al., 2007; Gregorini et al., 2008). This leads to longer retention time of ingesta in the rumen, changing the fermentation pattern (Gregorini et al., 2008) and potentially increasing methanogens and enteric CH_4 emissions (Ellis et al., 2008).

The home-grown maize silage strategy resulted in a significant reduction in urinary-N per unit of land and product, but overall did not add more mitigation or profitability to the system. The maize silage farm showed a large amount of surplus feed that could have been used by more animals if it were not for the constraint put on production per hectare. In this case pasture yield could not be reduced further by reducing N fertilizer, because fertilizer use was already zero. The maize system has the potential to be fine-tuned to achieve more mitigation than that shown in this study for instance by exploring different proportions of the farm for home-grown maize, and including maize in the system under conditions where high pasture quality is difficult to achieve.

5. Conclusions

If the assumptions used in the simulations could be implemented on a Waikato dairy farm in New Zealand there is potential to decrease GHG emissions by 27–32% while there is an opportunity to increase profitability by saving on cow and fertilizer costs. 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 lower involuntary culling, use of crossbred cows with high genetic merit and able to produce 430 kg MS yr^{-1} from pasture managed to increase quality by 1 MJ ME kg DM^{-1} relative to an average farm. With these improved efficiencies, stocking rate can be reduced from 3 to 2.3 cows ha^{-1}. Nitrogen fertilizer rates can be reduced drastically, and should include "best practice" application of DCD to maintain DM yield. Considerable GHG mitigation can be achieved by farming with high precision, maximizing efficiency, minimizing wastage, and better targeting fertilizer 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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