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Modelling New Zealand dairy farm systems to design greenhouse gas mitigation strategies

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Abstract

Dairy cattle in New Zealand account for about 17% of the country’s total greenhouse gas (GHG) load. As the nation progresses in its efforts to reduce these emissions, is likely that the dairy industry will face physical constraints and/or financial costs associated with their mitigation. For this study, a non-linear optimization model was developed to analyse the cost-effectiveness of diverse mitigation strategies for reducing GHG loads between 10–30% within systems of different production intensity in the main dairy farming regions of New Zealand: Waikato and Canterbury. Pastoral dairy farms, as found in New Zealand, are complex farming systems with many interdependent management variables and any change in one of these variables in order to reduce GHG emissions will inevitably affect the system as a whole, generating changes in its physical and economic outputs. Computer modelling is thus highly suited to evaluate alternative strategies, given its capacity to represent and consider these interdependencies simultaneously.

De-intensification, by reducing any combination of stocking rate, nitrogen fertiliser and supplement use, was a key strategy in reducing GHG emissions in an economic manner across the whole range of farming systems and regions considered in this study, as well as for all levels of emissions constraints tested. The mean farm profit reduction found under this level of mitigation across all studied systems was 6%, when no other mitigation strategies were available. To achieve this, the mean reduction in stocking rate was 8.8% and the mean nitrogen fertilizer reduction was 36%. Nitrogen fertiliser usage increases GHG emissions by increasing the available mineral nitrogen in soil and thus increasing denitrification and also by increasing enteric methane emissions as more fibrous feed is available to be consumed. The mean profit reduction was 6.9% and 4.9% for the Waikato and Canterbury regions, respectively.

The Canterbury medium-input system had a lower cost of mitigation than the other systems, associated with the use of more supplements with high embedded GHG emissions in the baseline. Accordingly, the use of this kind of supplement was quickly reduced by the optimization model in the mitigation scenarios. At the other end, the Canterbury high input system had the highest cost of mitigation, arising from a combination of larger GHG-e reductions required in absolute terms and the low profitability of the baseline plan, given its

high use of imported supplement. In contrast, the abatement cost in the Waikato systems was intermediate between these two extremes.

Improved reproductive performance and improved genetic merit of the herd were selected as optimal in all cases where specific mitigation strategies were available. Profit was reduced by 1.6%, on average, in this case when 10% GHG emissions reductions were imposed. To adapt to this constraint, stocking rate was reduced by 8.1%, while N fertilizer was reduced by 30.7%, on average. Thus, although the availability of specific mitigation strategies was valuable in reducing the profit losses arising from mitigation, these were not sufficient to reduce emissions without some degree of de-intensification.

Other mitigation strategies, like removing cows from pasture or the use of denitrification inhibitors, were not always cost effective and only entered the optimal solution when higher levels of mitigation were imposed. This demonstrates that the high cost of adopting these specific mitigation strategies is only warranted when systems are exposed to larger profit reductions associated with higher levels of de-intensification. A quick calculation using average reduction in milksolids production found in this study shows that the loss of revenue of the dairy industry if 30% mitigation of GHG is imposed can represent as much as half the export earnings of the entire beef industry of the nation.

Published papers appearing in thesis

Chapter 3 has been published:

Adler, A.A., Doole, G.J., Romera, A.J., and Beukes, P.C. (2013), 'Cost-effective mitigation of greenhouse gas emissions in different dairy systems in the Waikato region of New Zealand', *Journal of Environmental Management* 131, pp. 33–43.

The contributions of each author were: Adler (80%), Doole (10%), Romera (5%) and Beukes (5%).

Chapter 4 has been submitted to a journal:

Adler, A.A., Doole, G.J., Romera, A.J., and Beukes, P.C. (2013), 'Managing greenhouse gas emissions in two major dairy regions of New Zealand', Submitted to *Agricultural Systems*.

The contributions of each author were: Adler (80%), Doole (10%), Romera (5%) and Beukes (5%).

Appendix 1 has been published:

Doole, G.J., Romera, A.J., and Adler, A.A. (2013), 'A mathematical optimisation model of a New Zealand dairy farm', *Journal of Dairy Science* 96, pp. 2147–2160.

The contributions of each author were: Doole (60%), Romera (20%) and Adler (20%).

Appendix 2 Has been published:

Adler, A.A., Doole, G.J., Romera, A.J., and Beukes, P.C. (2012), "Identification of cost-effective management options for reducing greenhouse gas emissions by 10% on a Waikato dairy farm"

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Chapter 1

Introduction

Climate change has been a concern of New Zealand (NZ) environmental policy makers for a long time, and this motivated the country to sign the Kyoto protocol in May 1998. Under this international agreement, NZ committed itself to reduce greenhouse gas (GHG) emissions to 1990 levels or else pay for any excess. NZ ratified the Kyoto protocol in 2002 after designing a comprehensive emissions trading scheme (ETS) that was implemented in some industries, including the energy sector and forestry, but failed to ratify it again in 2013. In August 2013, the NZ government announced new GHG emissions targets to be achieved by 2020. The new target is to reduce GHG emissions to 5% below 1990 levels and was taken under the United Nations Framework Convention rather than the Kyoto Protocol itself. By doing this NZ was joining other developed and developing countries that collectively cause more than 70% of GHG emissions, including USA, China, and Brazil, in efforts against global warming.

NZ is unusual in being a developed country that relies on agriculture for a large proportion of its income: agriculture accounts for about 10% of GDP and more than 50% of total exports, and this is reflected in its emissions profile, with 47% of emissions due to agricultural activities (MfE 2012). This generates a double interest in NZ in reducing GHG emissions: firstly because climate change can have a negative effect on agriculture; and secondly because the image of NZ as a provider of clean, healthy, safe food can be affected by the position the country assumes. Agricultural emissions in other developed countries sit generally at around 12% of total emissions (MfE 2012).

Due to the country's economic dependence on agriculture, any policy designed to reduce agricultural GHG emissions needs to be based upon sound knowledge of the real costs and benefits of this action in order to achieve the desired objectives. Therefore, there is interest in determining the specific cost associated with a reduction of emissions arising from pastoral farming. Even without an ETS in place, it is hard to imagine any serious effort from NZ to reduce GHG emissions that does not incorporate agriculture.

Overall, NZ GHG emissions increased by about 20% from the 1990 level to 72,834.9 Gg CO2-e in 2011 (MfE 2013). In that time, agricultural emissions increased by 12.1%, due primarily to an increase in emissions from dairy cattle and secondarily to an increase in nitrous oxide emissions from agricultural soils (MfE 2012). Direct emissions of methane from farmed ruminants account for about one-third of the total NZ GHG emissions and have risen 5.7% from 1990 to 2011, while nitrous oxide emissions from agricultural soils account for about one-sixth of the national load and have risen 25.5% in the same period as a consequence of an increase of nitrogen fertiliser usage to sustain higher stock numbers (MfE 2012). Nevertheless, agricultural emissions have declined as a proportion of total emissions from about 52% in 1990 to 47% in 2011 (MfE 2013).

Led by the dairy industry, the increase in agricultural GHG emissions arises from a proportionally larger increase in output from farming systems. Therefore, while total emissions increased, the emissions intensity or emissions per unit of product have decreased, following an increase in the individual performance of the animals that has a dilution effect on the energy required for maintenance and on corresponding emissions. Throughout this study, the focus will be on total farm emissions or emissions per unit of land. This approach is not consistent with much of the previous work done on GHG emissions in which emissions per unit of product was the focus, but has its justification in the fact that reducing total emissions of the country is the aim. This also responds to the conclusion reached by Antony Wolken (Wolken 2009, 138 pp) that "targeting emissions per unit of output is not a viable option, as lowering this ratio is difficult while reducing total emissions."

The primary objectives of this thesis are (1) to quantify the cost associated with a 10% mitigation of GHG emissions on New Zealand dairy farms and (2) to identify the abatement options required to achieve this degree of mitigation. A 10% target is relevant because agriculture as a whole has increased emissions since 1990 by about that much (MfE 2012) and under the Kyoto protocol NZ has committed to reducing its GHG load to 1990 levels. To achieve that objective, a detailed non-linear optimization model – the Integrated Dairy Enterprise Analysis (IDEA) model (Doole et al. 2013) – has been developed and farm survey data from DairyBase (Dairybase.co.nz) have been used to model representative dairy systems within the two major dairy regions of NZ, which contain around 55% of the total number of dairy cows in this country. IDEA is described in Annex 1 and includes all of the primary physical and economic elements found within a typical pasture-based NZ dairy system. It also includes all equations needed to calculate GHG emissions associated with these systems.

In the following chapters, the calculations of GHG emissions included in IDEA follow the revised 1996 Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC 2006) using the specific NZ emissions factors for farm-level modelling (MfE 2010). Total emissions were calculated not only as emissions arising directly from the farm but also taking into consideration all the emissions embedded in all farm inputs, such as supplementary feed, fertilisers, fuel and energy and replacement animals grazing off-farm.

The options for abatement of methane and nitrous oxide emissions from dairy farms will be discussed in detail in the next chapter. Methane emissions are tied to the amount of feed ingested by ruminants; therefore, any action to increase feed conversion efficiency (FCE) will, in turn, reduce methane emissions at a given production level. This increase in efficiency can be achieved primarily by feeding the individual animals at an optimum level and also, in the case of dairying, by reducing the number of unproductive animals in the system (i.e. replacements). Another way to increase FCE is by stocking animals of higher genetic merit. This can be modelled in IDEA, but most of the work presented in the following chapters does not include increased genetic merit as a mitigation option. The reasons for that are that it is not realistic for a farm to make a sudden big step in that regard, particularly if an improvement across the whole industry is desired, and at the same time all herds improve over time. A further reason relates to the difficulty of assigning a realistic cost of changing the cows in IDEA in order to obtain meaningful results.

Nitrous oxide appears as part of the nitrogen cycle, produced largely by bacteria that transform nitrates to elemental nitrogen through an anaerobic process (de Klein and Eckard 2008). The rate of this process depends mainly on soil nitrate content and aeration. Nitrogen is the main macro-nutrient of plants; therefore any reduction of nitrous oxide emissions based on reducing its availability will cause a reduction in pasture production. Aeration of soil depends on soil physical properties and weather events presenting less opportunity to reduce emissions other than by incorporating drainage, but this practice can be expensive and not every soil is suitable.

Agricultural soils are also susceptible to losing significant amounts of carbon dioxide. This process is more important in soils subject to intensification by increasing nitrogen fertiliser usage and stocking rate. This is generally the case when land is converted from sheep and beef production to dairy but also occurs when the dairy system is intensified. In this study, soil carbon dioxide emissions are not considered because is generally assumed that soil carbon in New Zealand dairy farms is in a steady state (Jackman 1964; Tate et al. 2005).

In the next chapter, a review of the literature on GHG emissions from dairy farms is presented.

Chapter 3 presents a published paper on the cost of mitigation of GHG emissions from dairy farms. This paper includes analysis of three farming intensity levels on typical Waikato-Bay of Plenty dairy farms and centres the discussion on the costs and systems changes necessary when a 10% reduction in emissions is required. Additionally, the predictions from IDEA are compared with those of Farmax (Brian et al. 2010) a detailed whole farm systems model and OVERSEER (Weeler et al. 2003) a nutrient budgeting model with capability to calculate on-farm GHG emissions.

Chapter 4 presents a comparative study of two contrasting dairying regions of New Zealand – Waikato and Canterbury – for two different levels of inputs (medium and high). A range of mitigation options are discussed in an analysis that involves higher levels of mitigation – up to 30% – providing insights into the different mitigation costs involved in different systems.

Chapter 5 presents the general conclusions and limitations of the study as well as matters identified as worthy of further research. Appendix 1 is a published paper that describes the IDEA model in detail and compares its predictions with trial data and predictions from a less detailed linear model This paper shows that the rich descriptions of real biophysical processes contained within IDEA increase the accuracy of predictions outside the calibrated scenarios, while avoiding infeasible situations when dealing with large changes to the calibrated scenarios. In Appendix 2, a conference paper with an analysis of GHG mitigation costs for a medium-input system farm in the Waikato-Bay of Plenty area is presented.

Chapter 2

Literature review

2.1 Global warming

The rise in the average temperature of Earth's atmosphere and oceans that has occurred since the late 19th century and its projected continuation is known as global warming. The Earth's mean surface temperature has increased by about 0.13 °C per decade in the last 50 years, nearly twice the rate of the last 100 years (IPCC 2007). There is agreement that this global warming is primarily caused by increasing concentrations of greenhouse gases produced by human activities, primarily the burning of fossil fuels and also as a result of deforestation (IPCC 2007)

In the current century, Earth's mean surface temperature is estimated to increase a further 1.1°C to 6.4°C (Meehl *et al.*, 2007). This warming will vary among regions around the globe with the higher levels expected in higher northern latitudes. Its effects include a rise in sea level and changes in the amount and pattern of precipitation as well as more frequent occurrence of other extreme weather events like heat waves, droughts and heavy rainfall that represent a threat to food security from decreasing crop yields and loss of habitat from inundation (Battisti, David; Naylor 2009)

Responses to global warming currently include mitigation by emissions reduction and adaptation to its effects. With the objective of preventing dangerous anthropogenic climate change, the United Nations Framework Convention on Climate Change (UNFCCC) has been created, involving most countries. These countries have agreed that future global warming should be limited to below 2.0°C relative to the pre-industrial level and deep cuts in emissions are necessary to achieve that target. Consequently, policies have been adopted to reduce GHG-e. Nevertheless, the United Nations recognizes an increasing gap between the 2.0°C goal and the reality, suggesting that the efforts incurred up to date are inadequate (UNEP 2011).

2.2 GHG in the world and NZ

Human activities result in emissions of four long-lived GHGs: carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); and halocarbons (IPCC 2007). In 2004 the global emissions based on the CO_2 potential of the 3 main GHGs were CO_2 74%; CH_4 14% and N_2O 8% (IPCC 2007). Total emissions have increased 66% in the period 1970-2004 with emissions of CO_2 leading the increase with 124% growth. Global methane emissions have remained relatively constant since 1990 (IPCC 2007).

In New Zealand, total greenhouse gas emissions increased nearly 20% to 71,657.2 Gg CO_2-e between 1990 and 2010, representing an average annual growth rate of 0.9 per cent per year (MfE 2012). The four emission sources that contributed the most to this increase in total emissions in New Zealand were road transport, dairy enteric fermentation, agricultural soils, and public electricity and heat production.

The agriculture sector in New Zealand has been historically the largest source of emissions, with the exception of 2008, in which the energy sector was the largest source. In 2010, it contributed 47.1% of total emissions (MfE 2012). New Zealand has a unique emissions profile amongst developed countries. In most other developed countries, agricultural emissions are typically less than 12 per cent of total emissions. Agricultural emissions in New Zealand have increased 12.1% from 1990 to 2011, reaching 34,387.3 Gg CO2-e (MfE 2013). The increase since 1990 is primarily due to a 5.7% increase in methane emissions and a 28.8% increase in nitrous oxide emissions from agricultural soils (MfE 2013).

The continued increase in emissions by the agricultural sector has its roots in a continuous increase in the national dairy cattle population. The number of milking cows increased from 2.4 million in 1990 to over 4.6 million in 2011. In the same period, milk solids processed by the industry increased from 599 million kg in 1990 to 1,685 million kg in 2011 (LIC-DairyNZ 2012). This sector has almost doubled its emissions in the period 1990 to 2010, while in contrast, the population of sheep has experienced important reductions. Enteric fermentation from dairy cattle and sheep, and nitrous oxide emissions from agricultural soils were also the largest sources of emissions from the agricultural sector in 2010.

Following IPCC 2006, the equivalency factors for livestock systems are based on the 100-year global warming potentials for methane (CH_4), nitrous oxide (N_2O) and carbon dioxide CO_2 of 25, 298 and 1, respectively (IPCC 2006).

Methane is a by-product of digestion of fibre in ruminants, and some non-ruminant animals, such as swine and horses. Within the agricultural sector, ruminants are the largest source of CH_4 as they are able to digest cellulose. The amount of CH_4 released depends on the type, age and weight of the animal, the quality and quantity of the feed, the energy expenditure of the animal and the amount of feed consumed. Globally, ruminants produce 33% of anthropogenic emissions of CH_4 (Beauchemin et al., 2008). In New Zealand methane emissions also account for about a third of total GHG emissions.

Nitrous oxide (N_2O) emissions happen largely at a soil level when ammonium and nitrates are free in the soil solution. Denitrification is an anaerobic process that reduces NO_3^- to N_2 and is responsible for most N_2O emissions from agriculture. An aerobic process (nitrification) that oxidizes ammonium to nitrate is another soil process responsible for this emission (de Klein and Eckard, 2008). Lower concentrations of inorganic N reaching the soil surface will reduce N_2O emissions per ha. Nitrous oxide emissions account for 10% of global greenhouse emissions (CO_2-e), with 90% of these emissions derived from agricultural practices (Smith et al., 2007). In New Zealand, N_2O emissions account for about 15% of total GHG emissions.

2.3 Kyoto Protocol

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty that sets binding obligations on industrialized countries to reduce emissions of greenhouse gases. The UNFCCC is an environmental treaty signed in 1992 by around 150 countries, with the goal of preventing dangerous anthropogenic interference in the climate system. The Kyoto Protocol was signed in 1997 and entered into force in 2005.

As part of the Kyoto Protocol, 37 developed countries, including New Zealand, agreed to legally enforce limitations on their emissions of greenhouse gases in two commitment periods. The first commitment period applied to emissions between 2008 and 2012, and the second commitment period applies to emissions between 2013 and 2020. The protocol was amended in 2012 to accommodate the second commitment period, but this amendment has (as of January 2013) not entered into legal force. New Zealand, along with Japan and Russia, participated in Kyoto's first round, but has not taken on new targets in the second commitment period. Other developed countries without second-round targets are Canada (which withdrew from the Kyoto Protocol in 2012) and the United States (which has not ratified the Protocol).

Under the Protocol, countries must meet their targets primarily through national measures. However, the Protocol also offers them an additional means to meet their targets by way of three market-based mechanisms, which are: international emissions trading; clean development mechanisms; and joint implementation (www.unfccc.int).

Currently, the Kyoto targets only apply to a small share of annual global emissions. Countries with second round Kyoto targets made up 13.4% of annual global anthropogenic greenhouse gas emissions in 2010. At the global scale, existing policies appear to be too weak to prevent global warming exceeding the level indicating potentially serious climate change set by the UNFCCC.

2.4 IPCC role and calculations

The IPCC was established in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP), thus recognising the increasing evidence of anthropogenic climate change. Signing the UNFCCC required countries to develop, update periodically and publish national GHG emissions using standard methodologies. In order to meet UNFCCC reporting requirements, the IPCC published guidelines for calculating national GHG inventories (IPCC 1997). These guidelines are updated and allow for quantification of national emissions based on readily available activity data including fertiliser sales, animal numbers and land use change, as well as associated emission factors for each activity.

Continual development of IPCC guidelines is dependent on input from global experts in the respective sectors. For example, the 2006 guidelines involved contributions from over 250 experts worldwide.

In terms of agriculture, the IPCC guidelines provide widely applicable defaults for compiling national GHG inventories. However, the robustness of these inventories is dependent on developing country-specific emission factors and verifying emissions inventories via modelling and/or direct measurement (IPCC 1997). Consequently, the IPCC developed a three tier system for quantifying emissions sources and sinks, with each successive tier having an increased level of detail and accuracy, allowing for increased inventory refinement where possible.

2.5 Previous modelling work

2.5.1 Role of whole farm models

Although IPCC methodologies provide guidelines for transparent compiling and reporting of national GHG inventories, they have some limitations when modelling at a farm level, mainly because variations that arise due to differences in farming systems and regions are not considered. Alternatively, whole farm system models have been developed and are widely used. These models provide more flexibility and sensitivity to capture farm level activity and a better description of the effects of any system change in all the emissions associated with production. They also present however, concerns for their comparisons due to differences in structure and data sources. Ellis et al. (2010) evaluated 9 equations used to predict methane emissions in whole farm models and found that the predictions were poor. Overall, whole farm approaches provide the most robust and comprehensive method for developing and implementing effective mitigations strategies (Crosson et al. 2011), but they should not be seen as a replacement for IPCC methodology (Schils et al. 2007).

Whole farm systems modelling studies can differ in the boundaries assumed for the calculations of GHG emissions, ranging from on-farm emissions plus emissions embedded in purchased feed to a life cycle assessment methodology in which the potential environmental impacts of a product are assessed by quantifying the resources consumed and the emissions to the environment at all stages of its life cycle, ranging from the extraction of raw materials to the reuse, recycling or disposal of the final product. Most agricultural studies include on-farm and pre-farm emissions, such as emissions embedded in purchased feedstuff. They also generally account for indirect emissions from ammonia volatilization and nitrogen leaching, but more variation seems to appear for machinery and buildings-related emissions (Crosson et al. 2011).

Whole farm models have also been used as a potential policy analysis tool (Ramilan et al. 2007). The best solutions to pollution control problems require knowing each farm marginal abatement cost, hence the importance of modelling the results of policies at a disaggregated level to capture firm heterogeneity in terms of their physical environment and the economic behaviour of the farmers.

2.5.2 Whole Farm Model research applied to GHG emissions

In a dairy system modelling study, Beukes et al. (2010) evaluated the effects of different mitigation strategies (reduced replacement rates, higher genetic merit of cows, improved pasture management and the inclusion of home grown maize silage that increases total metabolizable energy while reducing nitrogen intake) on GHG emissions over different climate years for a pasture-based farm in Waikato, New Zealand, using the DairyNZ Whole Farm Model framework. Their objective was to maintain production levels in the mitigated farm scenarios similar to those recorded for the baseline (non-mitigated) scenario. The simulations suggested that the combined effect of these strategies could decrease GHG emissions by 27% with potential for increased profitability. Feed conversion efficiency increased significantly as mitigation strategies were added, except for growing maize on-farm. Cumulative effects of herd efficiencies and animal genetics resulted in a 15% reduction in CH_4 ha^{-1} compared with baseline farms. These effects also resulted in the lowest deposition of urinary N, potentially reducing N_2O emissions per unit of land by up to 14%. This emissions reduction was possible due to a reduction of CH_4 emission driven by a lower total dry matter intake (DMI) and a lower total urine N output, with a consequent reduction in potential N_2O emissions (de Klein and Eckard, 2008), while maintaining production by stocking fewer cows with higher feed conversion efficiencies. Another two mitigation strategies were tested on the already mitigated scenarios. These were standing cows off pasture on a loafing pad and the application of a nitrification inhibitor (DCD). A further 5% reduction in GHG emissions was found with the application of DCD, giving a total reduction of 32% with respect to the baseline level, but no effect on GHG emissions was found by standing cows off pasture during wet conditions or by including a maize crop in the system.

The ability to maintain production while reducing stocking rate was the main reason for increased farm profitability. Higher feed quality also resulted in higher feed conversion efficiency but because of the higher CH_4 kg DM^{-1} eaten, quality did not translate to a significant reduction in CH_4 ha^{-1}.

In another modelling study that built on this previous analysis, Beukes et al. (2011) evaluated the effects of five mitigation strategies (improving reproductive performance, increasing genetic merit of the cows, standing lactating cows on a loafing pad for 12 hours a day for 2 autumn months, growing low-protein cereal crops on a portion of the farm to feed lactating cows, and reducing N fertiliser use while simultaneously employing nitrification inhibitors and gibberellins) on a typical pasture-based Waikato dairy farm in New Zealand. The authors found that reducing total DM intake, together with a reduction in N input and a dilution in dietary N, decreased GHG emissions by 15-20% per hectare, while milk production per ha increased 15-20%. This was possible because the combination of strategies achieved a reduction of the proportion of feed diverted to maintenance, leaving more for production, together with a reduction of total nitrogen input and therefore less nitrogen excreted onto pastures.

Similarly, Dynes et al. 2011 modelled a highly productive dairy farm in the Canterbury region of New Zealand using Farmax Dairy Pro® (Bryant et al. 2010) and OVERSEER® (www.overseer.co.nz). They tested alternative scenarios including reduced nitrogen fertiliser use, increased genetic merit, reduced stocking rate, use of nitrification inhibitors and the impacts of grazing replacement animals on and off the areas grazed by milking cows. The results showed that while emissions per ha were reduced up to 14% with respect to the base farm, emissions intensity (emissions per unit of product) varied from 33% more than that of the baseline to 16% less, showing that these outputs can be independent. Nevertheless, farm profit per ha varied far more than emissions defined either per ha or per unit of product. The authors concluded that farmers should place greater emphasis on profit in deciding on the best system for their farm, which will normally have a correlated beneficial effect on GHG emissions intensity, and that it is possible to achieve a combination of emissions efficiency and high profit at the same time. They further indicated that these outcomes are generally associated with farming systems that increase production per cow.

In addition, O'Brien et al. (2010), when modelling a combination of 3 cow strains and 3 feed systems for Irish dairy farms, found a variation in profitability of 80% while system GHG emissions changed 22% and 17% per ha and per unit of product respectively. They tested the influence of cow genetics across different feeding systems using a whole farm simulation model of grassland-based dairy systems and found that GHG emissions per ha increased generally with more intensive systems (higher stocking rate and/or more concentrate feeding). This increment was due to higher herd total feed intake. They also reported that the most profitable combination was the NZ strain in a high stocking rate system (2.74 cows/ha). This combination resulted in a 12% reduction in GHG emissions per ha when indirect emissions were included, compared with the high concentrate system (1445 kg of dry matter concentrate offered per cow), demonstrating that grass-based systems can achieve high profitability and decrease GHG emissions simultaneously. The results also demonstrated that the lowest GHG emission per unit of product and maximum profitability were achieved with Holstein-Friesian cows, combining high genetic potential for both production and fertility traits, since higher genetic merit for fertility translates into a reduction in non-productive animals and consequent increase in total milk yield.

Basset-Mens et al. (2009) studied the effect of intensification of New Zealand dairy farms using life cycle assessment to compare an average NZ dairy farm system with those of three dairy farmlet systems representing a wide range of intensification scenarios. The average NZ dairy farm had 114 kg per ha of N fertiliser, 1.1t DM pasture silage per ha per year and 2.74 cows/ha The three intensification scenarios were: 1: A low input system with no N fertiliser, no brought-in feed supplement, and a stocking rate of 2.3 cows/ha; 2: A moderate input system with 170 kg of N fertiliser per ha, no brought-in feed supplement, and 3 cows per ha and 3: A high input system with 170 kg of N fertiliser per ha, 13 t DM maize silage per ha per year and 5.2 cows/ha. These authors found that the low input system had the lowest GHG emissions per kg of milk and also the emissions per ha were very similar to those of the average NZ farm which had the lower emissions per ha. The other two scenarios had the most emissions per ha, suggesting that any further intensification of the farm system by means of increasing nitrogen or supplement usage to sustain higher stocking rates is likely to create an increase in GHG emissions. This is consistent with the findings of Beukes et al. 2010 and 2011 and Dynes et al. 2011 where reducing stocking rate was always associated with a reduction of GHG emissions per ha.

There is a high positive relationship between GHG emissions and nitrogen leaching, which is a potential pollutant of NZ waterways (Doole, 2012; Smeaton et al. 2011; Ledgard et al. 2010) but the association between these two emissions parameters and farm profitability is weak (Smeaton et al. 2011; Dynes et al. 2011). Apparently, the strategies that can potentially achieve high dairy farm profit and low GHG and N leaching emissions at the same time are: lower stocking rate combined with high per head performance; much higher than average breeding worth herds; restrained but not nil use of nitrogen fertiliser; use of nitrification inhibitors; and lower replacement rates (Smeaton et al. 2011). Systems with these characteristics recall the mitigated scenarios of the studies of Beukes et al. (2010 and 2011) These practices may not be readily adopted by farmers because they may be very costly, difficult to achieve in practice or require a significant increase in managerial skill or a combination of all three. They also may increase the economic risk of the system by increasing the risk of reduced pasture utilisation and quality.

There are, however, commercial examples of highly efficient dairy farms in New Zealand. These farms typically feed less than 10% of imported supplements and carry moderate stocking rates of 2.5 to 3.3 cows per ha. These farms are run by farmers who have particular personal characteristics – typically highly organized, committed and flexible – and have a highly proactive approach to pasture management (Vibart et al. 2011). The high managerial skills needed to efficiently run a lower SR dairy system without reducing pasture utilisation and losing pasture quality appear to be a condition, in addition to the right number of the right (efficient) cows (Vibart et al. 2011)

In extensive modelling work, Christie et al. (2011) modelled 60 Tasmanian dairy farms with a range of levels of milk production, grain feeding, nitrogen fertiliser application rates and reliance on irrigation for pasture and crop production. The model used was DGAS, which combines IPCC and Australian methodologies for GHG emissions. They found that milk production was an accurate way to predict GHG emissions since this accounted for 90% of the difference in estimated total farm GHG emissions. Nonetheless, the variations in GHG emissions intensity were in the range 0.83 to 1.39 kg CO_2 per kg of milk and the variation was most influenced by feed conversion efficiency and the amount of nitrogen fertiliser applied. The proportion of grain in the diets varied between 0 and 390 g per kg of dry matter and there was a positive linear relationship between the proportion of grain in the diet and feed conversion efficiency, with increments of 9% in feed conversion efficiency for every 10% increase in grain in the diet. Inclusion of grain in the diet as a GHG emissions reduction strategy will be touched on several times in this review. This strategy may lead to increased stocking rates with consequent increases in methane emissions per cow and per unit of land, even though emission intensity is likely to be reduced.

2.6 On-farm abatement options and opportunities

2.6.1 Enteric Methane

Ruminant livestock produce 80 million tonnes of CH_4 per year globally, about one third of the total anthropogenic CH_4 load. Enteric methane is the methane produced in the rumen by methanogenic Archaea: this process uses CO_2 and H_2 that is a byproduct of microbial metabolism, allowing the rumen's ecosystem to continue functioning by acting as a sink of H_2. Accumulation of H_2 in the rumen would inhibit re-oxidation of NADH therefore inhibiting microbial growth, rumen digestion and production of volatile fatty acids. Methane is not absorbed in the rumen; therefore, it is released to the atmosphere via the breath (Eckard et al.2010). Out of the three more important volatile fatty acids, microbial processes that produce acetate and butyrate result in production of H_2 while synthesis of propionate consumes $H_{2,}$ resulting in lower methane production. Digestion of fibre results in low levels of propionic acid, while fermentation of starch and protein results in high levels and fermentation of sugars produces intermediate levels of propionic acid (Van Soest 1994).

The amount of CH_4 produced by a ruminant depends mainly on the amount of feed digested in the rumen. Methane yield is typically 6 to 10% of the total gross energy ingested by dairy cows. IPCC methane yield is calculated as 6.5% of the gross energy intake for cattle. Apart from the implications for global warming, this loss represents a significant inefficiency in the farm system. Several options have been considered to reduce enteric methane emissions. Eckard et al. 2010 group them in 3 classes: animal manipulation, diet manipulation and rumen manipulation.

In terms of animal manipulation, the options in dairy systems seem to be reduced to breeding cows for lower methane yield or reducing the number of unproductive animals. A variance of 15% in grams of methane per kg of DMI has been reported between dairy animals. Similar variation has been reported in sheep and steers, suggesting that animal breeding could achieve a significant reduction in methane losses from rumen digestion. Waghorn and Hegarty (2011) argue that part of the variation found between individuals in methane yield is due to the measuring method and note that the selection of more efficient animals can be used in both intensive and extensive systems and should complement selection for improved health, productivity and profitability. Therefore the emphasis should be more on breeding for improved feed efficiency since breeding for reduced methanogenesis is unlikely to be compatible with other breeding objectives (Eckard et al. 2010). Reducing the number of unproductive animals by improving reproduction or extending lactation can also reduce methane emissions and improve farm profitability at the same time.

There are more options that potentially reduce methane emissions through dietary manipulation. Consideration of several factors and interactions that potentially affect the risk of N and CH_4 losses from cattle must be taken when evaluating cost-effective mitigation options. Improvement of forage quality has been shown to reduce methane emissions: hemicellulose digestion yields about a third as much methane as cellulose, and at the same time these structural carbohydrates yield more methane than non-structural carbohydrates. This can be manipulated by improving pasture management, by changing C4 grasses to C3 where applicable, by increasing the proportion of legumes in the sward (legumes have lower fibre content and condensed tannins and this is associated with lower methane yield) and by plant breeding. Pinares Patiño et al. 2003 found that methane yield did not differ between vegetative and senescence stages per unit of feed dry matter intake but large differences were found in methane yield per unit of dry matter digested. Higher feed quality also increases voluntary intake, with a consequent reduction in retention time in the rumen promoting more energy-efficient post-ruminal digestion and thus reducing the proportion of dietary energy converted to methane. Assessing the impact of any improvement in pasture quality on GHG emissions of the farming system using whole farm modelling is particularly important, as this can be used by farmers as an opportunity to increase stocking rates, thus not only reducing the magnitude of the desired effect but also increasing emissions of nitrous oxide from the soil.

Cattle consuming high starch diets have less methane emissions per kg of intake than cattle on fibrous diets (Johnson and Johnson 1995), partially because the concomitant lowering of ruminal pH will stimulate formation of propionate over acetate or butyrate (Dijkstra et al.

2011), but whether this translates to a reduction of GHG emissions of the farm is still unclear and depends on the farming system (Beauchemin et al. 2010). Addition of high starch grains to the diet have the supplementary benefit of also reducing N excretion in the urine. However, it must be remembered that grain supply is also limited, feeding grains is not always profitable, and that while ruminants are highly efficient at producing human food, in terms of human edible food produced per human edible food consumed, they are less efficient than monogastrics (such as chickens) in the digestion of starch, which can also be directly eaten by humans. When evaluating the effects of grain supplementation on dairy farm GHG emissions LCA methodologies are more relevant since they consider all the emissions involved to produce and transport the material.

Some plant secondary compounds like condensed tannins can reduce methane production by having a direct toxic effect on methanogens. Reductions of 13-16% have been found, but in high concentrations such compounds can reduce feed intake and digestibility (Eckard et al. 2010). Condensed tannins can also reduce urinary nitrogen excreted, with a concomitant reduction in nitrogen leaching and nitrous oxide emissions.

Fat is another secondary compound that has been proven to reduce methane synthesis. Methane reduction of 10-25% can be achieved with fat intakes above 6% to 7% of the diet, but fats can decrease cattle performance if fed at a high level. Also, the applicability of this strategy in pasture-based systems is limited since the fatty acid content of grasses is typically 1.5 to 3% (Dewhurst et al. 2001).

Dietary supplements like yeast cultures can also potentially be an option, but the reduction in methane achieved seems to be variable (McGinn et al. 2004). Enzymes, such as cellulase and hemicellulase, can be used too. They are produced in quantity and at a reasonable price, and improve ruminal fibre digestion and productivity, but more research is needed to identify the right yeast strains and enzymes that confer significant abatement potential (Eckard et al. 2010).

Finally, rumen manipulation also has potential to reduce methane production. A range of intervention methods have been tested including the introduction of chemicals, particular microbes, and vaccination. However, in general, these methods do not represent a viable solution in the near future. The reasons for that are that they are either too expensive, their effect is not consistent and/or too transitory, they can be dangerous for the animals, or they are unlikely to gain public acceptance.

2.6.2 Nitrous oxide

Denitrification is the main cause of nitrous oxide production in agricultural soils. It is an anaerobic process that reduces NO_3 to N_2 with N_2O as an intermediate. Nitrification, on the other hand, is an aerobic process that occurs in the soil with N_2O as a byproduct. Soil nitrate levels and soil aeration are probably the most important factors affecting N_2O emissions from grazing systems but available soil carbon, soil temperature and pH among others also affect and regulate the rate of these processes (Eckard et al. 2010). All of these characteristics of the soil are constantly changing as a result of environmental and managerial factors, generating large spatial and temporal variability in N_2O emissions.

2.6.2.1 Soil management options

Soil aeration has been regarded as the main factor affecting N_2O emission (Luo et al. 1999) and is dependent on soil water content which varies with rainfall and soil texture. Therefore improving drainage on paddocks can potentially be an option to reduce N_2O emissions, but this can increase nitrogen leaching. Soil compaction is another important variable determining N_2O emission. Forage crops grazed during winter months are particularly vulnerable to treading damage and consequent compaction, potentially doubling the N_2O emissions (Oenema et al. 1997). Reduced tillage or direct drilling can reduce the subsequent compaction and N_2O emission. On the other hand, Velthof et al. (2009) found that N_2O emissions were higher after renovation without ploughing comparing with ploughing, presumably because ploughing increases soil aeration, thus reducing denitrification.

Standing cows off pasture on a loafing pad can reduce N_2O emissions by reducing excreta deposition at times where the risk of soil compaction and denitrification are higher. About 10% reduction in N_2O emissions is plausible (Luo et al. 2010), but the time animals spend off pasture has to be long: over 3 to 4 months in late autumn and winter. The main disadvantages of this option are the need for high capital investment, high maintenance costs and the need for extra feed to compensate for reduced grazing time. In applying this technology, collection and application of large quantities of effluents is necessary for the efficient use of N, as there are several opportunities to generate losses from effluent systems. In addition, the beneficial effect of reducing treading damage on pasture growth rates can be outweighed by the reduction of quality in pastures that can remain ungrazed for several months, with consequent negative effects on animal performance and methane emissions.

Nitrogen-fertilised grass pasture appears to have higher N_2O emissions than grass-clover pasture even with some nitrogen fertiliser applied. This is due to the lower soil mineral nitrogen content of grass-clover pastures compared with fertilised grass pasture. Also, N_2O emissions increase exponentially with increasing N rates when conditions are suitable for denitrification, so application of N fertiliser or effluents in the colder wetter months when plant uptake is slow should be very limited. Irrigation can often create conditions for greater N_2O emissions, but irrigation through extended dry conditions can actually reduce them by reducing the building-up of NO_3 by increasing plant uptake.

Nitrification inhibitors inhibit the oxidation of NH_4 to NO_3 in soils, reducing N leaching and N_2O emissions from NH_4-based fertilisers and urine. Potential reduction on-farm is still uncertain but has been measured at up to 70%. These products are currently banned in New Zealand.

2.6.2.2 Animal management options

Reducing nitrate levels in soil can potentially reduce N_2O emissions. Nitrogen surplus (N input minus N in products) is linearly related to N input levels (Ledgard et al. 1997). In order to manage lower inputs without a reduction in pasture growth rates and reduced farm profit, it is necessary to apply strategies that improve feed conversion efficiency and/or the efficiency of nitrogen cycling in the animal-pasture-soil system.

More than three quarters of the nitrogen ingested by dairy cows will be excreted in urine and dung; this proportion can be up to 90% (de Klein et al. 2010). Dung N excretion is relatively constant, whereas increasing excess N ingestion will be excreted in urine, creating patches of pasture that receive a rate of 800 to 1300 kg of N per ha (Eckard et al. 2006). That concentration cannot be efficiently utilised by the soil-plant subsystem. Urinary N is mainly urea and is rapidly nitrified to NO_3 that is vulnerable to leaching and also accounts for about 60% of N_2O emissions from pasture (de Klein 2005). Therefore the risk of urinary N being lost is very high. In New Zealand dairy farms, these patches are likely to cover about 25% of the grazing area every year and overlapping is possible (Hynes and Williams 1993). The first and obvious option to reduce the incidence of urine patches is to reduce the number of animals on the farm. The implications of this option on GHG emissions and profitability were discussed previously with regard to the results of Beukes et al. 2010 and 2011, Dynes et al. 2012, and Smeaton et al. 2012.

A number of other strategies have been proposed to reduce the amount of nitrogen excreted as urine. These include: breeding animals with higher feed conversion efficiency, reducing nitrogen content in the diet and feeding condensed tannins (CT). Animals with higher feed conversion efficiency should partition more of their intake into production and less into N excretion, reducing potential N_2O losses. Also, breeding animals for higher productivity should reduce N losses by diverting more N into products (Rius et al. 2012)

Pasture-based systems have lower opportunities to reduce nitrogen concentration in the diet, because the high quality pasture required to run the system efficiently typically has levels of protein higher than the animals' requirements. This is particularly true for nitrogen-boosted spring ryegrass pastures. The addition of low-protein concentrates (e.g. maize grain) to the diet or novel high sugar perennial ryegrass has been proven to effectively reduce nitrogen excreted by 10 to 30%. This reduction could translate to a 20 to 30% reduction in N losses per kg of milk (de Klein et al. 2010). However, high sugar grasses will only reduce urinary N if the extra sugar levels come at the expense of protein. Eliss et al. (2011), using a mechanistic model, demonstrated that high sugar levels, at the expense of fibre, reduced faecal N excretion but not urinary N excretion with small changes in N efficiency. Another option that offers potential to reduce the N concentration in urine is the addition of salt to the diet. High salt diets increase water uptake by the animals, reducing the concentration of urinary N and increasing the frequency of urination and therefore the area covered by the urine patches, increasing the opportunity for growing plants to use additional N.

Feeding condensed tannins can reduce the proportion of N excreted as urine with respect to the total N excreted by forming complexes with protein: this results in either better digestion of amino acids in the duodenum or more N excreted in the dung (Eckard, 2010). In general, adding CT to the ruminant diet will reduce the proportion of urinary N by 25 to 50% and increase dung N by 20 to 60%, with concomitant reduction in nitrogen losses at least in the short term. Apart from the high cost of condensed tannins, Grainger et al. (2009) also found that cows eating a high condensed tannins diet produced 10% less milk.

Not all of the available options have the same potential for reducing GHG emissions. Kohn et al. (1997) developed a model of nitrogen management on dairy farms to perform sensitivity analysis with the objective of determine the relative importance of manipulating herd nutrition, manure management and crop selection in reducing N losses. They found that animal diet and management techniques that increase the conversion of feed N to animal product by 50% would increase total farm N efficiency by 48% and reduce N losses per unit of product by 36 to 40%, while selecting crops and soil management that can use soil nutrients 50% more efficiently would improve total farm efficiency by up to 59% and reduce N losses by up to 41% depending on the predominant N sources for the farm. This study demonstrated that there is considerable potential to reduce N losses from dairy farms, without adverse effects on production. The potential for reducing nutrient losses by altering diet formulation or herd management is clearly evident. But there is less opportunity to reduce nitrogen losses by improving manure storage and application methods.

2.7 Soil carbon and nitrogen changes

Although it has generally been considered that the levels of carbon and nitrogen in developed pastoral land are in a steady state, there is recent evidence of significant changes within dairy farmland in New Zealand. Tate et al. (1997) found no change in pasture topsoil (15 cm) between 1950 and 1992. Schipper et al. (2010) noted, however, that the majority of these samples were taken prior to the increased intensification of dairy systems in New Zealand that occurred in the 1990s by increasing the use of N fertilisers to support higher livestock numbers. Schipper et al. (2007) found large losses of carbon and nitrogen (1.06 t of carbon and 91 kg of nitrogen per ha per year) when sampling intensive dairy land to a 1 m depth. In a follow-up study, Schipper et al. (2010) found losses of carbon of 1.21 t and N of 112 kg per ha per year from land under dairy farming and no change in land devoted to other grazing uses. This suggested that the losses are associated with management practices between the different land uses since there was considerable spatial overlap of the different land uses making it unlikely that recent changes in climate generated different changes in the dynamics of soil carbon and nitrogen. Similar carbon and nitrogen losses were found across the 12 soil orders sampled. In addition to the important consequences of carbon losses from the soil in terms of global GHG balance, there may be important consequences of nitrogen accumulation due to changes in land use or farming practices. Most of the growth in the NZ dairy industry was over land already under pasture but managed at lower intensity (sheep and beef) and part was converted from forestry land. This can generate net immobilization of nitrogen at rates that decrease over time but can continue for a century; enriched soils can have more nitrogen available for plants to uptake, but losses can be also enhanced (Schipper et al., 2010).

However, a key shortcoming is that the effect of combined GHG mitigation options on a wide range of dairy farm systems within different regions of New Zealand has not yet been reported, particularly in an optimized modelling environment. This study seeks to resolve this deficiency, evaluating a combination of different mitigation options.

Chapter 3

Cost-effective mitigation of greenhouse gas emissions from different dairy systems in the Waikato region of New Zealand

In this chapter, Alfredo A. Adler was primarily responsible for the writing and the literature review. He also generated the baseline farms through an extensive review of dairy farm data and gathering of expert opinion. This involved Farmax and OVERSEER modelling.

Graeme J. Doole calibrated and ran the IDEA model and presented the tables for the discussion.

Alvaro J. Romera participated in the design of the study, giving valuable contribution to the process that led to the selection of the farms used in the study.

Pierre C. Beukes contributed to the writing and added to the discussion.

Cost-effective mitigation of greenhouse gas emissions from different dairy systems in the Waikato region of New Zealand

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Abstract. The New Zealand dairy industry produces approximately 17% of this country's total greenhouse gas emissions (GHG-e) and it is also this nation's largest export industry. The industry needs to reduce GHG-e under proposed policy directives and for ongoing market security. Given these pressures, there is a need to identify cost-effective management strategies to reduce on-farm GHG-e. The objective of this study was to investigate how the management of dairy farms in the Waikato region of New Zealand could change to minimize the abatement costs associated with GHG-e mitigation. Three typical farm systems importing low (less than 10%), medium (10 to 20%), and high (more than 20%) amounts of supplement were modelled using a non-linear optimisation model.

A reduction in nitrogen fertiliser application was the production factor that changed the most to achieve the cap in all of the simulated systems, followed by a reduction in stocking rate. With the prices used in this study, decreasing farming intensity by reducing nitrogen fertiliser by 21–42% and stocking rate by 8–10% represented a cost of \$68–\$119/ha and a production reduction of 54–117 kg MS/ha for the three systems studied. Improving reproductive performance proved to be effective in reducing GHG-e, allowing for fewer replacement cows to be supported. However, it did not have a significant effect on profit when emissions were unconstrained. Nitrification inhibitors and stand-off pads were not identified as useful mitigation options, given their high cost relative to de-intensification.

Key words. Dairy production, intensification, mitigation, optimisation model.

3.1. Introduction

Dairy farming accounts for about 17% of greenhouse gas emissions (GHG-e) in New Zealand (NZ) and emissions from NZ agriculture are believed to have increased by around 10% over the period 1990–2008 (MfE, 2010). However, the dairy industry is also the largest export industry in New Zealand, producing 3% of GDP and 26% of total merchandise exports (NZIER, 2010). The economic importance of this industry, considered alongside its level of emissions, highlights the need for the identification of cost-effective management strategies to reduce on-farm GHG-e. GHG-e from the dairy industry arise from diverse sources, but major contributions are from enteric fermentation during digestion by cattle, urine deposition on pasture, manure storage, and nitrogen fertiliser and manure application to crops and pastures (de Klein and Eckard, 2008; Eckard et al., 2010). Moreover, emissions from this sector are forecast to increase, with FAO (2006) predicting that meat and milk consumption will double by 2050, relative to 2000 levels, due to population growth and rising income.

Previous studies have used farm systems modelling to identify cost-effective options for reducing GHG-e on dairy farms. Beukes et al. (2010) evaluated the effects of a combination of different mitigation strategies on GHG-e. These strategies were:

1. Reduce replacement rates to decrease the number of non-lactating animals.
2. Introduce cows of higher genetic merit to increase feed conversion efficiency.
3. Improve pasture management to increase quality and compensate for less N fertiliser.
4. Use less imported supplements and their associated embedded emissions.

These simulations suggested that the combined effect of these strategies could decrease GHG emissions per ha by 27–32% without compromising milk production, with potential for increased profitability. In another study, Beukes et al. (2011) found that these strategies resulted in reductions in total feed intake, but increases in milk production. These improvements in feed conversion efficiency, together with a reduction in N input and a dilution in dietary N, were found to have potential to decrease GHG emissions per ha by 15–20% while increasing milk production. Additionally, Anderson and Ridler (2010) used a linear-programing model of a New Zealand dairy farm to investigate the GHG-e and profit implications of using a lower replacement rate and reduced mortality. Profit increased by 17% and GHG-e per ha decreased by 4%, when replacement rate decreased from 27 to 18% and cow mortality decreased from 4% to 2% .

The studies of Beukes et al. (2010, 2011) involved a system model with a rich description of biophysical processes. However, that model cannot be used to identify the most profitable combinations with the lowest GHG-e for different combinations and intensities of mitigation strategies because is not an optimisation model. The model used by Anderson and Ridler (2010) allowed optimisation, but left out some known mitigation strategies like restricted-grazing regimes to reduce excreta deposited directly onto pastures (de Klein and Clark, 2002) or the use of nitrification inhibitors (NI) to reduce emissions from N fertilisers and urine (Di and Cameron, 2002). Moreover, these studies did not consider optimal responses by producers to exogenous limits on GHG-e. Such considerations are important because proposed legislation states that farmers will begin to pay for their GHG emissions from 2015 under the *Climate Change Response (Moderated Emission Trading) Amendment Act 2009*.

The objective of this study was to investigate how the management of dairy farms in the Waikato region of New Zealand could change to minimise the abatement costs associated with GHG-e mitigation. Representative farm systems of different production intensity were identified for the region and an optimisation model was used to find the most-profitable management strategies at certain predefined GHG-e restrictions or caps. Key areas of interest within each farm type were how the farm system could be adapted to the GHG-e restriction, how costly this restriction would be, and what would be the system impacts if mitigation options were implemented. The Waikato region is the focus of this study since it is the main dairy region in New Zealand, containing around 25% of the national dairy cow population (LIC/DNZ, 2011). Waikato dairy farming systems are based on the grazing of pasture by cows for the entire year (Macdonald et al., 2008). The temperate climate means that housing is generally not required, though it is sometimes used in the cooler, southern regions of New Zealand.

3.2. Methods

3.2.1 IDEA description

A comprehensive nonlinear programming model of a New Zealand dairy farm – the Integrated Dairy Enterprise Analysis (IDEA) model (Doole et al., 2013) – has been expanded to incorporate GHG-e and a broad set of mitigation options. This section provides a concise overview of the IDEA model; more detail is provided in Doole et al. (2013). The degree of nonlinearity within IDEA is significant; thus, the model is very stable relative to linear programming models and is not prone to taking extreme values for most, if not all, of its important decision variables (Doole et al., 2013).

IDEA incorporates the basic structure of the farm-level model utilised by Doole (2010). However, this framework was expanded in various ways to provide a closer description of real systems. Additions include:

1. Grazing strategies involve both rotation length and post-grazing residual herbage mass as decision variables.
2. Rotation length and post-grazing residual herbage mass impact the subsequent growth and digestibility of pasture.
3. Intake regulation is an important strategy on NZ dairy farms to help match feed demand and feed supply. Accordingly, cows can be fed below potential intake to varying degrees.
4. The body condition of individual cows influences feed intake, milk production, and conception rate.
5. The level of pasture utilisation achieved is conditional on stocking rate (SR).

3.2.1.1 Feed module

IDEA identifies the feeding strategy that maximises annual profit. The model is defined over 26 periods to provide comprehensive insight into this feeding strategy across a typical management year. There are six primary sources of feed: grazed pasture, pasture silage, maize silage, palm kernel expeller (PKE), maize grain, and turnips.

IDEA determines how much of each of these feeds is provided to the cow herd in a given period. Grazed pasture is the primary source of feed in NZ dairy systems, often comprising more than 70% of total feed eaten. Surplus pasture is ensiled on-farm during periods when feed supply exceeds feed demand, especially in spring. Maize silage can be purchased or harvested from a crop grown on-farm. PKE and maize grain are purchased, while turnips are grown as a crop on-farm and harvested directly by the cows. Ten percent of the farm is re-grassed each year, in line with industry practice. The less-productive pastures are renewed; this area is allocated to maize and/or turnip crops before being re-grassed, but the model can also choose to renew pasture directly without the use of break crops. Nitrogen fertiliser promotes pasture growth, with the rate and timing of pasture response derived from the decision tree of Zhang and Tillman (2007). Silages, PKE, maize grain and turnips complement pasture intake, and losses during harvesting and feeding are accounted for in the model. Moreover, their feeding compromises pasture intake through substitution (replacement of pasture by supplement), to a degree determined by the stage of lactation, supplement type, cow liveweight, and level of pasture intake.

NZ dairy farms are rotationally grazed, with areas of the farm grazed at very high stocking densities and then rested for periods of 20–90 days, depending on the season, to allow grass regrowth. The primary set of decision variables that describes the grazing rotation in IDEA determines the area grazed or cut for silage to a given residual (post-harvest pasture biomass level) in each period. Accounting for the duration of rest since the last grazing and the residuals at the previous and current grazing or cutting events allows management to impact pasture digestibility (and therefore energy content) and growth. The model includes 26 periods and ten levels of pasture residuals. A detailed simulation model of pasture dynamics (Romera et al., 2009) was extended to incorporate tissue age structure and used to compute pasture growth and digestibility for each potential grazing or cutting event.

3.2.1.2 Cow module

A large number of cow types (17,640) are defined in IDEA to allow a rich description of herd structure. Optimisation of IDEA identifies the optimal number of each cow type, given the constraints that exist (e.g. feed availability, calving distribution, and so on). The total number of cow types consists of diversity across several dimensions:

1. There are 7 alternative levels of feeding, in which annual cow intake is proportionally lower than potential. Cows on NZ dairy farms are typically fed less than they can potentially consume to conserve feed or sustain higher stocking rates.
2. There are 4 alternative age groups (1, 2, 3, and 4+ lactations).
3. There are 5 alternative levels of genetic merit (expressed in terms of potential milk yield).
4. There are 9 alternative calving dates.
5. There are 7 alternative lactation lengths.
6. There are 2 alternative classes of cow: standard or those culled after lactation. Cows are culled primarily due to disease and their failure to become pregnant.

There are 5 levels of genetic merit considered among the cow attribute combinations. These represent potential milk yield, which is used as a broad proxy for genetic merit. The model requires that potential milk yield among the herd is normally distributed in each optimal solution. Thus, within each optimal solution, the herd will contain a low number of extreme individuals with very low and very high potential milk production, and a higher number of cows with an intermediate potential. The distribution defined in the model is based on data from 850,000 cows within a database provided by the Livestock Improvement Corporation (LIC).

The details of each attribute combination describing a given discrete cow type are determined in a large optimisation model external to IDEA. This external model is used to compute data for all attribute combinations across each fortnight, and that data is then used in IDEA. The relevant data computed are: potential intake, metabolisable energy requirement, liveweight, body condition, and pregnancy rate. This "cow" model identifies the levels of these variables that optimise milk production for a given cow type. The dynamic equations in this model are based on information from existing simulation models (e.g. Johnson et al., 2008; Freer et al., 2010), but are calibrated to represent NZ dairy cows.

The number of cull cows depends on fixed rates of natural mortality and culling for disease (drawn from Lopez-Villalobos et al., 2000), and the non-pregnancy rate computed in IDEA. Conception is based on the model of Beukes et al. (2010). The time after calving at which a cow first starts exhibiting oestrus is based on age and body condition at calving. The empty rate is computed as a function of the number of heats exhibited during the mating period, which depends on age and changes in cow liveweight prior to mating. The age structure describes the number of cows in each of the four age classes represented in the model. The age structure of the herd is determined endogenously in each solution of the model, as it is dependent on natural mortality, culling decisions, and the number of calves born. The presence of such circular associations is characteristic of mathematical programming, as the optimal values of all decision variables are determined simultaneously (see Doole et al. (2013) for further details). The planned start of calving can either be selected by the model user or determined as an output of the optimisation. Calving is distributed across an 8-week period following the start of calving.

2.1.3 Balance supply and demand

Feed demand and supply is reconciled by two constraints. A metabolisable energy constraint is defined in each period and requires total energy supply to exceed energy demand. The model will be infeasible, and thus return no solution, if this relationship is not satisfied. Also, an intake constraint ensures that cows cannot consume unrealistic amounts of feed. The model uses the intake function of Gregorini et al. (2009) to ensure that higher stocking rates result in lower intake per cow by reducing herbage allowance, but also result in higher pasture utilisation per unit of area.

3.2.1.4 Restricted grazing

A stand-off pad is a purpose-built loafing area where stock can be withheld from grazing during wet periods to minimise damage to pastures. These pads are constructed of free-draining material, such as sawdust, bark, woodchips, lime, or soft metal (rock) mix. A feed pad is a hard surface area, normally sited adjacent to the milking shed where stock can be held for a limited time (1–2 hours), either before or after milking, and provided with supplementary feed. These pads are usually included in a farm system to improve feed utilisation, compared to paddock feeding. The optimal proportion of time spent on the pad is determined in the optimisation. The use of a pad affects GHG-e and also the level of pasture utilisation (Doole et al., 2013).

3.2.1.5 Economic output

The goal of the optimisation process in IDEA is to identify the maximum level of operating profit, subject to the set of defined constraints. Operating profit consists of total revenue minus total cost. Total revenue is earned from the sale of milk, culled cows, and surplus calves and yearlings. Total cost is the sum of general variable costs incurred for each cow, fixed costs incurred per hectare of farm area, cost of purchased feed, cost of silage production, fertiliser cost, cost of grazing replacement stock off-farm, cost of establishing crops, re-grassing costs, and the cost of establishing and maintaining stand-off and/or feed pads.

3.2.1.6 Representation of farm systems

The production intensity of dairy farms in New Zealand is mainly described using the proportion of total feed offered made up of supplement imported to the milking platform. This has been necessary given the increasing rate of supplementation used on pasture-based New Zealand dairy farms (Hedley et al., 2006; Macdonald et al., 2008). Production systems 1, 2, 3, 4, and 5 import 0, 4–14, 10–20, 20–30, and 25–50% of total feed offered, respectively (Hedley et al., 2006; DairyNZ, 2012). Moreover, these systems differ in that imported feed is used to support dry cows only (system 2); late lactation and dry cows (system 3); early and late lactation and dry cows (system 4), and all cows all year round (system 5). Thus, though farms in system 2 and 3, for example, may have the same percentage of imported feed, their classification will differ depending on when the additional feed is utilised.

For the season modelled here (2008–2009), 3 production systems were identified using survey data (www.dairybase.co.nz). These comprised low (system 1), medium (system 3), and high input (system 4) farms importing 0, 10, and 20%, respectively, of the total feed offered to the cows. Production system is an input in IDEA and restricts the amount of imported supplement used, as a proportion of total feed offered, and also when this feed may be used.

3.2.1.7 Software

IDEA is solved using the General Algebraic Modelling Systems (GAMS) using the CONOPT3 nonlinear programming solver (Brooke et al., 2012).

3.2.2 Modification of IDEA to represent GHG-e and mitigation options

The IDEA model was modified to incorporate GHG-e through the addition of IPCC methodology calculations (IPCC, 2006) and emission factors specific for NZ obtained from MfE (2010). Conversion factors are taken from Solomon et al. (2007). These modifications to IDEA are described in detail in an online appendix. Coefficient values are fixed in the IDEA model at the values reported in the tables presented in the online appendix. This is necessary as the model is a deterministic framework

The methods used to estimate GHG emissions within the IPCC (2006) and MfE (2010) framework are relatively straightforward. This simplicity allows widespread usage, imposing realistic data requirements on practitioners who are seeking to compute emissions at the farm level. However, there are limitations in these simple equations, associated with the high uncertainties surrounding the structure of the equations and the coefficients involved. This may have significant implications for management. For example, in the case of methane emissions, simple empirical equations may not capture dietary changes well, particularly short term changes (Ellis et al., 2010). Dijkstra et al. (2006) demonstrated, using a highly-detailed rumen fermentation model, that CH_4 emissions from dairy cattle in the Netherlands were reduced over 1990–2003 due to changes in diet. This diet effect had not been captured by IPCC methods, which do not account for the effects of diet manipulation.

Nevertheless, the use of the more straightforward IPCC system is justified for a number of reasons. First, given the high structural uncertainty involved with any complex simulation model and the need to parameterise them for a broad range of geographical locations, a simplistic and transparent framework is often pertinent (Doole and Pannell, 2013). Second, IDEA is an optimisation model that describes the processes within the agricultural system at a rather general level, especially relative to more detailed simulation models (e.g. Beukes et al., 2010). Accordingly, the generality of the IPCC methods is consistent with that of the overall model. This consistency allows the use of optimisation to identify how best producers can respond to different constraints imposed on the farm system. Third, while it is recognised that uncertainties exist, the IPCC framework is based on a rigorous scientific process involving extensive soliciting of expert opinion and peer review (IPCC, 2006). Last, the use of IPCC methodology is also justified, given that it would likely be used, at least in part, as a basis for measuring the GHG-e of New Zealand producers if any regulatory instrument were introduced to reduce agricultural emissions in this nation.

3.2.2 Representation of options to reduce GHG-e in IDEA

Options were grouped as either involving de-intensification or actions with a specific focus on GHG-e reduction (hereafter denoted "mitigations"). De-intensification may be used by farmers for reasons other than mitigation, such as to reduce labour requirements or increase profit. However, mitigations are assumed to be specifically selected for GHG-e reduction. De-intensification involved manipulating key production variables: stocking rate, N fertiliser application, and level of imported supplement feed. Mitigation options included:

1. Improved herd reproduction to reduce non-pregnant cows, culling, and replacement rates.
2. Application of NIs. NIs help to reduce GHG-e by slowing the conversion of ammonium to nitrate in the soil by *Nitrosomonas* bacteria (Di and Cameron, 2002). No additional pasture growth was assumed to be obtained with the application of NI, consistent with Macdonald et al. (2010). The cost of NI is set at $150/ha (Doole and Paragahawewa, 2010).
3. Avoiding depositing excreta directly on pastures during certain times of the year by standing cows on a bark-covered pad for a certain number of hours per day (stand-off).

The IDEA model is an equilibrium model. Management during the transition from the current state to an improved state is not studied, only the steady-state outcomes are identified. This approach is consistent with previous work (e.g. Gibson et al., 2008; Anderson and Ridler, 2010) and allows much greater focus on detailed farm processes (Doole et al., 2013). Accordingly, though mitigation options like an improved replacement rate may take time to establish, their inclusion in the model is nevertheless valid.

Cow empty rate is determined based on the model of Beukes et al. (2010). Empty rate is a function of reproductive management, cow health, rate of embryonic loss, and the number of heats exhibited during mating. The number of heats observed is based on age and changes in cow liveweight prior to mating. The link between genetic merit for fertility and reproductive performance is not incorporated, as the model is already very complex and large (around 500,000 equations). This omission is also consistent with the general approach used in optimisation models of grazing systems, with no previous models including this aspect (e.g. Anderson and Ridler, 2010).

3.2.3 Model runs

Section 3.3.1 presents a comparison of model output from IDEA and Farmax, a detailed simulation model of a NZ dairy system (Bryant et al., 2010). The comparison is performed to provide insight into the ability of IDEA to describe adequately different components of farming systems in the study region. Farmax is used to obtain a complete and coherent set of biophysical outputs for each farm. This model comparison is justified, as Farmax has been extensively validated for New Zealand dairy farms (e.g. Bryant, 2006; Bryant et al., 2010). Moreover, in a recent paper, Doole et al. (2013) demonstrate the capacity of IDEA to replicate data from farmlet trials performed in the Waikato region.

The optimisation model (IDEA) may be expected to perform better than the simulation model (Farmax) in terms of identifying solutions with a higher level of profit associated with them. However, the approach used in this study follows standard theory for mathematical programming models of agricultural systems (e.g. Howitt, 1995; Pannell, 1996, 1997) and involves calibration of the model to represent average or expected performance on real farms. Doole et al. (2013) demonstrate the ability of the IDEA model to replicate farmlet trial data, without recourse to nonlinear calibration functions (e.g. Howitt, 1995) that can bias model output away from the calibrated baseline or the use of constraints to fix decision variables (e.g. Anderson and Ridler, 2010), given that these obviously restrict the predictive capacity of the model. Rather, Doole et al. (2013) describe in detail how the model has been calibrated to represent the Waikato region through the use of input data (e.g. pasture growth and digestibility information, how pasture utilisation is affected by stocking density) particular to this area. This was done without reference to Farmax output since separate authors were responsible for each step.

The following prices were used in this study. The milk price was $5.50 per kg milk solids (MS). Fixed costs were $900 per ha, while variable costs were $500 per cow. The cost of urea was $500 per tonne, while nitrification inhibitors cost $200 per ha. Dairy meal, maize silage, and PKE cost $650, $300, and $350 per tonne of dry matter (DM).

In Section 3.3, four scenarios for each of these farm systems are discussed. These scenarios differ in whether or not a cap is present that requires producers to reduce GHG-e by 10% and the possibility to implement mitigations (Figure 1). The 10% mitigation goal is based on the New Zealand target for 2008–2012 set under the Kyoto Protocol and the fact that agriculture in this nation has increased emissions by that amount since 1990 (MfE, 2010).

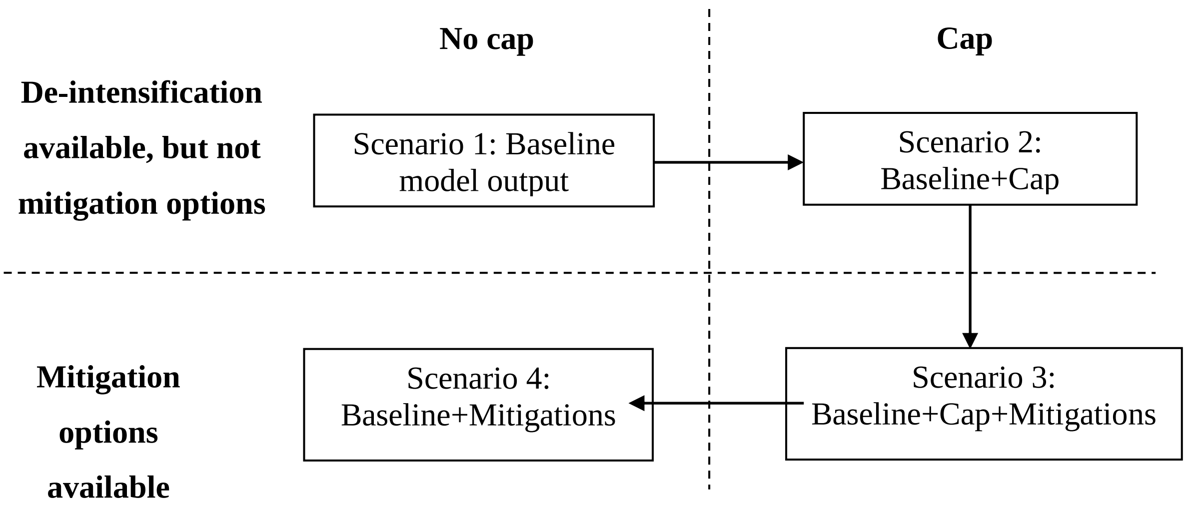

Figure 1: The four modelling scenarios evaluated for each production system.

Reduced costs in mathematical programming theory represent the decrease in the cost of a given activity required for it to enter the optimal solution (Pannell, 1997). Reduced costs are computed for nitrification inhibitors and stand-off pads to identify the change in their cost required for them to enter the optimal solution, where appropriate. These are not computed for improved reproduction, which is selected in all model runs in which it is available.

Sensitivity analysis is important to provide an understanding of how parametric uncertainty can affect the key conclusions of the study. There is uncertainty surrounding the coefficients used in the IPCC calculations applied in this paper (IPCC, 2006; MfE, 2010). Thus, the implications of variability in the most uncertain parameters driving methane and N_2O emissions are explored. MfE (2010) highlighted that the most uncertain factor in the computation of methane emissions is the amount of CH_4 emitted per unit of intake. The lower/upper bound studied in sensitivity analysis is 5 standard errors below/above the mean value. Accordingly, the simulated values for the amount of CH_4 emitted per unit of intake (*CI*) are a low value ($CI_L = 0.0186$), medium value ($CI_M = 0.0216$), and high value (CI_U=0.0246). In addition, MfE (2010) stated that the most uncertain factor driving N_2O emissions is the emission factor for dung and urine deposited onto pasture (c_{32}). The implications of a 20% decrease/increase relative to the baseline scenario are tested. Accordingly, the simulated values for the emission factor for dung and urine deposited onto pasture are a low value ($c_{32}^L = 0.008$), medium value ($c_{32}^M = 0.01$), and high value ($c_{32}^H = 0.012$). Sensitivity analysis involves computing Scenarios 1 and 2 for the medium-input farm (PS3) under each of these alternative values.

3.3 Results

3.3.1 Comparison of Farmax and IDEA

IDEA outputs were compared with those of Farmax to provide an assessment of how well IDEA represents each farm system. For the medium-input system (Table 1), there were few differences between the two models for most of the key performance indicators considered. Nitrogen fertiliser application was 7% higher in IDEA, relative to Farmax. This difference reflects that N fertiliser use is determined in IDEA through optimisation, which balances the marginal benefit and cost of application. The higher N use in IDEA resulted in an increase in grazed pasture eaten and grass silage eaten. The consequence of this was a prediction of 7%

Table 1: Baseline model output for the system 1, 3, and 4 farms.

Variable	Units	System 1			System 3			System 4		
		FMX	IDEA	Diff.	FMX	IDEA	Diff.	FMX	IDEA	Diff.
Imported feed	% diet	0	0	0	10	10	0	20	20	0
Farm profit	$ ha^{-1}	928	959	+3	1,227	1,252	+2	1,521	1,525	+1
Stocking rate	cows ha^{-1}	2.71	2.61	-4	3.08	3.02	-2	3.61	3.71	+3
Milk production	kg MS cow^{-1}	308	307	-1	340	344	+1	398	392	-2
Milk production	kg MS ha^{-1}	835	801	-4	1,047	1,035	-1	1,437	1,454	+1
Lactation length	Days	277	271	-2	271	276	+2	290	303	+4
Grazed pasture eaten	t DM ha^{-1}	9.76	10.35	+6	12.05	12.5	+4	14.48	15.17	+5
Grass silage eaten	t DM ha^{-1}	0.42	0.42	0	0.53	0.59	+11	0.18	0.16	-11
Maize silage eaten	t DM ha^{-1}	0.56	0.52	-7	0.37	0.37	0	2.6	2.3	-12
Maize grain eaten	t DM ha^{-1}	-	-	-	-	-	-	1.24	1.46	+18
PKE eaten	t DM ha^{-1}	0	0	0	1.66	1.54	-7	0	0	0
N fertiliser applied	kg N ha^{-1}	66	69	+5	105	112	+7	150	149	-1
Crop area	% area	2.75	2.6	-5	1.7	1.7	0	2.62	2.5	-5

Columns represent data from Farmax modelling (labelled “FMX”), IDEA modelling (labelled “IDEA”), and the percentage difference (labelled “Diff.”). The “Diff.” column is shaded for each scenario.

less PKE than Farmax. The differences between the models are minor, especially considering that pasture utilisation depends on stocking rate in IDEA, but is user-defined in Farmax.

The predictions were also very close for the low-input system (Table 1), with the IDEA model representing a slightly more pasture-oriented system. This system achieved a 3% higher farm profit, with a 4% lower stocking rate and with substitution of maize silage by grazed pasture eaten. This 6% increase in pasture eaten is achieved, in part, by a 5% increase in N fertiliser, but also through the optimisation of rotation management in IDEA, relative to Farmax.

IDEA found an optimum with similar profit compared with Farmax for the high-input system. This solution also involved a 3% increase in stocking rate for this system (Table 1). The largest difference observed was an 18% increase in maize grain eaten, though this translated into an increase in maize grain consumption of only 0.22 tonnes/ha. Maize grain is used to substitute for grass and maize silage in the IDEA solution, highlighting that this feed appears to be a more cost-effective feed source when optimisation is used to determine feed allocation at the price levels used in the model.

3.3.2 Model output for the low input system

In the low-input system, the cost of a 10% cap on GHG-e (Scenario 2) was a reduction of $67/ha or 7% in operating profit when only de-intensification was available (Table 2). To achieve the emission reduction in the capped scenario (Scenario 2), the optimal solution involved a reduction of N fertiliser input by about 45% and SR by about 9%. This reduction in N fertiliser resulted in a reduction of 820 kg (8%) of pasture eaten per ha, but due to the reduced cow numbers, cow performance increased by 8 kg MS/cow in a lactation that was 12 days longer. The decrease in production intensity also involved grass silage eaten decreasing by 29%.

When mitigation options were available without a cap (Scenario 3), improved reproductive performance was the only option used to reduce the cost of emissions reductions. This involved a lower replacement rate, 23% below that of the baseline level. As fewer replacements were required, the balance of the GHG-e allowance was used to increase the

Table 2: Key model output for Scenarios 1 to 4 for the low-input system (system 1).

Variable	Units	Scenario[ϕ]			
		1	**2**	**3**	**4**
Imported feed	% diet	0	0	0	0
Farm profit	$ ha^{-1}	959	892	924	972
Stocking rate	cows ha^{-1}	2.61	2.37	2.42	2.63
Milk production	kg MS cow^{-1}	307	315	316	307
Milk production	kg MS ha^{-1}	801	747	765	807
Lactation length	Days	271	283	281	268
Grazed pasture eaten	t DM ha^{-1}	10.35	9.53	9.7	10.43
Grass silage eaten	t DM ha^{-1}	0.42	0.30	0.32	0.39
Maize silage eaten	t DM ha^{-1}	0.52	0.52	0.51	0.52
Maize grain eaten	t DM ha^{-1}	-	-	-	-
PKE eaten	t DM ha^{-1}	0	0	0	0
N fertiliser applied	kg N ha^{-1}	69	38	42	70
Crop area	% area	2.6	2.6	2.6	2.6
Replacement rate	%	22.7	22.6	17.5	18.1
Methane emissions	kg CH_4 ha^{-1}	238.58	219.57	223.29	240.31
N_2O emissions	kg N_2O ha^{-1}	6.29	5.23	5.41	6.28
GHG emissions	kg CO_2-eq. ha^{-1}	8,912	8,021	8,021	8,797
Emissions intensity	kg CO_2-eq. kg MS^{-1}	11.13	10.74	10.48	10.9
Mitigations used	-	-	-	Improved repro.	Improved repro.
Mitigations not used[‡]	$ ha^{-1}	-	-	NI: 15 SO: 301	NI: 19 SO: 312

[ϕ] Scenario description: 1. Baseline situation. 2. 10% reduction in baseline emissions without mitigation options. 3. 10% reduction in baseline emissions with mitigation options. 4. No reduction in baseline emissions with mitigation options.

[‡] In this row in Table 2, NI denotes nitrification inhibitors and SO denotes stand-off pad. The dollar values following each label denote the reduction in cost associated with each mitigation that is required for this practice to enter the optimal solution.

number of milking cows compared to Scenario 2. The SR was 7% lower than that of the baseline and intake per cow increased slightly by 0.5%, permitting a 3% increase in the individual performance of the cows. These changes resulted in a partial recovery of operating profit, which increased to $924/ha from that achieved in Scenario 2 ($892/ha).

When mitigation options were available in the absence of a cap (Scenario 4), the most-profitable solution involved the adoption of a 20% reduction in replacement rate, relative to the baseline (Table 2). Despite having a slightly higher total stocking rate than the baseline solution and similar levels of nitrogen fertiliser application, GHG-e were slightly reduced, both per kg milk solids and per ha, while profit increased by 1.4%, compared to the baseline.

Emissions intensity (kg CO_2-eq./kg MS) decreased by 4% with the reduction in GHG-e in the Base+Cap simulation (Scenario 2), but decreased by 6%, relative to the baseline, in the Base+Cap+Mitigations (Scenario 3) simulation for the low-input system (Table 2). Total emissions are the same under both scenarios, but Scenario 3 has greater milk production associated with it, which reduced intensity. The availability of mitigations without the cap (Scenario 4) reduced emissions intensity below the baseline by 2%, since improved reproduction reduces GHG-e, but also (marginally) improves milk production.

3.3.3 Model output for the medium input system

When the emissions cap was introduced (Scenario 2) in the medium-input system scenarios, nitrogen fertiliser input was reduced, but to a lesser extent compared with the low-input system (Table 3). A 24% reduction in applied N was observed, compared with a 45% decrease in the low-input system. This system also had a 10% reduction in SR when only de-intensification was used to meet the cap constraint. Cows showed a small increase in individual performance, but total feed intake was lower by about 8%. Operating profit decreased by only 5%, despite production per ha being more than 7% lower, due to cost reductions associated with de-intensification.

When mitigation options were available (Scenario 3), a 33% reduction in replacement rate was used. With a reduction in emissions from replacement cows, N fertiliser levels could be

Table 3: Key model output for Scenarios 1 to 4 for the medium-input system (system 3).

Variable	Units	Scenario[ϕ]			
		1	**2**	**3**	**4**
Imported feed	% diet	10	10	10	10
Farm profit	$ ha^{-1}	1,252	1,185	1,226	1,268
Stocking rate	cows ha^{-1}	3.02	2.7	2.75	3.01
Milk production	kg MS cow^{-1}	344	357	358	346
Milk production	kg MS ha^{-1}	1,039	964	985	1,041
Lactation length	Days	276	290	286	275
Grazed pasture eaten	t DM ha^{-1}	12.62	11.71	11.9	12.63
Grass silage eaten	t DM ha^{-1}	0.59	0.31	0.65	0.58
Maize silage eaten	t DM ha^{-1}	0.37	0.37	-	0.37
Maize grain eaten	t DM ha^{-1}	-	-	-	-
PKE eaten	t DM ha^{-1}	1.54	1.4	1.42	1.54
N fertiliser applied	kg N ha^{-1}	112	85	100	113
Crop area	% area	2.5	2.5	2.5	2.5
Replacement rate	%	23.4	22.2	15.8	18.1
Methane emissions	kg CH_4 ha^{-1}	295.77	272.05	277.77	295.94
N_2O emissions	kg N_2O ha^{-1}	8.69	7.6	7.93	8.64
GHG emissions	kg CO_2-eq. ha^{-1}	11,122	10,010	10,010	10,890
Emissions intensity	kg CO_2-eq. kg MS^{-1}	10.7	10.38	10.16	10.46
Mitigations used	-	-	-	Improved repro.	Improved repro.
Mitigations not used[‡]	$ ha^{-1}	-	-	NI: 21 SO: 317	NI: 26 SO: 329

[ϕ] Scenario description: 1. Baseline situation. 2. 10% reduction in baseline emissions without mitigation options. 3. 10% reduction in baseline emissions with mitigation options. 4. No reduction in baseline emissions with mitigation options.

[‡] In this row in Table 3, NI denotes nitrification inhibitors and SO denotes stand-off pad. The dollar values following each label denote the reduction in cost associated with each mitigation that is required for this practice to enter the optimal solution.

maintained closer to that of the baseline, while still meeting the 10% emissions cap constraint. Stocking rate was still 9% lower than the baseline, but production per cow increased by around 4%. Despite the fact that milk production per ha was more than 5% lower than that of the baseline, profit was only reduced by 2%, primarily due to the replacement of (more expensive) imported PKE by cheaper pasture grown on-farm, since N fertiliser application was only 10% below that of the baseline.

When mitigations were available in the absence of a cap (Scenario 4), operating profit increased by 1% and production remained the same, compared with the baseline. This was the result of a relatively large reduction in replacement rate of about 23%.

Emissions intensity was reduced by 3% with Scenario 2 for the medium-input system, but decreased by 5% in Scenario 3, relative to the baseline (Table 2). Total emissions were the same under both scenarios, but intensity under Scenario 3 was lower given the positive impact of improved reproductive management on milk production. Improved reproduction without the cap (Scenario 4) decreased emissions intensity by 2%, compared to Scenario 1, given the dual benefit of improved reproduction on both production and emissions.

3.3.4 Model output for the high input system

In Scenario 2 in the high-input system, the changes were very similar to those observed in the low-input system, but in this case individual cow performance remained unchanged (Table 4). Nitrogen application was reduced by about 40% to 90 kg N/ha, relative to the baseline, resulting in about an 8% reduction in SR, milk production per ha, and profit. To compensate for the reduced pasture and grass silage offered, around 16% more maize silage was imported in Scenario 2.

In Scenario 3, improved reproduction was the only mitigation strategy incorporated (Table 4). This improved reproduction allowed for a 19% reduction in the replacement rate, compared with the baseline. 19% more N fertiliser was applied compared to the Baseline+Cap scenario. Profit was reduced by about 4% compared with the Baseline, while milk production per ha decreased by more than 6%.

Table 4: Key model output for Scenario 1 to 4 for the high-input system (system 4).

Variable	Units	Scenario[ϕ]			
		1	2	3	4
Imported feed	% diet	20	20	20	20
Farm profit	$ ha^{-1}	1,525	1,410	1,462	1,541
Stocking rate	cows ha^{-1}	3.71	3.40	3.43	3.66
Milk production	kg MS cow^{-1}	392	394	398	397
Milk production	kg MS ha^{-1}	1,454	1,340	1,365	1,453
Lactation length	Days	303	304	308	307
Grazed pasture eaten	t DM ha^{-1}	15.17	14.22	14.30	15.12
Grass silage eaten	t DM ha^{-1}	0.16	0.07	0.10	0.17
Maize silage eaten	t DM ha^{-1}	2.3	2.67	2.62	2.3
Maize grain eaten	t DM ha^{-1}	1.46	0.69	0.8	1.45
PKE eaten	t DM ha^{-1}	0	0	0	0
N fertiliser applied	kg N ha^{-1}	149	90	107	149
Crop area	% area	2.5	2.5	2.5	2.5
Replacement rate	%	26.1	25.7	21.1	21.3
Methane emissions	kg CH_4 ha^{-1}	374.24	339.16	345.76	373.3
N_20 emissions	kg N_20 ha^{-1}	10.3	8.65	8.9	10.21
GHG emissions	kg CO_2-eq. ha^{-1}	14,131	12,719	12,719	13,797
Emissions intensity	kg CO_2-eq. kg MS^{-1}	9.72	9.49	9.32	9.5
Mitigations used	-	-	-	Improve d repro.	Improved repro.
Mitigations not used[‡]	$ ha^{-1}	-	-	NI: 38 SO: 332	NI: 45 SO: 358

[ϕ] Scenario description: 1. Baseline situation. 2. 10% reduction in baseline emissions without mitigation options. 3. 10% reduction in baseline emissions with mitigation options. 4. No reduction in baseline emissions with mitigation options.

[‡] In this row in Table 4, NI denotes nitrification inhibitors and SO denotes stand-off pad. The dollar values following each label denote the reduction in cost associated with each mitigation that is required for this practice to enter the optimal solution.

A similar replacement rate was obtained with both scenarios involving mitigation strategies in the high-input system (Scenarios 3–4, Table 4). Nitrogen fertiliser use returned to its baseline level of 149 kg N/ha when the cap was removed in Scenario 4. The other production factors differed slightly. Accordingly, farm profit only increased by 1% and total GHG-e was only around 2% lower.

Emissions intensity decreased by 2% with Scenario 2 for the high-input system, but decreased by 4% in Scenario 3, relative to the baseline (Table 2), given the impact of improved milk production. Improved reproduction without the cap (Scenario 4) decreased emissions intensity by 2%, compared to Scenario 1.

3.5 Results of the sensitivity analysis

Table 5 presents the key model output for changes in the amount of CH_4 emitted per unit of intake. For Scenario 1, it is observable that optimal management of the farming system is robust to all simulated changes in *CI* (Table 5). Additionally, the N_2O emissions are equivalent across the three simulations (Table 5). However, methane emissions change significantly. Methane emissions per ha decrease by 13% with the low value of *CI*, decreasing total GHG-e emissions by 8%. Methane emissions per ha increase by 17% with the high value of *CI*, increasing total GHG-e emissions by 9%. These impacts are intuitive, given that a given decrease/increase in *CI* decreases/increases the amount of CH_4 emitted per unit of intake for a given management plan. For Scenario 2, it is observable that optimal farm management remains robust to the simulated changes in *CI*. Indeed, no differences in farm management are observed with the introduction of the GHG-e cap with any of these simulated changes. CH_4 emissions fall by 13% with the low value of *CI*, 8% with the medium value of *CI*, and 11% with the high value of *CI*. In comparison, N_2O emissions exhibit only very minor changes. Overall, it is observable that the simulation of extreme perturbations to the most uncertain factor present in the methane calculations used in the model has a negligible impact on output. Methane, and consequently GHG, emissions decrease/increase with a decrease/increase in *CI*, but the optimal production response does not change.

Table 5: Key model output for the medium-input system when the amount of CH4 emitted per unit of intake takes different values.

Variable	Units	Scenario 1			Scenario 2		
		$CI_L = 0.0186$	$CI_M = 0.0216$	$CI_H = 0.0246$	$CI_L = 0.0186$	$CI_M = 0.0216$	$CI_H = 0.0246$
Imported feed	% diet	10	10	10	10	10	10
Farm profit	$ ha^{-1}	1,252	1,252	1,252	1,185	1,185	1,185
Stocking rate	cows ha^{-1}	3.02	3.02	3.02	2.7	2.7	2.7
Milk production	kg MS cow^{-1}	344	344	344	357	357	357
Milk production	kg MS ha^{-1}	1,039	1,039	1,039	964	964	964
Lactation length	Days	276	276	276	290	290	290
Grazed pasture eaten	t DM ha^{-1}	12.62	12.62	12.62	11.71	11.71	11.71
Grass silage eaten	t DM ha^{-1}	0.59	0.59	0.59	0.31	0.31	0.31
Maize silage eaten	t DM ha^{-1}	0.37	0.37	0.37	0.37	0.37	0.37
Maize grain eaten	t DM ha^{-1}	-	-	-	-	-	-
PKE eaten	t DM ha^{-1}	1.54	1.54	1.54	1.4	1.4	1.4
N fertiliser applied	kg N ha^{-1}	112	112	112	85	85	85
Crop area	% area	2.5	2.5	2.5	2.5	2.5	2.5
Replacement rate	%	23.4	23.4	23.4	22.2	22.2	22.2
Methane emissions	kg CH_4 ha^{-1}	257.91	295.77	344.7	237.88	272.05	307.33
N_2O emissions	kg N_2O ha^{-1}	8.69	8.69	8.69	7.62	7.6	7.58
GHG emissions	kg CO_2-eq ha^{-1}	10,232	11,122	12,043	9,209	10,010	10,839
Emissions intensity	kg CO_2-eq kg MS^{-1}	9.85	10.7	11.59	9.55	10.38	11.24

Scenario 1 is the baseline, while Scenario 2 involves a 10% cap

Table 6 presents the key model output for changes in the emission factor for dung and urine deposited onto pasture (c_{32}). For Scenario 1, it is observable that optimal farm management does not change for any of the simulated values of c_{32} (Table 6) Moreover, the calculated methane emissions are the same across all of the simulations for this scenario. Nonetheless, N_2O emissions decrease by 12% with a 20% decrease in c_{32}, decreasing total GHG-e by 4%. In contrast, N_2O emissions increase by 11% with a 20% increase in c_{32}, increasing total GHG-e by 4%. These impacts are in line with expectations, as a decrease/increase in the emission factor for dung and urine deposited onto pasture decreases/increases the amount of N_2O emitted for a given farm management plan. For Scenario 2, it is again observable that optimal farm management is very robust to changes in this key parameter. A high value for c_{32} does change the optimal production plan a little, but the effects are negligible. Methane emissions with a GHG-e cap change less than 0.4%. However, N_2O emissions vary considerably. N_2O emissions fall by 14% with the low value of c_{32}, 13% with the medium value of c_{32}, and 12% with the high value of c_{32}. This identifies that a higher value for the emission factor c_{32} increases the N_2O contribution of a given management plan and thus makes it slightly less attractive as a factor to change in response to regulation. Overall, it is observable that the simulation of significant perturbations to the most uncertain coefficient present in the nitrous oxide calculations used in the model has a negligible impact on output. Nitrous oxide, and consequently GHG, emissions decrease/increase with a decrease/increase in c_{32}, but the optimal production response does not change.

3.4. Discussion

3.4.1 Level of emissions reported by IDEA

The OVERSEER model (Wheeler et al., 2003) is the most common software used to evaluate the GHG-e associated with alternative farm management plans in New Zealand. Total GHG-e calculated by IDEA (11,122 kg CO_2-eq./ha) were in line with the results of OVERSEER for the baseline farm as modelled in Farmax (10,437 kg CO_2-eq./ha). They were also similar to those values reported by Basset-Mens et al. (2009), who also used OVERSEER. For example, total GHG-e in t CO_2-eq./ha for the medium-input system of this study was

Table 6: Key model output for the medium-input system EF for manure deposited onto pasture (CI) takes different values.

Variable	Units	Scenario 1			Scenario 2		
		$c_{32}^{L}=0.008$	$c_{32}^{M}=0.01$	$c_{32}^{H}=0.012$	$c_{32}^{L}=0.008$	$c_{32}^{M}=0.01$	$c_{32}^{H}=0.012$
Imported feed	% diet	10	10	10	10	10	10
Farm profit	$ ha^{-1}	1,252	1,252	1,252	1,185	1,185	1,179
Stocking rate	cows ha^{-1}	3.02	3.02	3.02	2.7	2.7	2.69
Milk production	kg MS cow^{-1}	344	344	344	357	357	358
Milk production	kg MS ha^{-1}	1,039	1,039	1,039	964	964	963
Lactation length	Days	276	276	276	290	290	291
Grazed pasture eaten	t DM ha^{-1}	12.62	12.62	12.62	11.71	11.71	11.73
Grass silage eaten	t DM ha^{-1}	0.59	0.59	0.59	0.31	0.31	0.31
Maize silage eaten	t DM ha^{-1}	0.37	0.37	0.37	0.37	0.37	0.37
PKE eaten	t DM ha^{-1}	1.54	1.54	1.54	1.4	1.4	1.4
N fertiliser applied	kg N ha^{-1}	112	112	112	85	85	85
Crop area	% area	2.5	2.5	2.5	2.5	2.5	2.5
Replacement rate	%	23.4	23.4	23.4	22.2	22.2	23.4
Methane emissions	kg CH_4 ha^{-1}	295.77	295.77	295.77	272.05	272.05	271.2
N_2O emissions	kg N_2O ha^{-1}	7.65	8.69	9.65	6.61	7.6	8.52
GHG emissions	kg CO_2-eq. ha^{-1}	10,677	11,122	11,589	9,609	10,010	10,430
Emissions intensity	kg CO_2-eq. kg MS^{-1}	10.28	10.7	11.15	9.97	10.38	10.83

Scenario 1 is the baseline, while Scenario 2 involves a 10% cap.

comparable with the N fertilised farm system (NF) in Basset-Mens et al. (2009). These systems had the same stocking rate and level of intake, but 112 kg N/ha are used in IDEA, compared to 200 kg N/ha used in the NF scenario of Basset-Mens et al. (2009). The IDEA solution predicted emissions of 11.12 t CO_2-eq./ha, compared with 9.5 t CO_2-eq./ha in the NF system. The difference is mainly due to the fact that Basset-Mens et al. (2009) did not include any imported feed in their NF system, while the system 3 farm simulated in IDEA imported 10% of total feed offered and also grew a crop of maize to produce silage. Accordingly, the levels of emissions intensity, measured as kg CO_2-eq./kg MS, identified here are higher than those reported by Basset-Mens et al. (2009). The baseline level of emissions intensities in the system 1, 3, and 4 farms simulated in this study are 11.13, 10.7, and 9.72 kg CO_2-eq./kg MS. These are higher than those reported by Basset-Mens et al. (2009), which were 7.56, 8.92, and 8.82 kg CO_2-eq./kg MS for a system 1 farm with no nitrogen fertiliser, a system 1 farm with nitrogen fertiliser, and a system 5 farm with a high level of feed importation.

3.4.2 De-intensification scenarios

For all of the farming systems, reduction in N fertiliser application and stocking rate were the largest changes implemented when the GHG-e constraint was introduced and only de-intensification was available. Reducing N fertiliser application, and consequently the level of dry matter produced and consumed by the cows, reduces GHG-e from pastoral systems in multiple ways. The main reasons are:

1. Less N is lost as N_2O as direct emissions from fertiliser application.
2. A reduction in N uptake by pasture leads to a reduction of N recycled back to pasture, primarily as urinary N, which reduces the rate of direct gaseous N losses through nitrification and denitrification.
3. A reduction in methane emissions, as less pasture is available and therefore less pasture is grazed per unit of land, which is the main driver of methane losses from pastoral dairy systems. (This is true provided the losses in pasture yield are not replaced with imported supplements that do not reduce methane yield.)

Our finding that de-intensification can achieve GHG-e reductions, albeit at some cost, is in line with previous research and general intuition. Luo et al. (2008) estimated GHG-e from trial data for two different dairy farming systems. N_2O emissions from a higher SR system were higher than in the control when embedded emissions were counted, even though losses from the whole system were 22% lower per tonne of milk produced. In comparison, Foley et al. (2011) found that emissions per hectare in beef systems increased with higher stocking rates, while GHG-e per unit of product decreased.

The application rate, type of fertiliser, and timing are important factors affecting N losses from N fertiliser application. When conditions are suitable for denitrification, some authors have highlighted that N_2O emissions can exponentially increase with application rate (de Klein and Eckard, 2008; Eckard et al., 2010). Nevertheless, the effects of these factors were not explored in this study, as this effect is not present in the IPCC methodology used in IDEA. Moreover, manipulation of fertiliser type and the amount applied in each application have limited potential for N_2O abatement throughout Australasia, leaving total amount of N as the main factor governing these emissions (de Klein and Eckard, 2008). Fertiliser type and application rate

have limited potential for abatement in this region because grazing systems predominate there, with urine and dung deposition accounting for 80% of the N_2O losses in New Zealand, compared with only 15% from N fertiliser and 5% from effluent (Luo et al., 2008; de Klein et al., 2010; Eckard et al., 2010).

Model results showed that decreases in stocking rate, and concomitant increases in individual cow performance, were effective ways to minimise losses in profit when the availability of feed is reduced by decreasing N inputs to the farm in response to a GHG-e constraint. For this to be a cost-effective management response to GHG-e restrictions, such adaptation of the system implies that a larger proportion of the total feed consumed has to be directed to the production of a saleable product, instead of livestock maintenance, causing an improvement in feed conversion efficiency. This is possible since:

1. There is a linear increase in energy requirements per hectare for maintenance, activity, and pregnancy as stocking rate increases (Macdonald et al., 2008).
2. Fewer replacements are needed with lower stocking rates. This reduces emissions and cost.

The focus on the loss of revenue that de-intensification implies is the obvious effect, but cost savings are just as important. For example, limiting GHG-e imposes an inherent restriction on the amount of feed that can be consumed; therefore, considerable savings are possible through reducing those factors that drive higher intakes, such as N fertiliser application and supplement importation. The use of an optimisation model allowed these effects to be captured explicitly.

3.4.3 Mitigation options

Improved reproduction was the mitigation option selected by the IDEA model in any of the simulations. This option is beneficial because fewer animals are needed to replace the cows that failed to become pregnant during the mating period, resulting in a reduction of the proportion of non-lactating animals needed in the system. This is consistent with the findings of Garnsworthy (2004), who found that methane emissions decreased with improving fertility.

In IDEA, the option of improved reproductive performance, and consequently reduced replacement rate, is associated with an extra variable cost for improving heat detection and increasing the body condition score of the cows at calving, which requires the expenditure of additional energy. The economic benefit of this option is the cost saving of sustaining fewer replacements grazed off the milking platform (e.g. reared by a grazier). The model balances the relative profit accruing to energy allocation between improved reproductive performance and milk production. It is entirely feasible that the lowest replacement rate will not be optimal, as the marginal profit accruing to investing in improved reproductive performance is below that of milk production. For these reasons, improved reproductive performance was very effective at minimising the cost of imposed emissions caps, but did not lead to large increases in farm profit when the cap was removed. In the scenarios involving improved reproduction without an emissions constraint, operating profit increased marginally (usually around 1%) with respect to the baseline scenarios and emissions intensity decreased by around 2%. A similar result was found by Beukes et al. (2011), who reported a reduction of GHG-e of 2–5% from fewer replacement animals, but with only a slight concomitant increase in milk production, when replacement rate was reduced from 21% to 16%.

Improved reproductive management is used across all model solutions when mitigations are available (Tables 2–4). Accordingly, milk production may be expected to increase, as a decline in replacement rate increases the proportion of older, more productive cows in the herd (Lopez-Villalobos and Holmes, 2010). This facet is incorporated in the IDEA model (Doole et al., 2013). Nevertheless, this result is not observed in this model, as the older cows require more energy given their greater size and it is uneconomic to increase milk production per cow above those levels produced at a high replacement rate. The capacity to identify profitable outcomes in an integrated model of a farming system is a key benefit of optimisation, particularly relative to biophysical research that focuses on improving production without necessarily considering its economic implications (Doole and Pannell, 2008).

NI and stand-off pads were not selected by IDEA as cost-effective mitigation options. In the case of NI, incurring the cost of $150/ha was not warranted at a $5.50 milk price. This result is also consistent with the findings of Doole and Paragahawewa (2011), who identified that unrealistic pasture responses were required to warrant the adoption of this technology, given its high cost. Similarly, the high cost of stand-off pads does not warrant their use in the context of the 10% GHG-e reduction investigated here. Indeed, with the set of prices for outputs and inputs used here, reducing production intensity was less costly than the use of either NI or stand-off pads.

Reduced costs reveal the degree to which the cost of NI or stand-off pads needs to decrease for the relevant mitigation to enter the optimal plan. NI require a cost reduction of $15, $21, and $38 under the GHG-e cap (Scenario 3) to enter the optimal plans for the low-, medium-, and high-intensity systems, respectively (Tables 2–4). This demonstrates that the value of nitrification inhibitors is promoted where less imported feed is utilised, mainly given the high protein content of grazed pasture in New Zealand dairy systems. In comparison, stand-off pads require a cost reduction of $301, $317, and $332 under the GHG-e cap to enter the optimal plans for the low-, medium-, and high-intensity systems, respectively (Tables 2–4). This cost reduction is much higher than that identified for NI, reflecting the high costs associated with a stand-off pad, mainly due to construction, depreciation, and ongoing maintenance. The value of a stand-off pad decreases with the amount of imported feed, highlighting once again the value of mitigation practices when greater amounts of high-protein feed, such as grazed pasture, are utilised (Beukes et al., 2011). The cost reductions required for NI and stand-off pads to enter the optimal solution are greater without a cap (Scenario 4) (Tables 2–4). For example, the reduced costs for NI are 18–27% higher, while those for stand-off pads are 4–8% higher. This demonstrates how the presence of a cap promotes the value of a mitigation strategy.

The trends identified for emission intensity are consistent across all simulations. First, the introduction of a cap on GHG-e emissions reduces intensity, but only by a minor amount (2–4%). Second, this is further supported by the presence of mitigations, as improved reproduction decreases the number of replacements (and therefore emissions) and increases milk production. Last, the availability of mitigations without a cap improves emissions intensity, but only by 2% across all farming systems. These factors identify that improvements in emissions intensity accompany the presence of a cap and mitigations. Moreover, it is identified here that emissions intensity for any given scenario declines with the availability of imported supplement. Total GHG-e build as the level of imported feed increases; however, emissions intensity declines due to increased milk production per ha.

3.5. Conclusions

A nonlinear optimisation model was used to identify cost-effective strategies to reduce GHG emissions by 10% on representative dairy farms of different production intensities in the Waikato region of New Zealand. With the prices used in this study, decreasing farming intensity by reducing N fertiliser by 21–42% and SR by 8–10% represented a cost of $68–$119/ha and a production reduction of 54–117 kg MS/ha for the three systems studied. Improving reproductive performance proved to be effective in reducing GHG-e, allowing for fewer replacement cows to be supported. However, it did not have a significant effect on profit when emissions were unconstrained. This is due to the minor scale of the savings associated with raising less replacement stock, relative to other costs incurred on these farms. Nitrification inhibitors and stand-off pads were not identified as cost-effective mitigation options. This highlights that their high cost limits their utility for GHG-e mitigation, at least for the types of system represented, the prices used, and the scenarios analysed here. Sensitivity analysis indicates that model output is extremely robust to broad changes in the most uncertain parameters within the GHG-e equations employed in this study.

A number of areas are worthy of further research. First, extension of modelling to consider other dairy farming regions in New Zealand is worthwhile. Second, it would be interesting to consider the interdependency between strategies to mitigate both GHG-e and N leaching.

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Chapter 4

Managing greenhouse gas emissions in two major dairy regions of New Zealand

In this chapter, Alfredo A Adler was primarily responsible for the writing and the literature review.

Graeme J. Doole calibrated and ran the IDEA model, presented the tables for the discussion and also contributing to the writing.

Alvaro J. Romera participated in the process of selection of the objective farms and contributed ideas to the discussion.

Pierre C. Beukes contributed to the review of the writing.

Managing greenhouse gas emissions in two major dairy regions of New Zealand

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Abstract. De-intensification and the use of specific mitigation strategies can reduce greenhouse gas emissions (GHG-e) from dairy farms, but these options are generally costly. In this study, a farm-level model is used to analyse the cost of GHG-e abatement for different levels of mitigation in medium- (10–20% imported feed) and high-input (20–40% imported feed) systems in the two major dairy regions of New Zealand (Waikato and Canterbury). The focus of the study is to assess the cost-effectiveness of a variety of mitigation strategies aimed at reducing the negative impact of emissions constraints on farm profit. A combination of reduced N fertiliser application and lower stocking rates were the larger changes experienced in the studied systems when GHG-e reductions were introduced. Nitrification inhibitors were only useful mitigations once GHG-e reductions were so stringent that their high cost was warranted to offset the significant costs associated with de-intensification in the high-input systems. Stand-off pads were too expensive to warrant their use. Overall, de-intensification of the farming system proved to be more profitable than the use of specific mitigation practices when reduction of GHG-e was required. Maintaining a given proportion of imported feed in the diet reduces the degree to which de-intensification can be used, thus inflating the cost of abatement on high-input farms.

Keywords. Agriculture, greenhouse gas emissions, optimisation, livestock.

4.1. Introduction

The agricultural sector is the largest export earner in New Zealand, being responsible for 57% of merchandise exports by value in 2011 (Statistics New Zealand 2012). The dairy industry is the largest exporter within the agricultural sector, reaching 12.9 billon dollars (48% of the agricultural sector) exported in 2011 (Statistics New Zealand 2012). The dairy industry is also the largest employment provider within rural New Zealand, employing around 35,000 workers and up to 25% of the labour force in some parts of the Waikato region.

However, at the same time, New Zealand agriculture is responsible for 47% of the total greenhouse gas emissions (GHG-e) of the country (MfE 2010). There are two main greenhouse gases (GHGs) that dairy farms emit: methane (CH_4) from enteric fermentation in the rumen and nitrous oxide (N_2O), mainly from denitrification of urinary N in the soil (MfE 2010). A different pool of mitigation options has to be applied to reduce emissions of each GHG (Eckard et al. 2010). Methane from enteric fermentation is the major source of these emissions (65%) and increased by 4% in the period 1990–2008. Nitrous oxide from agricultural soils represents 33% of agricultural emissions and increased by 21% in the same period (MfE 2010). Agriculture is included in the New Zealand Emissions Trading Scheme and livestock farmers are likely to be levied for their emissions in the future, although currently there is no legislated date for when biological agricultural emissions will face costs under the ETS. The New Zealand Government has indicated that biological emissions from agriculture will have surrender obligations in the NZ ETS only if there are economically viable and practical technologies available to reduce emissions, and if the trading partners make more progress on tackling their emissions in general (http://www.climatechange.govt.nz). Therefore, a good understanding of the economic implications of different levels GHG-e restrictions on New Zealand dairy farms is desirable.

Dairy farming is widely spread across New Zealand. Waikato has traditionally been the main dairy region of New Zealand, comprising about 30% of the country's herds and around a quarter of the total dairy cows and land (LIC 2011). In comparison, Canterbury is the second largest region in terms of cow numbers, and has been growing steadily as land is converted from less-intensive sheep farming through the use of irrigation to support higher feed demand. This region now accounts for 8% of the national herds and 15% of the country's dairy cows, evidence of the larger average herd size of 755 cows in Canterbury, relative to the average herd size of 318 cows in the Waikato (LIC, 2011).

In a study using farm systems modelling to identify cost-effective options for reducing GHG-e on dairy farms, Beukes et al. (2010) evaluated the effects of a combination of different mitigation strategies, mostly based on efficiency gains. These strategies were:

1. Reducing replacement rates to decrease the number of unproductive animals on a farm.
2. Improving pasture management to increase pasture quality and compensate for growing less pasture given reductions in N fertiliser use.
3. Using less imported supplement and N fertiliser, as this decreases GHG-e when embedded emissions are accounted for (c.f. Basset-Mens, 2009).

These simulations suggested that the combined effect of these strategies could decrease GHG-e by 27% without compromising milk production, with potential for increased profitability. Furthermore, the inclusion of nitrification inhibitors allowed for an extra 5% mitigation. In another study, Beukes et al. (2011) found that these strategies resulted in reductions in total feed intake, but increases in milk production. These improvements in feed conversion efficiency, together with a reduction in N input and a dilution in dietary N, were found to have potential to decrease GHG emissions by 15–20% while increasing milk production by 15–20%. These studies are consistent with those of Dynes et al. (2011), where farm systems simulations identified management scenarios where there could be decreased emissions and increased profit for New Zealand dairy farms. Overall, these studies suggest that win-win solutions may exist whereby production and profit are increased and GHG-e is reduced. Rather than testing mitigation options individually with a simulation model as in previous studies, the present study uses an optimisation model. The use of an optimisation model is valuable, as the optimal level of all mitigation options available can be identified simultaneously.

The objectives of this study are: (1) to assess the cost implied in different levels of mitigation for contrasting dairy farm systems in the Waikato and Canterbury regions of New Zealand, and (2) to evaluate a variety of promising mitigation strategies in this context. A whole farm model, the Integrated Dairy Enterprise Analysis (IDEA) framework, is used for this purpose. This non-linear optimisation model provides a comprehensive description of a pasture-based dairy farm in New

Zealand and has been demonstrated to accurately replicate farmlet trial information, particularly compared to linear programming models (Doole et al., 2013). The paper is structured as follows. Section 2 describes the methods, while Section 3 presents the results. Section 4 provides discussion of the results, while Section 5 concludes.

4.2. Methods

4.2.1 Production system description

Dairy systems in New Zealand are pasture based, with grass directly harvested by the cows generally comprising more than 70% of the cow diet. Seasonal calving is standard, with cows starting to calve as early as the beginning of July in Waikato and the beginning of August in Canterbury. In Canterbury, pasture growth rates in winter are very low and it is common practice for cows to graze on crops off-farm during the winter period when they are dry. In Waikato, this practice is not as common.

Dairy production systems in New Zealand are defined according to the proportion of total feed that consists of imported supplement and the time during which this feed is used. Production systems 1, 2, 3, 4, and 5 import 0, 4–14, 10–20, 20–30, and 25–50% of total feed offered, respectively (DairyNZ 2012). Moreover, these systems differ in that imported feed is used to support dry cows only (system 2); late lactation and dry cows (system 3); early and late lactation and dry cows (system 4), and all cows all year round (system 5). System 3 and 4 farms are used in this study, and are referred to as medium- and high-input systems, respectively. These two systems are selected because they comprise the bulk of the dairy farms in the represented regions, particularly Canterbury. Thus, 4 representative farms were simulated. The two farms in the Waikato region are denoted WM (medium input) and WH (high input). Accordingly, the Canterbury farms are denoted CM and CH.

Feed pads are defined in the WH and CH systems since these are common to improve feed utilisation in high-input systems. Their use affects the GHG-e output predicted by IDEA since the manure is managed in ponds and sprayed later after the respective losses are accounted for.

Information from DairyBase (www.dairybase.co.nz), a database used for benchmarking purposes by storing physical and financial data for individual New Zealand dairy farms, was used to define the representative farms for the Waikato region. In contrast, the representative farms in the Canterbury region were developed based on information from benchmarking and farm consultants. DairyBase information could not be used solely, given that the data sample was too small to be conclusive. Milk price for this modelling exercise was fixed to $5.50 per kg of milk solids (MS). Other costs were urea at $500 t; palm kernel expeller (PKE) at $350 t of dry matter (DM); and dairy meal at $650 t DM.

The WM system had the lowest SR of the studied systems, with 3.08 cows ha^{-1}. The other 3 systems did not differ much in terms of SR (3.71–3.8 cows ha^{-1}), but an important difference in per cow production was responsible for a broad difference in milk production per ha (Table 7). Milk production was 1.04 t MS/ha in the WM farm, and 30% higher in the WH farm. In contrast, milk production was 1.36 t MS/ha in the CM farm, and 25% higher in the CH farm. This reflects the higher stocking rates and levels of per cow production typically found on Canterbury farms. In Waikato, the high-input system uses nearly 30% more nitrogen (N) fertiliser than the medium-input system, and the stocking rate is around 24% higher. N fertiliser application increases grass growth, while a higher stocking rate improves pasture utilisation (Doole et al., 2013). Accordingly, the amount of pasture eaten on the WH farm increased by 20%, relative to the WM farm. In Canterbury, the higher SR and level of milk per cow on the CH farm, relative to the CM farm, reflected the higher level of supplementation on the CH farm and the greater crop area, which support a much higher level of milk per cow (Table 7).

4.2.2 IDEA description

A comprehensive nonlinear programming model of a New Zealand dairy farm – the Integrated Dairy Enterprise Analysis (IDEA) model (Doole et al., 2013) – was used to analyse the impacts of restricting GHG-e and evaluate a broad set of mitigation options. This section provides a concise overview of the model; more detail is provided in Doole et al. (2013).

IDEA incorporates the basic structure of the farm-level model utilised by Doole (2010). However, some novel features of IDEA include: rotation length and post-grazing residual herbage mass as decision variables; a relationship between these variables and subsequent pasture digestibility and growth; capacity to feed cows below potential intake to varying degrees; a relationship between the body condition of individual cows and feed intake, milk production, and conception rate; and the level of pasture utilisation determined as a function of grazing density.

IDEA identifies the feeding strategy that maximises annual profit. There are six primary sources of feed: grazed pasture, pasture silage, maize silage, palm kernel expeller (PKE), maize grain, and turnips. IDEA determines how much of each of these feeds is provided to the cow herd in a given period. Ten per cent of the farm is re-grassed each year, and nitrogen fertiliser application promotes pasture growth. Silages, PKE, and turnips complement pasture intake, and losses during harvesting and feeding are accounted for in the model. Moreover, their feeding compromises pasture intake by substitution (replacement of pasture by supplement), to a degree determined by the stage of lactation, supplement type, cow liveweight, and level of pasture intake.

A large number of cow types (17,640) are defined in IDEA to allow a rich description of herd structure. The variables defining the different cows are:

- 7 feeding levels relative to potential.
- 4 age groups (1, 2, 3, and 4+ lactations).
- 5 genetic merit levels (defined upon potential milk yield).
- 9 alternative calving dates.
- 7 lactation lengths.
- Cows defined as standard cows or those to be culled after lactation.

A distribution of cows with varying levels of genetic merit is represented in each solution in IDEA. It is required that cows must have the same body condition at the start and the end of the management year as defined in IDEA. Also, younger cows must allocate energy towards growth. Energy intake is partitioned to body condition gain, growth, lactation, maintenance, and pregnancy. Energy is obtained from feed intake and loss of body condition.

The production system (1 to 5) of a modelled farm is a user-defined input in the IDEA model and this limits the amount of imported supplement used in the optimisation and when it is fed. This is valuable in situations where solutions for alternative production systems are compared, such as in sections 4.3 and 4.4.

IDEA is solved using the General Algebraic Modelling Systems (GAMS) software using the CONOPT3 nonlinear programming solver (Brooke et al., 2012). The CONOPT3 solver was used given its efficiency with large models and its strong capacity to deal with nonlinear constraints. The base model consists of 560,000 constraints and 708,000 decision variables.

The IDEA model was modified to incorporate GHG-e through the addition of IPCC methodology calculations (IPCC, 2006) and emission factors specific for NZ obtained from MfE (2010). A detailed description of the GHG-e component in the IDEA model is given in Adler et al. (2013).

4.2.3 Mitigation options in IDEA

Options are grouped as either production intensity status (options regarding intensification/de-intensification) of the farm system or part of a suite of actions with specific focus on GHG-e reduction (mitigation options). This grouping is necessary because certain options, like de-intensification, are often selected by farmers for reasons other than for the management of GHG-e (e.g. profitability, labour requirements, predominant practices), although they do have implications for GHG-e. On the other hand, mitigation options involve costs or changes to current management practices, and are specifically selected for GHG-e reduction.

The model is programmed to allow variation regarding intensity status when GHG-e reduction is required but mitigation options are not available. This allows greater insight into the relative value of mitigations. When mitigation options are available for GHG-e reduction, variation in intensity status is also allowed. The options to vary intensity status are limited to changes in SR, N fertiliser usage, and imported supplements within limits imposed by the farm system type represented. Mitigation options with specific GHG-e focus include:

1. Reduced replacement rates by improved herd reproduction and therefore reduced involuntary culling of cows that fail to conceive (Beukes et al. 2010; Dynes et al. 2011). In IDEA, the option of improved reproductive performance, and consequently reduced replacement rate, is associated with an extra variable cost for improving heat detection and increasing the body condition score of the cows at calving, which requires the expenditure of additional energy.
2. Application of nitrification inhibitors (NI). NI help to reduce GHG-e through slowing the conversion of ammonium to nitrate in the soil by *Nitrosomonas* bacteria (Di and

Cameron, 2002). In line with empirical evidence, no pasture response to inhibitor application is simulated (Macdonald et al. 2010).

3. Using starch-rich forage crops grown on-farm (e.g. maize grain) to feed energy-dense, low-protein feed in an attempt to reduce N intake and therefore N excreted via urine (Luo et al. 2008, Eckard et al. 2010).

4.2.4 Model runs

There is no consensus about the actual level of mitigation that could eventually be required from the New Zealand agricultural sector. Current emissions are about 10% above the 1990 level; therefore, this is taken as the primary level investigated in this analysis. Nevertheless, the implications of additional restrictions of 20% and 30% are also explored.

In Section 4.3.1, four scenarios for each of the farm systems are discussed. These scenarios differ in whether or not a cap is present that requires producers to reduce GHG-e by 10% and the possibility to implement strategic options (Figure 2).

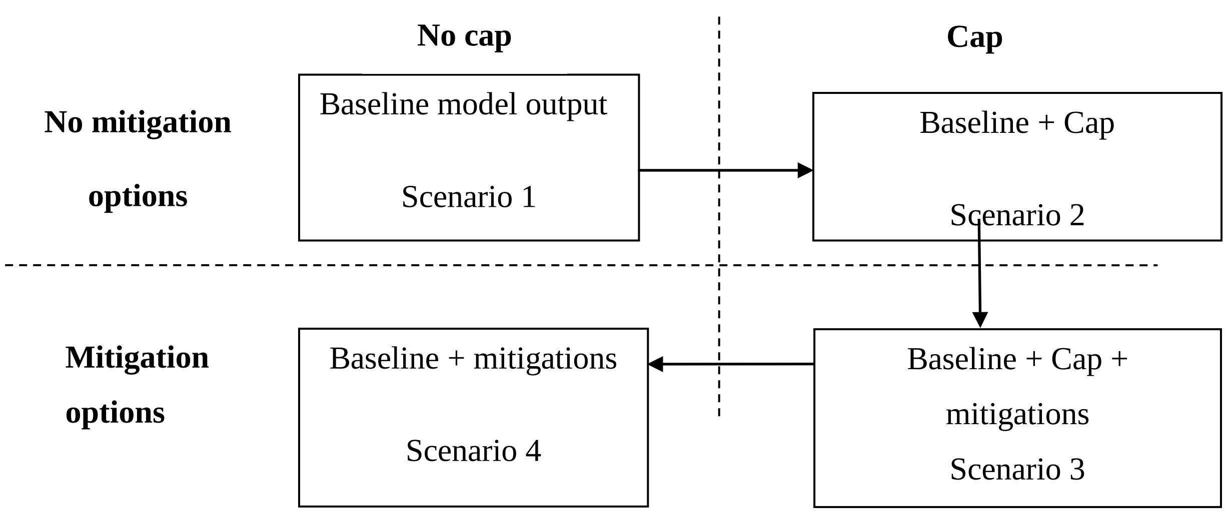

Figure 2: Four modelling scenarios investigated with the nonlinear optimisation model.

In Section 4.3.2, an extension of the first analysis was performed with IDEA for all of the farm systems studied. These runs allowed the use of mitigation options in all simulations, but with constraints requiring GHG-e to decrease by 10, 20, and 30% of the original optimised baseline emissions level. These model runs allowed the construction of mitigation cost curves to gain insight into the relationship between GHG-e mitigation and profit.

4.3. Results

4.3.1 Scenario output with 10% mitigation

For the medium- and high-input systems, the GHG-e per ha in Canterbury were at a higher level compared with Waikato. The CM farm was more profitable at the same level of emissions than the other systems, based on higher production per hectare and moderated production cost. In the CM farm, the profit was reduced only by 1% when the cap of 10% was introduced (Scenario 2, Table 8). In Scenarios 3 and 4 for that farm, the inclusion of improved reproduction as a mitigation option resulted in an increase in profit to a level of 5% and 6% above that of the baseline (about $100/ha more) for the “Cap” and “No cap” scenarios, respectively. To achieve the 10% reduction in GHG-e, IDEA reduced SR by about 7% to 3.5 cows per ha in the capped scenarios and N fertiliser was reduced by 25% to 138kg. These parameters trended back to baseline levels for Scenario 4 when the cap was removed, but the mitigation strategies were available (Table 8). The profit per kg MS was $1.32 for the baseline scenario and $1.47 for Scenario 3.

In the CH farm, profit decreased more when the cap was imposed, forcing a reduction of $93 or 8% when the mitigation options were unavailable (Table 8, Scenario 2) and $31 or 3% when mitigations were available. In Scenario 4, profits increased by 4% with respect to the baseline with SR and N fertiliser remaining equal to the baseline. In the capped scenarios, SR was reduced by about 6%, while N fertiliser was reduced by 103 and 77 kg ha^{-1} for scenario 2 and 3, respectively. Moreover, the replacement rate was reduced by 18% to a level of 22% in those scenarios, supported by an improvement in reproductive performance. In this case, the profit per kg of milk solid is $0.63 and $0.65 for Scenarios 1 and 3, respectively.

Table 7: Key model output for Scenarios 1 to 4 for CM.

Variable	Units	Scenario[ϕ]			
		1	**2**	**3**	**4**
Farm profit	$ ha^{-1}	1,797	1,776	1,892	1,907
Stocking rate	cows ha^{-1}	3.74	3.47	3.48	3.65
Milk production	kg MS cow^{-1}	364	364	371	371
Milk production	kg MS ha^{-1}	1,361	1,263	1,291	1,354
Lactation length	Days	261	261	266	266
Grazed pasture eaten	t DM ha^{-1}	14.91	14.22	14.31	14.84
Grass silage eaten	t DM ha^{-1}	0.75	0.78	0.77	0.76
PKE eaten	t DM ha^{-1}	2.42	1.82	2.13	2.47
N fertiliser applied	kg N ha^{-1}	184	138	138	184
Crop area	% area	-	-	-	-
Replacement rate	%	26	26	21.2	21.2
Methane emissions	kg CH_4 ha^{-1}	370	346	349.35	365.44
N_20 emissions	kg N_20 ha^{-1}	10.93	9.54	9.61	10.84
GHG emissions	kg CO_2-eq ha^{-1}	18,093	16,284	16,284	17,554
Mitigation practices	-	-	-	Improved repro.	Improved repro.

[ϕ] Scenario description: 1. Baseline situation. 2. 10% reduction in baseline emissions without mitigation options. 3. 10% reduction in baseline emissions with mitigation options. 4. No reduction in baseline emissions with mitigation options. These options are shown graphically in Figure 2.

In the WM farm, profit was reduced by $74 or 6% when the cap was imposed and by 4% in Scenario 3 when mitigation strategies were available (Table 9). SR was reduced by 10% and 9% in Scenarios 2 and 3, respectively, while N fertiliser was reduced by 21% and 17% to 88 and 93 kg ha^{-1}, respectively. In Scenario 4, farm profit was increased by 1% with the same SR and N fertiliser as the baseline. Again, improved reproduction was the only mitigation option selected by IDEA, reducing the replacement rate to about 18% in Scenarios 3 and 4. The profit per kg of milk solid was \$1.21 for the baseline and \$1.25 for Scenario 3, a value that is intermediate between the two Canterbury systems studied.

Table 8: Key model output for Scenario 1, 2, 3, and 4 for CH.

Variable	**Units**	**Scenario$^{\phi}$**			
		1	**2**	**3**	**4**
Farm profit	\$ ha^{-1}	1,079	986	1,048	1,121
Stocking rate	cows ha^{-1}	3.8	3.54	3.55	3.79
Milk production	kg MS cow^{-1}	447	448	451	448
Milk production	kg MS ha^{-1}	1,699	1,586	1,601	1,698
Lactation length	Days	279	279	280	280
Grazed pasture eaten	t DM ha^{-1}	14.43	13.43	13.6	14.47
Grass silage eaten	t DM ha^{-1}	4.31	3.99	4.03	4.36
Maize grain eaten	t DM ha^{-1}	0.81	0.76	0.76	0.81
N fertiliser applied	kg N ha^{-1}	184	81	107	184
Crop area	% area	19	19	19	19
Replacement rate	%	27	27	22	22
Methane emissions	kg CH_4 ha^{-1}	395.95	363.53	366.87	395.49
N_20 emissions	kg N_20 ha^{-1}	11.14	8.81	9.28	11.1
GHG emissions	kg CO_2-eq ha^{-1}	19,087	17,179	17,179	18,800
Mitigation practices	-	Feed pad	Feed pad	Feed pad Improved repro.	Feed pad Improved repro.

$^{\phi}$ Scenario description: 1. Baseline situation. 2. 10% reduction in baseline emissions without mitigation options. 3. 10% reduction in baseline emissions with mitigation options. 4. No reduction in baseline emissions with mitigation options. These options are shown graphically in Figure 2.

Table 9: Key model output for Scenario 1, 2, 3, and 4 for WM.

Variable	Units	Scenario[ϕ]			
		1	**2**	**3**	**4**
Farm profit	$ ha^{-1}	1,257	1,183	1,209	1,270
Stocking rate	cows ha^{-1}	3.08	2.69	2.73	3
Milk production	kg MS cow^{-1}	346	354	354	347
Milk production	kg MS ha^{-1}	1,038	952	966	1,041
Lactation length	Days	278	290	288	277
Grazed pasture eaten	t DM ha^{-1}	12.58	11.66	11.82	12.61
Grass silage eaten	t DM ha^{-1}	0.64	0.29	0.32	0.61
Maize silage eaten	t DM ha^{-1}	0.37	0.37	0.37	0.37
PKE eaten	t DM ha^{-1}	1.54	1.39	1.41	1.54
N fertiliser applied	kg N ha^{-1}	112	88	93	112
Crop area	% area	2.5	2.5	2.5	2.5
Replacement rate	%	23.3	22.6	17.8	18.3
Methane emissions	kg CH_4 ha^{-1}	295.08	270.13	274.04	295.69
N_20 emissions	kg N_20 ha^{-1}	8.68	7.65	7.79	8.64
GHG emissions	kg CO_2-eq ha^{-1}	12,745	11,471	11,471	12,546
Mitigation practices	-	-	-	Improved repro.	Improved repro.

[ϕ] Scenario description: 1. Baseline situation. 2. 10% reduction in baseline emissions without mitigation options. 3. 10% reduction in baseline emissions with mitigation options. 4. No reduction in baseline emissions with mitigation options. These options are shown graphically in Figure 2.

In the case of the WH farm (Table 10), profit fell by 8% ($119) when the emissions constraint was imposed with no mitigation options available (Scenario 2). When mitigation optionswere available and this constraint was incorporated (Scenario 3), predicted profit was 4% lower than that of the baseline. The SR in Scenarios 2 and 3 is about 8% lower than in the baseline scenario, with a reduction in N fertiliser usage of 57 kg N (38%) and 39 kg N (26%), respectively. Similar milk production per cow was achieved when the cap was included, but mainly due to an increase of 16% and 14% in maize silage eaten in Scenarios 2 and 3, respectively (Table 10). In this case, the replacement rate decreased to 21% in the scenarios involving the presence of mitigation strategies. The profit per kg of milk solid was $1.04 for the baseline and $1.07 for scenario 3, again intermediate between the Canterbury systems and slightly below that of the WM farm.

Table 10: Key model output for Scenario 1, 2, 3, and 4 for WH.

Variable	Units	Scenario$^{\phi}$			
		1	**2**	**3**	**4**
Farm profit	$ ha^{-1}	1525	1406	1458	1541
Stocking rate	cows ha^{-1}	3.71	3.41	3.43	3.66
Milk production	kg MS cow^{-1}	392	392	398	397
Milk production	kg MS ha^{-1}	1,454	1,337	1,365	1,453
Lactation length	Days	303	303	308	307
Grazed pasture eaten	t DM ha^{-1}	15.17	14.02	14.19	15.12
Grass silage eaten	t DM ha^{-1}	0.16	0.08	0.12	0.17
Maize silage eaten	t DM ha^{-1}	2.3	2.67	2.62	2.3
Maize grain eaten	t DM ha^{-1}	1.46	1.46	0.8	1.45
PKE eaten	t DM ha^{-1}	0	0	0	0
N fertiliser applied	kg N ha^{-1}	149	92	110	149
Crop area	% area	3.05	3.05	3.05	3.05
Replacement rate	%	26.1	26.1	21.4	21.3
Methane emissions	kg CH_4 ha^{-1}	374.24	339.27	344.12	373.3
N_20 emissions	kg N_20 ha^{-1}	10.3	8.65	9	10.21
GHG emissions	kg CO_2-eq ha^{-1}	15,004	13,504	13,504	14,666
Mitigation practices	-	Feed pad	Feed pad	Feed pad Improved repro.	Feed pad Improved repro.

$^{\phi}$ Scenario description: 1. Baseline situation. 2. 10% reduction in baseline emissions without mitigation options. 3. 10% reduction in baseline emissions with mitigation options. 4. No reduction in baseline emissions with mitigation options. These options are shown graphically in Figure 2

4.3.2 Cost of higher levels of mitigation

The CM farm had the smallest reduction in profit of \$212 ha^{-1} (11%) when 30% mitigation was imposed (Table 11), relative to the CH farm. The CH farm had the greatest loss of \$488 ha^{-1} (44%) when 30% mitigation was imposed. In comparison, in the Waikato region, the WM farm observed a cost of 29%, while the WH farm experienced a cost of 30% (Table 12). Thus, in both regions the high-input system experienced a greater cost of abatement, though this was only marginal in the Waikato region. The SR was reduced gradually on all of the farms, with a higher reduction found in the medium-input systems in both regions, compared with the SR reductions observed in the high-input systems (Tables 11, 12). For example, the WM farm experienced a 25% reduction in SR between the 0 and 30% mitigation scenarios, while the WH farm experienced a 21% decrease in SR. Moreover, the CM farm experienced a 20% reduction in SR between the 0 and 30% scenarios, while the CH farm experienced only a 17% reduction in SR between the two extreme scenarios.

No N fertiliser was used with the 30% cap in all cases; except for the WH farm in which only 32 kg N ha^{-1} were still used (Tables 11, 12). It is realistic to run 2.9 cows on a New Zealand dairy farm without the addition of N fertiliser, because imported supplement provides the energy and protein to fill the feed gaps experienced when this source of additional feed is removed. Note that phosphorus and sulphur are added to the soil at maintenance levels, in accordance with standard industry practice. Thus, though no N fertiliser is added with a 30% cap in most scenarios, the pasture still receives adequate sources of the other critical soil macronutrients.

Milk production per cow remained constant for most of the scenarios, resulting in production per ha progressively decreasing following the gradual reduction in SR and nitrogen fertiliser. Improved reproduction is still the only mitigation option selected by IDEA for the CM and WM farms (Tables 11, 12). At the simulated level of cost for inhibitors (\$150 ha^{-1}), NI were not applied in the medium-input systems. In the CH and WH farms, a feed pad was compulsorily included and NI was the only other option that the model selected as a cost-effective mitigation strategy. When a GHG-e reduction of 20% was simulated in the WH farm, NI were applied to 49% of the area of the farm, and with a 30% reduction, NI were applied on the entire farm. However, in the CH farm, NI application was only cost-effective in the 30% reduction scenario, but was applied to 100% of the farm area in this case.

Table 11: Key changes in farm management for the CM and CH farms for GHG-e reductions of 0, 10, 20, and 30 per cent.

Farm	Variable	Units	GHG-e reduction (%)			
			0[1]	10[2]	20	30
CM	Farm profit	$ ha^{-1}	1,907	1,892	1,818	1,695
	Stocking rate	cows ha^{-1}	3.65	3.48	3.19	2.9
	Milk production	kg MS cow^{-1}	371	371	371	371
	Lactation length	days	266	266	266	266
	N fert. applied	kg N ha^{-1}	184	138	78	0
	Methane emissions	kg CH_4 ha^{-1}	365.44	349.35	323.3	292.92
	N_20 emissions	kg N_20 ha^{-1}	10.84	9.61	7.99	6
	GHG emissions	kg CO_2-eq ha^{-1}	17,554	16,284	14,474	12,665
	Mitigation practices	-	Improv. repro.	Improv. repro.	Improv. repro.	Improv. repro.
CH	Farm profit	$ ha^{-1}	1,121	1,048	886	633
	Stocking rate	cows ha^{-1}	3.79	3.55	3.28	3.15
	Milk production	kg MS cow^{-1}	448	451	451	451
	Lactation length	days	280	280	280	280
	N fert. applied	kg N ha^{-1}	184	107	0	0
	Methane emissions	kg CH_4 ha^{-1}	395.49	366.87	336.09	314.44
	N_20 emissions	kg N_20 ha^{-1}	11.1	9.28	6.86	3.02
	GHG emissions	kg CO_2-eq ha^{-1}	18,800	17,179	15,270	13,361
	Mitigation practices	-	Feed pad Improv. repro.	Feed pad Improv. repro.	Feed pad Improv. repro.	Feed pad Improv. repro. NI (100% of farm)

[1] This result is equivalent to that for Scenario 4 for each farm type.

[2] This result is equivalent to that for Scenario 3 for each farm type.

Table 12: Key changes in farm management for the WM and WH farms for GHG-e reductions of 0, 10, 20, and 30 per cent.

Farm	Variable	Units	GHG-e reduction (%)			
			0[1]	10[2]	20	30
WM	Farm profit	$ ha^{-1}	1,270	1,209	1,077	903
	Stocking rate	cows ha^{-1}	3	2.73	2.48	2.24
	Milk production	kg MS cow^{-1}	347	354	356	356
	Lactation length	days	277	288	290	290
	N fert. applied	kg N ha^{-1}	112	93	52	0
	Methane emissions	kg CH_4 ha^{-1}	295.69	274.04	247.64	220.88
	N_20 emissions	kg N_20 ha^{-1}	8.64	7.79	6.49	5.07
	GHG emissions	kg CO_2-eq ha^{-1}	12,546	11,471	10,196	8,922
	Mitigation practices	-	Improv. repro.	Improv. repro.	Improv. repro.	Improv. repro.
WH	Farm profit	$ ha^{-1}	1,541	1,458	1,282	1,066
	Stocking rate	cows ha^{-1}	3.66	3.43	3.27	3.03
	Milk production	kg MS cow^{-1}	397	398	398	398
	Lactation length	days	307	308	308	308
	N fert. applied	kg N ha^{-1}	149	110	63	32
	Methane emissions	kg CH_4 ha^{-1}	373.3	344.12	325.32	302.68
	N_20 emissions	kg N_20 ha^{-1}	10.21	9	6.01	3.3
	GHG emissions	kg CO_2-eq ha^{-1}	14,666	13,504	12,003	10,503
	Mitigation practices	-	Feed pad Improv. repro.	Feed pad Improv. repro.	Feed pad Improv. repro. NI (49% of farm)	Feed pad Improv. repro. NI (100% of farm)

[1] This result is equivalent to that for Scenario 4 for each farm type.

[2] This result is equivalent to that for Scenario 3 for each farm type.

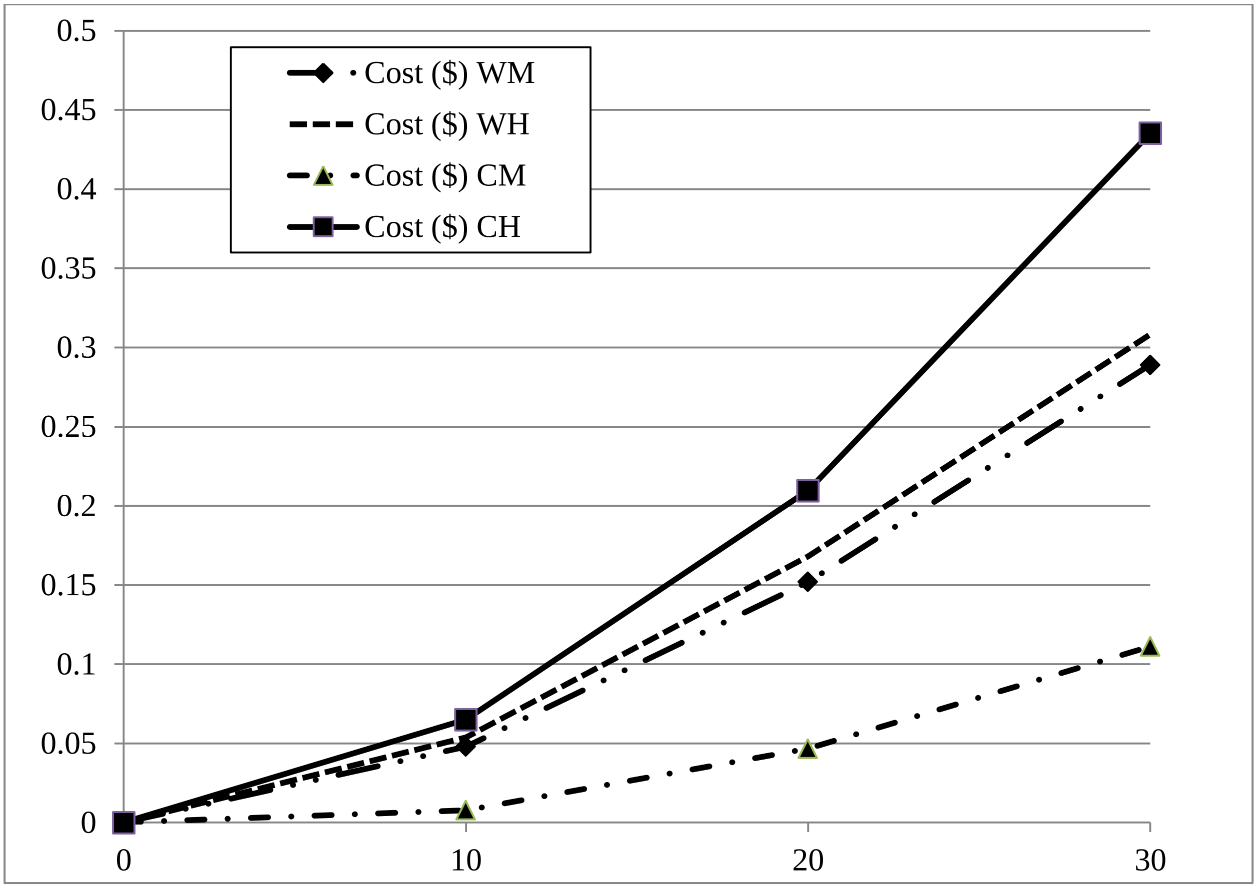

Figure 3: Relative reduction in profit with higher levels of mitigation.

Figure 3 shows the cost of GHG emissions abatement. The two Waikato systems had similar cost of mitigation through all the different mitigation stages; this cost was intermediate to that of the Canterbury region systems. The CH system presented the higher cost of mitigation, particularly at 20 and 30% GHG emissions reductions in which this system experienced a reduction in profit of about 20 and 44% respectively. The CM farm presented the lower cost of mitigation, being particularly low at the GHG-e limit of 10%, at which profit changed less than 1%. Nevertheless, this system had a reduction in profit of about 5 and 10% when limits of 20 and 30% to baseline GHG-e were imposed.

4.4. Discussion

In this chapter, the analysis of the Canterbury region is introduced alongside that for the Waikato region, increasing the scope of the discussion. Firstly, more intensive systems are found in the Canterbury region, using more N fertiliser to sustain higher stocking rates than the ones used in the Waikato region. Secondly, imported supplements were used more by Canterbury farms, giving different plans of response and cost of mitigation depending on the nature of the supplement due to the high use and embedded emissions of PKE. The rest of this chapter focuses on how optimal responses to GHG-e limits vary in the medium- and high-intensity units in the Canterbury and Waikato regions, given these key disparities.

The reduction in N fertiliser application and SR were the largest changes implemented for all of the farms when the GHG-e constraint was introduced. Reducing N fertiliser application, and consequently the level of dry matter produced and consumed by the cows, reduces GHG-e from pastoral systems in multiple ways. First, less N is lost as N_2O as direct emissions from fertiliser application. Second, less N is recycled back to pasture as urinary N, reducing direct gaseous N losses through nitrification and denitrification. Last, less pasture is available, which reduces one of the key drivers of methane losses from pastoral dairy farms (de Klein and Eckard 2008). This is true, provided that the reduction in pasture yield is not replaced with imported supplements. Indeed, the level of supplement fed to cows does not change. Accordingly, the level of production per cow does not experience much reduction; as pasture production declines, supplement feeding helps to support higher production levels through timely feed supply. Smeaton et al. (2011) identify high per cow production as one of the characteristics of dairy farms that are efficient from a GHG-e perspective. Nevertheless, the optimisation model identifies that it is more cost-effective to reduce stocking rate and N application, without large changes in milk production per cow.

Although the changes in milk production per cow are minor, reductions in milk per ha are significant and the primary methods of mitigation vary. There is also broad variation in abatement costs. When the cap was introduced in Scenario 2, both regions experienced a change in milk per ha of around 7–8%. Nevertheless, there were broad differences in profit both within and between regions (Section 4.3.2). The main result was that the medium-input farms (CM and WM) had much lower abatement costs than the high-input farms (CH and WH). This reflects that the high-input systems involve higher costs (mainly for infrastructure and supplement), thus requiring greater levels of production to warrant their greater intensity. Restrictions on GHG-e directly threaten the capacity of these high-input farms to cover these additional costs, by reducing their ability to produce as much as they can in the absence of regulation. GHG-e restrictions essentially dampen the marginal value of imported supplement through restricting the productive capacity of high-input farms, reducing their profit with mitigation to a greater degree relative to less-intensive systems under equivalent constraints.

In absolute terms, the cost of mitigation was similar for the WM, WH and the CH farm. In contrast, the CM farm was quite disparate, being the most cost-effective. These costs closely follow the changes in profit per kg of milk solids. In both regions, the medium-input systems earned higher levels of profit per kg of milk solids, compared to the high-input systems. This is a direct result of lower operating costs per kg of miksolids due to their lower levels of imported feed compared with the high-input systems. When the costs of mitigation are observed relative to the baseline levels, the CH farm presented the highest costs due to a combination of larger GHG-e reductions required in absolute terms and the low profit of the baseline.

The finding that de-intensification can achieve cost-effective reductions in GHG-e, albeit at some cost, corresponds with previous research. Luo et al. (2008) estimated GHG-e from trial data for two different dairy farming systems. The control treatment consisted of grazed pasture only with a SR of 3 cows ha^{-1}, and the more intensive system consisted of grazed pasture plus imported maize supplementation and a SR of 3.8 cows ha^{-1}. N_2O emissions ha^{-1} from the higher SR system were greater than in the control when embedded emissions from the growing and transport of supplements were counted, even though losses from the whole system were 22% lower per tonne of milk produced. Likewise, Foley et al. (2011) found that emissions per hectare in beef systems increased with higher SRs, while GHG-e per unit of product decrease. Dynes et al. (2011), on the other hand, found a 10% increase in profit above the baseline of a Canterbury dairy farm when improved genetic merit was used as a mitigation option, combined with a reduction in SR. In that study, total GHG-e of the farm fell only 3% below the baseline, as N fertiliser application was maintained at the baseline rate. Profit and GHG-e were reduced by 12% and 14%, respectively, in another scenario in which the only mitigation option was reducing N fertiliser application by 50%. This supports one of the key findings of this study, that N fertiliser application is a significant lever for reducing GHG-e in dairy systems.

The use of a stand-off pad (standing cows on a bark-covered loafing pad for a certain number of hours per day) was not optimal in any situation, despite its capacity to reduce GHG-e through avoidance of manure deposition onto pastures. de Klein et al. (2010) reported reductions in total GHG-e ranging from 7 to 11% on dairy farms, but this option has a significant cost associated with it, which reduces its value relative to the other simulated mitigations.

Improved reproduction is the only mitigation option that was used by IDEA in all mitigated scenarios with a cap for both regions. This helped to reduce costs because fewer replacement animals needed to be raised, thus allowing greater emissions from the milking herd. For example, in the WM farm, improved reproduction was selected by IDEA, reducing the replacement rate to about 18% in Scenarios 3 and 4. Replacement rates could be further reduced, but this entails a cost in terms of increasing cow condition, which is not warranted in this case.

The lower mitigation costs observed on the CM farm were associated with a higher use of N fertiliser in the initial point, which allowed for a more economic reduction of GHG-e through N_2O emissions, together with a reduction of stocking rate. Even though the same level of initial N fertiliser application was applied on the CH farm, this system could not reduce the SR as flexibly or as economically, given that it must maintain a high level of imported feed (Table 11). This was also true for the WH farm (Table 12). Similarly, the WM had less N fertiliser to reduce. Therefore, SR must be reduced by a larger proportion than in the CM farm to achieve the 30% reduction in GHG-e. Another feature of the CM farm was that most of the supplement imported was PKE, which has the largest GHG-e of all the supplements evaluated in this study when embedded emissions are considered. Significant amounts of this supplement present in the baseline meant that this farm could cost-effectively reduce GHG-e by reducing its use, while other systems did not have this opportunity (Table 6).

Nitrification inhibitors were selected only for the high input system in both regions, and only when 20% or more mitigation is required. No extra growth rates were considered with its application, following results from MacDonald et al. (2010). Indeed, with the set of prices for outputs and inputs used here, reducing production intensity was less costly than the use of inhibitors, reflecting their high cost and low marginal benefit for reducing farm emissions.

New Zealand depends on the export of commodities for 70% of its national overseas income, with dairy products accounting for 25–30% of all goods exported (NZIER 2010). Based on LIC-DairyNZ (2013), total milk production for the 2012-13 dairy season was 1,658 million kg of milk solids. It is important to estimate the potential national implications of a loss in production due to GHG-e limits, although obviously difficult to do. This is done here through estimation of the loss of national export revenue due to the imposition of these restrictions. The following computations are performed using the average reduction in milk solids production observed for the four systems (CM; CH; WM; WH) in this chapter. These mean reductions in production for the 10, 20, and 30% levels of mitigation are 5.9; 12.8 and 19.3%, respectively. Based on total export earnings of the sector of $13,659 million for the 2012 season (MPI 2013) this reduction in production can add to $1,745 million for the 20% mitigation which is more than the entire export value of the wine sector or $2,639 million for the 30% mitigation, value that exceeds the export value of the entire New Zealand beef industry ($2,010 million) and the entire lamb export value of $2,310 million (MPI 2013).

4.5. Conclusions

A combination of reduced N fertiliser application and stocking rate were the largest changes in all the studied systems when GHG-e reduction was introduced. Meanwhile, the use of supplements and the individual performance of cows did not present large changes, except for PKE that has large embedded GHG-e. The higher-input systems experienced a larger reduction in profit, while having a similar reduction in milk production, given their high use of imported feed and the need to reduce a larger amount of GHG-e in absolute terms. Mitigation costs will generally be smaller for systems that use more N fertiliser and possess a higher replacement rate, as they have more room to maneuvre. Reducing replacement rate can help to reduce abatement cost but it was found to be largely ineffective at increasing profitability when no cap on emissions is in place. Nitrification inhibitors were only useful mitigations once GHG-e reductions were so stringent that their high cost was warranted to offset the significant costs associated with de-intensification in the high-input systems. Furthermore, nitrification inhibitor use was never valuable on the medium-input farms, given their lesser intensity. Stand-off pads were never selected due to their cost.

Overall, de-intensification of the farming system proved to be more profitable than the use of specific mitigation practices when reduction of GHG-e was required. High-input systems possess a comparative disadvantage under GHG-e reductions, due to the need to maintain production intensity as imposed by higher feed demand and existing farm infrastructure.

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Chapter 5

Conclusions

5.1 Motivation

Globally, ruminants produce 33% of anthropogenic emissions of CH_4 (Beauchemin et al., 2008), while nitrous oxide emissions account for 10% of global greenhouse emissions (CO_2-e), with 90% of these emissions derived from agricultural practices (Smith et al., 2007). NZ is unusual among developed nations in that almost half of its total emissions are produced by the agricultural sector, in comparison with the typical 12% of other developed countries (MfE 2013). In addition, New Zealand dairy farms emit an average of 12.15 t of CO_2-e/ha annually (Beukes et al. 2010) and the area utilised by this industry has been growing steadily in recent years (LIC, 2013).

The primary objectives within this thesis are to (1) quantify the cost associated with a 10% mitigation of GHG emissions on New Zealand dairy farms, and (2) to identify the abatement options required to achieve this degree of mitigation.

5.2 Method

A comprehensive nonlinear optimisation model of a pasture-based dairy farm – the Integrated Dairy Enterprise Analysis (IDEA) framework (Doole et al., 2013) – was used. It provides a detailed description of many of the key biophysical processes observed within grazing systems that are absent from previous models (Doole and Romera, 2013). Its value in a greenhouse gas emissions context is that it studies decisions at the farm level and optimises management in this context. This allows the consistent identification of cost-effective solutions across diverse farming systems and constraints, such as those levied on emissions, that represent external constraints imposed on the farm. The inclusion of pasture residual mass, intake regulation, and pasture utilisation as key decision variables in IDEA proved to be valuable in designing optimal responses to new policies, prices, and technologies in complex pasture-based dairy systems, increasing the accuracy of the predictions outside of calibrated scenarios relative to less-detailed linear programming models. This research has indicated the utility of this method for further research on New Zealand dairy systems – for example, the mitigation of nitrogen leaching, where it can be used to test the effect of a wide range of options.

5.3 Key findings

5.3.1 De-intensification

De-intensification of the farming system is a key strategy dairy producers can use to respond to GHG emissions constraints. This means reducing nitrogen fertiliser use, stocking rate and supplement use, and the cost savings involved in this strategy can partially offset the reduction in revenue associated with decreased production that comes with a need to reduce GHG emissions.

This strategy has been proven effective in minimising potential profit losses across the whole range of farming systems and regions considered in this study, as well as for all levels of emissions constraints tested. In all cases considered, de-intensification of the farming system was sufficient to reduce GHG emissions by 10% and the range of farm profit reduction found under this level of mitigation was between 1.2% and 8.6% (average of the 9 cases studied was 6.0%) when no other mitigation strategies were available. To achieve this, the mean reduction of SR was 8.8% and the mean nitrogen fertiliser reduction was 36%. The average profit reduction was 6.9% and 4.9% for the Waikato and Canterbury regions, respectively, but the variation within the regions presented larger differences. While the profit reduction in all of the six Waikato cases were between 5.4% and 7.8%, the two Canterbury farms lay at both ends of the spectrum, with 1.2% and 8.6% identified for the medium- and high-input systems, respectively. The higher cost of mitigation in the Canterbury high-input system, was associated with a combination of larger GHG-e reductions required in absolute terms and the low profitability of the baseline plan, given its high use of imported supplement.

Nitrogen fertiliser was the single variable that changed the most in all the systems modelled, indicating that it is one of the most important levers in reducing GHG emissions in a cost-effective manner. A reduction in N fertiliser application not only affects nitrous oxide emissions from soils, but also affects methane emissions as less feed is available to the animals. Furthermore, when higher levels of mitigation were imposed, N fertiliser was heavily reduced, generally to nil, in order to achieve the reductions. The decision on how much nitrogen fertiliser should be used in a dairy system needs to be carefully taken under GHG emissions constraints, the large reductions experienced here in the mitigation scenarios is evidence of the low marginal value of its use under GHG restrictions. If the ratio of N fertilizer cost/milk price increases, its economic benefit is likely to be further reduced.

The relative changes observed in SR were much smaller than those for N fertiliser. This can be explained by the fact that production per cow did not change much across the scenarios, leaving little opportunity to compensate for any losses in production and revenue with a lower SR. In contrast, reductions in N fertiliser usage were partially compensated by the implied cost savings and could be masked by the adaptation of the rest of the system. This reinforces the idea of using N fertilizer as a tactical management tool to feed cows during periods of perceived scarcity, rather than maintaining regular high rates of application to support higher SR as a structural farming strategy. This is particularly important if producers are required to reduce GHG emissions and/or N leaching as part of a regulatory programme. In contrast, the fact that the individual performance of the cows did not present large variation across the scenarios for each individual farm shows the importance of maintaining production per cow at an optimum level using SR as a key tool to regulate intake capacity to achieve this.

5.3.2 Specific mitigation options

When specific mitigations strategies were available, the profit variation due to the 10% mitigation constraint was between -4.4% and +5.3% (average of the 9 cases was -1.6%). On average, SR was reduced by 8.1% while N fertiliser was reduced by 30.7%. Overall, the availability of specific mitigation strategies was valuable, but these were not sufficient to reduce emissions without some degree of de-intensification. In terms of specific mitigation strategies, improved reproductive performance and improved genetic merit of the herd were selected as optimal in this case. These options can reduce GHG emissions and increase profit by improving feed conversion efficiency. Since about two-thirds of farm emissions arise from enteric methane, which is a direct function of the gross energy intake of cattle, the reduction of feed going to maintenance and its diversion to milking cows can reduce the total GHG emissions without reducing production and revenue.

Other specific mitigation options were never selected by IDEA under a 10% emissions constraint. This showed that the use of nitrification inhibitors and the construction of structures to stand cows off pasture at certain times of the year are not cost-effective ways of reducing emissions at the prices of inputs and outputs represented here. Nevertheless, these options were selected by IDEA when higher levels of mitigation were enforced in the high-input systems for both regions. For example, the use of nitrification inhibitors was selected when mitigation required reductions of 20% or higher. However, these products are currently banned in NZ. Overall, this signifies that the high cost of adopting specific mitigation strategies is warranted only when stringent GHG constraints threaten to impose enormous costs via de-intensification.

Standing cows off pasture at certain times of the year is not cost effective in reducing GHG emissions, with its cost requiring a reduction of more than $300 per ha for these strategies to enter the optimal plan. However, the model output indicates that farm systems that used less imported supplement had less total GHG emissions, with an average of 13,987 kg CO_2-e per ha for the medium-input systems, compared with 16,074 kg CO_2-e for the high-input systems. Results indicate that it is more cost-effective to stand off cows in the medium-input systems given the high protein content of pasture and their greater reliance on this feed source. On the other hand, farm systems that import a larger proportion of the diet have more total GHG emissions but less emission intensity (emissions per kg of product), with the high-input systems averaging 10.4 kg CO_2-eq. kg MS^{-1}, compared with an average of 12.1 kg CO_2-eq. kg MS^{-1} for the medium-input systems. Nitrogen entering the system in supplements has the same fate as N fertiliser once excreted by the cows. These results highlight that focusing on emissions intensity in order to reduce total emissions is inappropriate.

The use of large quantities (about 20%) of supplements with high embedded GHG emissions, like Palm Kernel Expeller (PKE), was avoided when emissions constraints were included, indicating that this kind of feed has a similar effect on total GHG emissions as nitrogen fertiliser. If a reduction of GHG emissions from NZ agriculture is desired, the value of PKE as a structural means for increasing production will need to be appraised. In general, the amount of supplements imported was used as lever to reduce GHG emissions, but to a lesser extent than SR and N fertiliser, indicating that it is a relatively less important lever in managing GHG emissions from dairy farms.

The medium-input systems had a lower cost of mitigation than the higher-input systems, with an average 5% profit reduction in the medium-input system, compared with an average 8% reduction in the high-input systems, for the 10% emissions reduction target with no specific mitigations available. This changed to about 1% and 4% for the medium- and high-input systems, respectively, when mitigation strategies were allowed. In that regard, it is important to note that every modelled system has been constrained in the amount of supplements it is allowed to import, in order to keep it within the original range of farm intensity simulated. This is justified since farms of medium- and high-intensity in New Zealand possess high levels of farm-specific capital that have low malleability. The sunk costs associated with these investments work against farmers reducing farm intensity to decrease GHG loads arising from dairy production. The average farm profit of the baselines of the five medium-input systems analysed was \$1340 ha^{-1}, \$37 lower than the average farm profit of the three high-input systems. However, when the 10% emissions reduction was imposed, the medium-input systems averaged \$12 and \$36 more profit per ha for the de-intensification and mitigation scenarios, respectively. A key contributor here is that the high-input systems had achieve greater reductions in GHG emissions in absolute terms, as the GHG constraint was defined as a proportion of the baseline load.

5.4 Limitations and further research

Several limitations are evident in this study. Thus, they are worthy of further research.

Stand-off pads were used as a mitigation option, but following IPCC calculations, these created no difference compared to direct deposition of animal manure to pastures. The adaptation of IDEA to represent the potential gains of applying effluents evenly, instead of directly by the animals in urine patches, could yield different results by increasing the mitigation effect of this practice, in contrast to the IPCC methodology used here. This adaptation of IDEA could also be useful to represent reductions in N leaching, which is a potential pollutant of NZ waterways (Doole, 2012).

The results presented here comprise, in all cases, the representation of farms in an average year and in steady state. Moreover, the modelling is assuming that the farmer knows exactly what pasture growth and production will be observed at each time step. This is consistent with feed budgeting on farm, but is nevertheless a departure from reality. Farmers respond to yearly economic and physical environmental variation by adapting their systems, but this adaptation is difficult to describe meaningfully in optimisation modelling (see Kingwell et al. 1993, for a rare example).

GHG emissions, in particular nitrous oxide, have large spatial and temporal variability. Therefore, dynamic modelling over a series of years using actual climate on typical soils could enhance the relevance of the results. Since the nitrogen cycle is accurately depicted in IDEA, it could be valuable if a climate-driven module, representing water content of the soil, was included to predict drainage and de-nitrification to increase the accuracy of the way in which GHG emissions and N leaching are computed.

There was difficulty in assigning a realistic cost to increasing the genetic merit of the herd, when this is to be used as a mitigation option. The mismatch between the time taken to improve genetic merit and the static structure of the IDEA model emphasizes that a different modelling framework is required to evaluate this strategy correctly.

Using IPCC methodology with the NZ specific emission factors was a good starting point for analysing GHG emissions from dairy farms in this study. The boundaries of the calculations were set way beyond the farm-gate in order to capture embedded emissions in an LCA approach and this proved to be valuable for the analysis. However, this can limit the direct comparison of these results with previous work that has been done calculating only the emissions within the farm. This approach could also bias the evaluation of some of the mitigation options, such as feeding more low-protein, high-energy supplement as a methane mitigation strategy or the use of standing-off structures for mitigation of nitrous oxide, since IPCC assigns a fixed yield of methane per unit of gross energy intake and the managed manure has the same emission factor as manure deposited directly onto pasture. The development of equations that use in-depth available knowledge to calculate the impact of these pollutants and their subsequent integration into IDEA could significantly increase the usefulness of the model in finding cost-effective solutions to constraints placed on the environmental impacts of New Zealand dairy farms.

The IDEA model provides an ideal platform for further research regarding New Zealand dairy systems. A range of issues can be investigated using the model, some of them of practical relevance for farmers. Examples are the profitability accruing to a variety of system changes including changes in stocking rate, supplement use, feed base, pasture species, improved reproductive management, and determining the marginal value of feed across time. Other subjects that could also be investigated are relevant for government and policy makers like the cost-effective mitigation of nitrogen leaching or farming within water restrictions. Interesting extensions of the model also include the incorporation of tactical decision making (Pannell, 1996) and the representation of dairy farms in different regions of New Zealand. The former would allow the consideration of climate and price variability. It could also be useful to extend the model to consider multiple, interdependent years in a sequence such that capital infrastructure and equity decisions can be studied with greater precision, especially if variability were involved, as well.

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Appendix

Appendix 1

An optimisation model of a New Zealand dairy farm

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ABSTRACT. Optimisation models are a key tool for the analysis of emerging policies, prices, and technologies within grazing systems. A detailed, nonlinear optimisation model of a New Zealand dairy farming system is described. This framework is notable for its inclusion of pasture residual mass, pasture utilisation, and intake regulation as key management decisions. Validation of the model shows that the detailed representation of key biophysical relationships in the model provides an enhanced capacity to provide reasonable predictions outside of calibrated scenarios. Moreover, the flexibility of management plans in the model enhances its stability when faced with significant perturbations. In contrast, the inherent rigidity present in a less-detailed linear programming model is shown to limit its capacity to provide reasonable predictions away from the calibrated baseline. A sample application also demonstrates how the model can be used to identify pragmatic strategies to reduce GHG emissions.

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

A1 INTRODUCTION

The potential of grazing systems to increase global milk production is high, given the increasing costs associated with high levels of supplementation and environmental and welfare concerns associated with intensive dairy production (Dillon et al., 2005). Indeed, the total costs of milk production worldwide have been shown to decline nonlinearly as the proportion of grass contained in cow rations increases, with the greatest benefits observed in pasture-based systems, such as those most popular in New Zealand (Dillon et al., 2008). Nevertheless, pasture-based dairy farms are complex systems in which producers must consider multiple interactions between pasture growth and decay, supplement use, individual animal intake and efficiency, and herd size and structure.

Mathematical programming (MP) is an optimisation technique that has been broadly applied to analyse the integrated management of the multiple components within complex grazing systems (Cartwright et al., 2007). Primary applications include the assessment of agricultural innovations, evaluation of alternative management practices, experimental design, policy analysis, and research prioritization (Pannell, 1996). Berentsen and Giesen (1995) described a linear programming (LP) model of a Netherlands dairy system in which pasture growth was defined in terms of an annual total and pasture quality was fixed. McCall et al. (1999) presented a comprehensive LP model of a dairy farming system in which the length of grazing rotations was optimised. However, cow intakes and pasture residuals, digestibility and growth were fixed in each period to maintain tractability. Neal et al. (2007) used a detailed LP model to identify the most profitable mix of 36 alternative forage combinations on a farm in New South Wales, Australia. However, the focus on the evaluation of alternative forages meant that forage residuals, digestibility, and growth were fixed in each period. Doole (2010) extended the model of McCall et al. (1999) to incorporate a link between production and nitrate emissions from multiple farms. However, this work retained fixed pasture residuals, digestibility, and growth to maintain tractability and reduce data requirements.

The objective of this paper is to describe a nonlinear programming (NLP) model of a New Zealand dairy farm that incorporates a number of important processes within pasture-based dairy systems that are not considered in previous frameworks. The framework – the Integrated Dairy Enterprise Analysis (IDEA) model – is the first optimisation model of a grazing system to consider: (1) post-grazing residual mass as a decision variable of the producer, (2) pasture growth and digestibility that differ with residual pasture mass and rotation length, (3) pasture utilisation that varies by stocking rate, and (4) different levels of intake regulation. Model output is demonstrated to match data from system experiments with reasonable accuracy given these extensions. In contrast, the rigidity of a less-detailed LP model containing a high number of fixed relationships is shown to restrict its predictive capacity.

Optimisation allows the efficient identification of profitable system configurations, which can be time-consuming if manual trial-and-error is used, particularly in complex farming systems. Moreover, shadow prices that indicate the marginal value of different quantities are computed automatically during solution. For example, the IDEA model computes the shadow price of feed energy, the value of an additional MJ of metabolizable energy, in all fortnights over an average year. Also, the use of constrained optimisation allows the natural addition of constraints to identify how a system can optimally respond to new restrictions to farm management, such as constraints on greenhouse gas emissions. However, optimisation models require a certain structure and size to remain tractable. For example, it is problematic to include integer variables in nonlinear optimisation models. Additionally, all meaningful mathematical models of grazing systems require a large number of assumptions to be made given that these systems are inherently complex and dynamic (Kingwell, 2011). A key example is that most models describe farmers as profit maximisers, but in reality producers consider multiple, interacting objectives, such as risk, leisure, and sustainability.

A2 MODEL DESCRIPTION

This section describes a nonlinear optimisation model of a NZ dairy farming system. The model involves a single management year defined from 1 July to 30 June. The year is divided into 26 fortnights (14-day periods) to provide insight into the temporal allocation of feed. The first time period follows the last in a cyclical fashion to describe decisions that span the last and first time periods. The model is constructed to represent farming systems in the Waikato region of New Zealand, the primary dairy farming region in this nation.

The model integrates information from a wide range of sources. Many of the coefficients are drawn from the literature and industry publications, especially DairyNZ (2010, 2011). A more detailed description of the model and the sources of model coefficients is provided in Doole et al. (2012). IDEA is solved with the CONOPT3 solver in the General Algebraic Modelling System 23.0 (Brooke et al., 2008).

Overview

The solution algorithm for the NLP model identifies the set of decision variables that maximizes operating profit, which is total revenue minus fixed and variable costs. Decision variables in IDEA represent the key management decisions of farmers. These include crop area, type and amount of supplement to import, lactation length, pre-grazing and post-grazing pasture biomass, rotation length, silage conservation, and stocking rate. Decision variables are selected by the solution algorithm to maximize operating profit subject to the key constraints facing producers on a typical farm. Key constraints represent cost and quality of supplements, cow energy demands, cow intake, cow reproductive capacity, farm area, and the quantity and quality of pasture available under different management plans.

Feed supply consists of pasture, supplement, and crops. A fixed farm size is allocated between grazing, silage conservation, and cropping in the “Land use module” (grey box in Figure A1) in each period. The “Pasture module” determines the quantity and quality of grazed pasture based on residual pasture mass and rotation length decisions. A feature of IDEA is that livestock intensity and lactation length also drive pasture utilisation. The “Supplement module” (grey box in Fig. A1) ensures that supplement supply and demand are balanced, while accounting for different degrees of supplement utilisation. The degree to which potential intake decreases with supplement intake is computed in the “Substitution rate module”. The “Cow module” describes the production, energy demand, and potential intake of each cow type (Figure A1). These differ for each cow type based on age, calving date, degree of intake regulation, genetic merit, and lactation length. Energy supply and energy demand are balanced within the intake constraints of the herd in the “Integration module”, with an overall goal to maximize operating profit, which is determined in the “Profit module” (Figure A1).

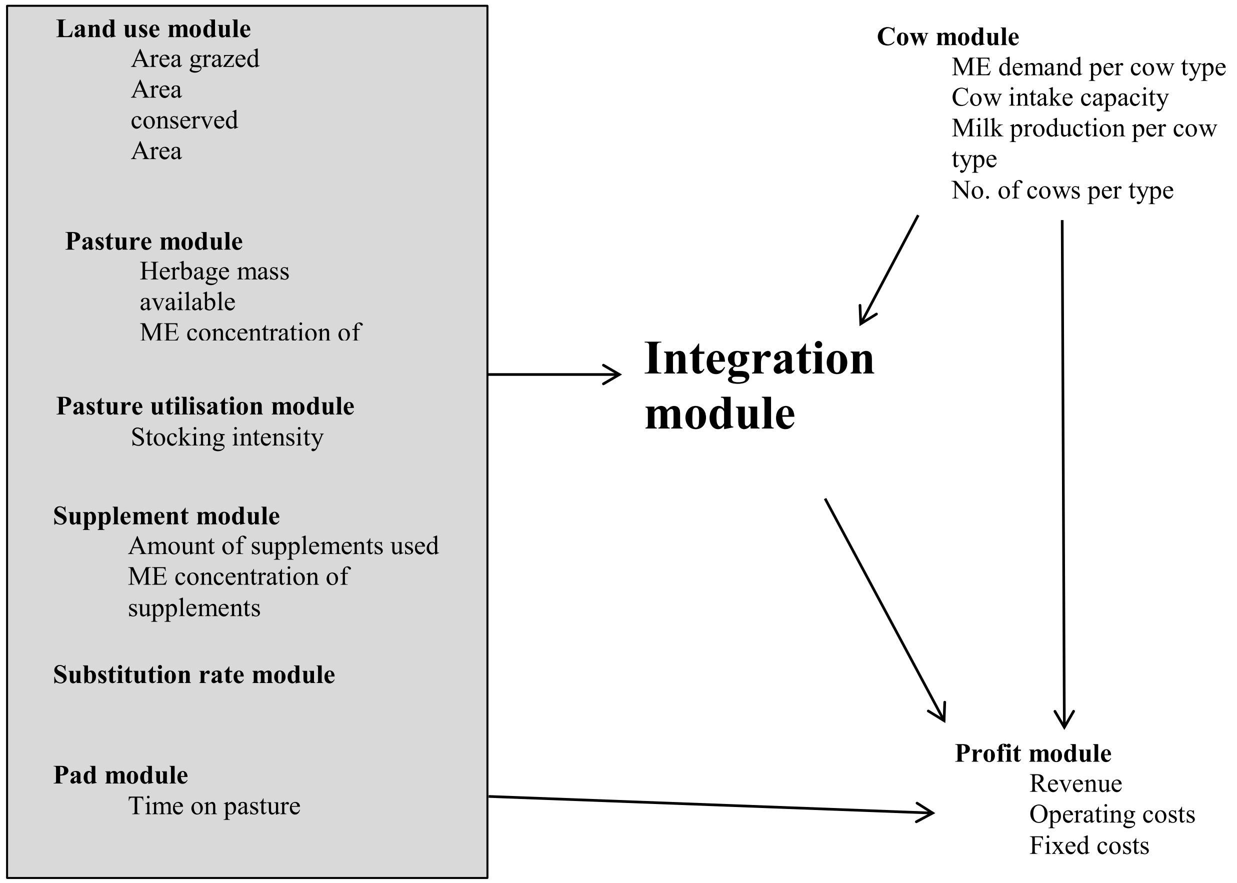

Figure A1: Conceptual diagram of the structure of the IDEA model. The grey box describes the modules that determine energy supply, while energy demand is computed in the cow module.

A2.1 Land use module

In any given fortnight, a proportion of the farm can be grazed directly by the cow herd, cut for silage conservation in spring or summer, or cropped (available crops are maize silage and turnips) at the appropriate times of the year. The model determines the optimum area allocated to each of these activities.

The length of a fortnight is $\delta = 14$ days. Time index $i = [1, 2, ..., 26]$ denotes the fortnight in which an area of pasture was previously grazed or harvested for silage. In comparison, time index *t*, where $t = [1, 2, ..., 26]$, denotes the fortnight in which an area of pasture is currently grazed, harvested for silage, or rested for future use. An additional index $u = [1, 2, ..., 26]$ is used where a (future) activity occurs in a period greater than *t*.

Two residual indices are defined:

- r_i : The pasture mass (t DM ha^{-1}) that exists after the paddock was grazed or cut for silage in period *i*.
- r_t : The pasture mass (t DM ha^{-1}) that exists after the paddock was grazed or cut for silage in period *t*.

The set of potential residuals is the same for both indices, with $r_i = r_t = \{0.8, 1, ..., 2.6\}$ t DM ha^{-1}. However, r_i can be – and typically is – different from r_t for any grazing strategy determined by the optimisation algorithm.

Two variables denote the area utilised over fortnight *t* for grazing or silage production:

- A^G_{i,t,r_i,r_t} : The area (ha) of pasture grazed at time *t* to a post-grazing residual of r_t that was last grazed or ensiled in period *i* to a residual of r_i.. This decision variable drives pasture eaten from the grazing rotation.
- A^S_{i,t,r_i,r_t} : The area (ha) of pasture ensiled at time *t* to a post-ensilement residual of r_t that was grazed or ensiled in period *i* to a residual of r_i.

Another equation requires residual lengths to remain consistent between periods:

$$\sum_i \sum_{r_i} \left[A^G_{i,t,r_i,r_t} + A^S_{i,t,r_i,r_t} \right] = \sum_u \sum_{r_u} \left[A^G_{t,u,r_t,r_u} + A^S_{t,u,r_t,r_u} \right] \quad (1)$$

Decision variables denote the area (ha) allocated to turnips (*TU*) and maize (*MA*). The first is a forage crop, while maize is harvested for silage. All land is regrassed after crops have been utilised. A proportion of a typical New Zealand dairy farm is also regrassed each year without crop establishment, primarily to replace degraded pasture. The area (ha) on which this is done is denoted *RG*. The total area that is regrassed each year (*AR*) after crops or degraded pastures are removed is:

$$AR = TU + MA + RG \quad (2)$$

Land use allocation in any period t is:

$$
\begin{aligned}
c_{z1} = AR + \sum_{i}\sum_{r_i}\sum_{r_t}\left[A^{G}_{i,t,r_i,r_t} + A^{S}_{i,t,r_i,r_t}\right] + \\
\sum_{i}\sum_{u}\sum_{r_i}\sum_{r_u}\left[A^{G}_{i,u,r_i,r_u} + A^{S}_{i,u,r_i,r_u}\right]_{\forall i\neq t, t>i, u>t, u>i} + \\
\sum_{i}\sum_{u}\sum_{r_i}\sum_{r_u}\left[A^{G}_{i,u,r_i,r_u} + A^{S}_{i,u,r_i,r_u}\right]_{\forall i\neq t, i>t, u>t, i>u} + \\
\sum_{i}\sum_{u}\sum_{r_i}\sum_{r_u}\left[A^{G}_{i,u,r_i,r_u} + A^{S}_{i,u,r_i,r_u}\right]_{\forall i\neq t, t>i, t>u, i>u}
\end{aligned} \tag{3}
$$

where c_{z1} is total farm size. The first line in eq. 3 accounts for the area removed from the grazing rotation (*AR*) and current land use. The second and third lines define land that is being rested for future use. The second line describes cases where $u > t > i$. One example is where land was last used in period 5, it is currently period 13, and it will be utilised once again in period 17 ($u = 17 > t = 13 > i = 5$). The third line describes cases where $i > u > t$. The last line describes cases where $t > i > u$. The third and fourth lines define cases where pasture is rested for a period encompassing both the last and first fortnights, consistent with the equilibrium structure of the model.

Pasture can be grazed prior to crops or new pasture being sown and after new pasture has successfully established following these land uses. The area of pasture available within area *AR* in period *t* is:

$$A_t^R = TU_{t=[23,7]} + MA_{t=[23,7]} + RG_{t=[23,18]} \tag{4}$$

where $AR \geq A_t^R$. Subscripts on the right-hand side of eq. 4 denote the periods that pasture is available on land allocated to a given crop or regrassing activity. For example, pasture is only available on land on which a turnip crop (denoted *TU*) is planted over fortnights 23–7, as it is in crop the remaining time. 10% of the farm must be regrassed each year, in accordance with industry practise.

A2.2 Pasture module

The detailed pasture module represents a number of key processes. For example, the model considers that grazing to a lower post-grazing residual can: (1) increase the amount of herbage available in the current grazing, (2) reduce the digestibility of material ingested in the current period due to the grazing of older plant material, (3) reduce subsequent pasture production due to defoliation of photosynthetic material, (4) decrease future losses to senescence, and (5) increase digestibility of regrowth due to reduced shading.

The grazing rotation yields a base amount of pasture eaten (t DM) (Q_t^G, t DM) in each period. The base amount of pasture eaten depends on the post-grazing residuals of the previous and current grazing events (denoted by r_i and r_t, respectively) and the growth that has occurred since the previous grazing.

A simulation model of pasture dynamics (Romera et al., 2009) incorporating daily climate information was extended to incorporate tissue age structure. It was subsequently calibrated to appropriate experimental information to generate pasture growth and digestibility data for the optimisation model. This is necessary given the unavailability of appropriate trial data. The model is run individually for each post-grazing residual mass that exists after grazing in period *i* ($r_i = \{0.8, 1, ..., 2.6\}$). The model was used to estimate the age structure and amount of pasture available to the herd in each of the seven subsequent fortnights (98 days). Growth differs according to the observed climate conditions and the post-grazing residual mass used as the initial condition for the dynamic process. The post-grazing residual mass in the current fortnight ($r_t = \{0.8, 1, ..., 2.6\}$) then determines how much of this estimated mass is eaten and what is the age structure of the ingested material. Mean pasture production and quality is determined for the decade 2000–2009 to account for temporal variation in pasture attributes, at least to some degree.

Residual mass decisions are not studied specifically for the grazing of pasture on the cropped and regrassed area *AR*. Instead, a set of typical residual masses is determined for this area, pasture growth is assumed constant given this set of residuals, and pasture grown is grazed in each period. This approach is necessary to maintain model tractability and follows the method of McCall et al. (1999). The amount of pasture produced on the cropped or regrassed area (Q_t^R, t

DM) is the product of the constant growth over the period of (q_t^R, t DM ha^{-1}) and the size of the cropped or regrassed area *AR*.

The variable N_i denotes the tonnes of nitrogen (N) fertiliser applied in time *i*. Constraints restrict application to 50, 100, and 400 kg every period, six weeks, and year, respectively (McCall et al., 1999). Following McCall et al. (1999), additional pasture growth from N fertiliser application is represented separately from the rotational-grazing system to maintain model tractability. The total amount of additional herbage mass available to grazing animals in period *t* arising from the application of N_i (Q_t^N) in period *i* is determined using the decision tree of Zhang and Tillman (2007).

Total herbage mass (t DM) grazed in time *t* is thus:

$$Q_t^H = Q_t^G + Q_t^R + Q_t^N \tag{5}$$

The total amount of herbage mass (Q_t^S, t DM) ensiled in period *t* is the product of the herbage mass ensiled on each unit area (q_{i,t,r_i,r_t}^S, t DM ha^{-1}) and the total area allocated to silage production (A_{i,t,r_i,r_t}^S, ha). The post-ensilement residual is determined optimally from the set $r_t = [1.4, 1.6, ..., 2.2]$ t DM ha^{-1}.

The energy obtained from each source of grazed pasture is determined through multiplication of the amount of feed consumed (t DM) and the energy of the consumed herbage (MJ ME t DM^{-1}). The energy of the material grazed in the standard rotation is the product of the digestibility of this herbage and a parameter that converts this digestibility into an energy content. The energy content of pasture on areas that have been cropped/regrassed and of pasture arising from N fertiliser application is the mean of that obtained in the standard grazing rotation.

A2.3 Pasture utilisation module

Research suggests that there is a strong, positive curvilinear relationship between cow intake and herbage allowance (Maher et al., 2003). This is included in the model to prevent unrealistic levels of herbage utilisation being realized at low stocking rates. The concave intake model of Gregorini et al. (2009), based on the formulation of McCall et al. (1986), is used to represent this relationship in IDEA. Pasture utilisation (PU_t) is a concave function defined as:

$$PU_{cd,t} = 1 - \exp[-K_{cd,ll,t} IS_t] \tag{6}$$

where IS_t is the instant stocking intensity (cows ha^{-1} day^{-1}); the number of cows divided by the area grazed on each day during each grazing period. The area grazed depends on the rotation length, which varies from period to period. $K_{cd,ll,t}$ is a variable describing the shape of the pasture-utilisation function and is defined for all calving dates *cd*, lactation lengths *ll*, and time periods *t*.[1] The variable $K_{cd,ll,t}$ is computed:

$$K_{cd,ll,t} = 0.011 \cdot \exp[-0.00346 \cdot DC_{cd,ll,t}] \tag{7}$$

where $DC_{cd,ll,t}$ is the number of days of lactation for a cow with lactation length *ll* at time *t* since calving occurred in period *cd* (days cow^{-1}). The parameter values defined in this function are from Gregorini et al. (2009).

Eq. 6 is illustrated in Figure A2 and implies that pasture utilisation increases curvilinearly as the stocking intensity increases, consistent with theory (e.g. Maher et al., 2003). Also, it is evident in Figure A2 that cows possess a greater drive to utilise more pasture as the number of days since last calving increases.

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[1] See “Cow module” section for a description of the *cd* and *ll* indices.

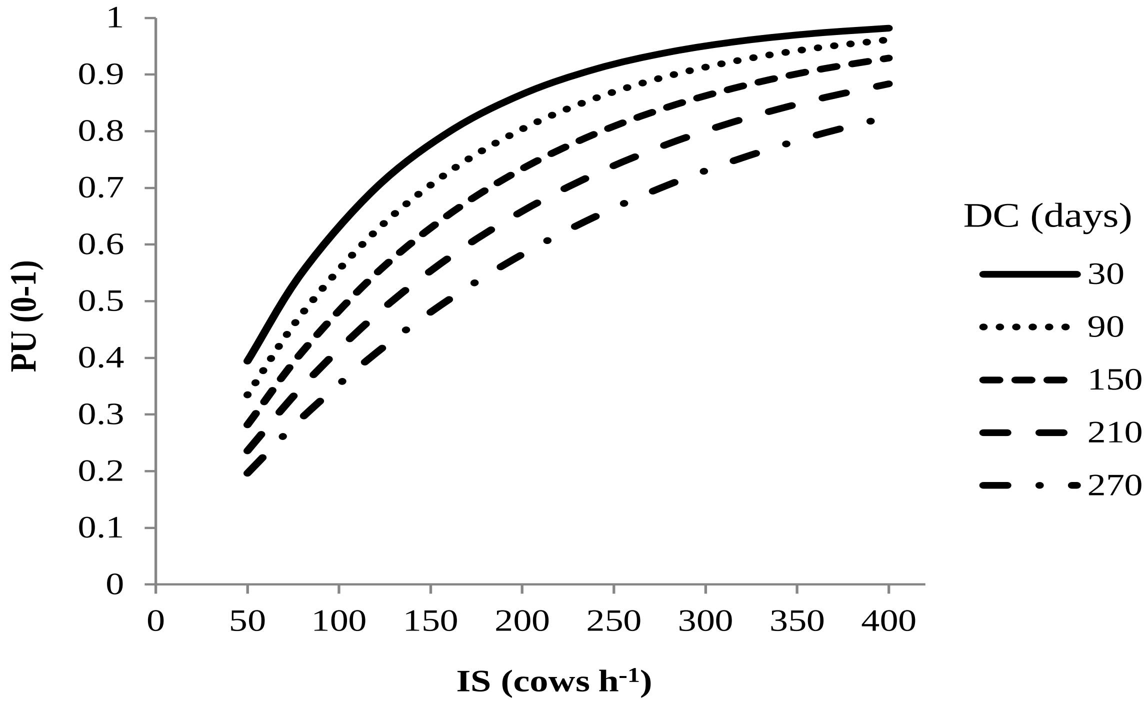

Figure A2: Pasture utilisation (PU: proportion of the pasture allocated for grazing that could be eaten) as a function of stocking intensity (IS) and days since last calving (DC).

The function stated in eq. 6 defines an upper bound on the total amount of pasture eaten. The total pre-grazing herbage mass from ground level is defined PM_t (t DM). The cow herd can only eat a proportion of the total herbage mass offered to them in each period, determined by PU_t (eq. 6). The upper limit for total pasture intake (TA_t, t DM) in period *t* is:

$$TA_t = \sum_{cd=1}^{9} \sum_{ll=1}^{7} PU_{cd,ll,t} CC_{cd,ll} \left[\frac{PM_t}{TC} \right] \tag{8}$$

where $CC_{cd,ll}$ is the number of cows that calve in *cd* and have a lactation length of *ll*, *TC* is the total number of cows on the farm, and the term in square brackets represents total pre-grazing herbage mass from ground level per cow (t DM cow^{-1}).

A limit on total pasture intake is then defined:

$$TA_t \geq Q_t^H \tag{9}$$

where total pasture mass consumed (Q_t^H) is calculated in eq. 5.

The relationships between stocking rate, herbage allowance, postgrazing herbage mass, and pasture utilisation possess a high degree of interdependency. For example, higher stocking rates increase pasture utilisation per unit area, decrease herbage allowance, and limit total ingestion, which restricts the amount of feed available, which partly determines stocking rate. The presence of such circular relationships is easily dealt with in MP, which simultaneously identifies the values of all decision variables in the model during solution.

A2.4 Supplement module

A number of supplementary feeds are available in IDEA. These are grass silage made on-farm or purchased, maize silage made on-farm or purchased, or palm kernel expeller (PKE) that is purchased. Turnip crops can also be grazed for forage.

The total amount of grass silage produced on the farm in each period is Q_t^S. The amount of grass silage eaten by cows (t DM) in each period is F_t^{SG} on the grazing area and F_t^{SP} on a feed pad (a concrete area on which cows are fed for 2–3 hours per day). The total amount of grass silage eaten is $F_t^S = F_t^{SG} + F_t^{SP}$. The amount of grass silage purchased (sold) is denoted *GAP* (*GSS*). Supply and demand is balanced through:

$$\sum_{t=1}^{26} Q_t^S (1 - c_{s1}) + GAP = \frac{\sum_{t=1}^{26} F_t^{SG}}{(1 - c_{s2})} + \frac{\sum_{t=1}^{26} F_t^{SP}}{(1 - c_{s3})} + GSS \tag{10}$$

where c_{s1}, c_{s2}, and c_{s3} are the proportional loss of grass silage at harvest and storage, feeding on the paddock, and feeding on a feed pad, respectively.

The tonnage of maize silage purchased (sold) is denoted *MAP* (*MAS*). The amount of maize silage eaten by cows (t DM) in each period is F_t^{MG} on the grazing area and F_t^{MP} on a feed pad.

The total amount of maize silage eaten is $F_t^M = F_t^{MG} + F_t^{MP}$. Supply and demand is balanced through:

$$c_{s4}(1-c_{s5})MA + MAP = \frac{\sum_{t=1}^{26} F_t^{MG}}{(1-c_{s6})} + \frac{\sum_{t=1}^{26} F_t^{MP}}{(1-c_{s7})} + MAS \qquad (11)$$

where c_{s4} is maize yield (t DM ha^{-1}) and c_{s5}, c_{s6}, and c_{s7} are the proportional loss of maize silage at harvest and storage, feeding on the paddock, and feeding on a feed pad, respectively.

The amount of PKE purchased is denoted *PAP*. The amount of PKE eaten by cows (t DM) in each period is F_t^{PG} on the grazing area, F_t^{PP} on a feed pad, and F_t^{PS} in a dairy-shed feeding system (a system that feeds cows as they are milked in the dairy shed). The total amount of PKE eaten is $F_t^P = F_t^{PG} + F_t^{PP} + F_t^{PS}$. Its use is governed by:

$$PAP = \frac{\sum_{t=1}^{26} F_t^{PG}}{(1-c_{s8})} + \frac{\sum_{t=1}^{26} F_t^{PP}}{(1-c_{s9})} + \frac{\sum_{t=1}^{26} F_t^{PS}}{(1-c_{s10})} \qquad (12)$$

where c_{s8}, c_{s9}, and c_{s10} are the proportional loss of PKE at feeding on the paddock, feed pad, and in a dairy-shed feeding system.

The amount of turnips eaten (t DM) in period *t* is F_t^T. Supply and demand is balanced by:

$$c_{s11}TU = \frac{\sum_{t=15}^{19} F_t^{T}}{(1-c_{s12})} \qquad (13)$$

where c_{s11} is the yield of the turnip crop and c_{s12} is the proportional loss of turnips at feeding.

Maximum bounds are set on the consumption of some supplementary feeds. These are set according to industry recommendations reported in DairyNZ (2010).

Substitution rate module

Substitution rates vary with pasture intake, as substitution will increase as ingestion limits imposed by potential intake are approached. LP models of dairy systems typically use fixed substitution rates, which reduces their capacity to represent such a relationship (McCall et al., 1999). Thus, the substitution rates used in the model are defined using regression equations estimated from data from 20 trials by Stockdale (2000), which includes the consideration of the level of unsupplemented pasture intake relative to the liveweight of cows. These relationships are suitable for New Zealand application, as substitution rates are relatively universal (Stockdale, 2000).

The substitution rate for grass silage (SR_t^S) and maize silage (SR_t^M) is:

$$SR_t^S = SR_t^M = -0.26 + 0.17\left[\frac{MI_t}{ML_t}\right] + 0.08se_t + 30\left(\frac{(F_t^S + F_t^M + F_t^P)}{\delta}\right) - 0.04 \qquad (14)$$

where MI_t is mean unsupplemented pasture intake (kg DM cow^{-1}), ML_t is mean cow liveweight (100 kg cow^{-1}), δ is the days in a fortnight, and se_t is an index indicating the time of year (+1 for spring, 0 for summer, -1 autumn and winter).

Similarly, the substitution rate for PKE (SR_t^P) is:

$$SR_t^P = -0.26 + 0.17\left[\frac{MI_t}{ML_t}\right] + 0.08se_t + 30\left(\frac{(F_t^S + F_t^M + F_t^P)c_{a5}}{\delta}\right) + 0.04 \qquad (15)$$

The substitution rates increase with unsupplemented pasture intake defined per unit of cow liveweight (the term in square brackets). For example, computed on a daily basis, if a 480 kg cow was fed 1 kg DM of maize silage daily in spring, this would offset 0.19, 0.36, 0.54, and 0.72 kg of pasture DM at intakes of 5, 10, 15, and 20 kg pasture DM for a 480 kg cow. The substitution rates also increase with daily supplement intake (the term in curved brackets). For example, if a 480 kg cow was fed 1, 2, 3, or 4 kg DM of maize silage in spring, this would offset 0.54, 0.57, 0.6, and 0.63 kg of pasture DM at a daily pasture intake of 15 kg pasture DM. Further scenarios are shown in Figure A3.

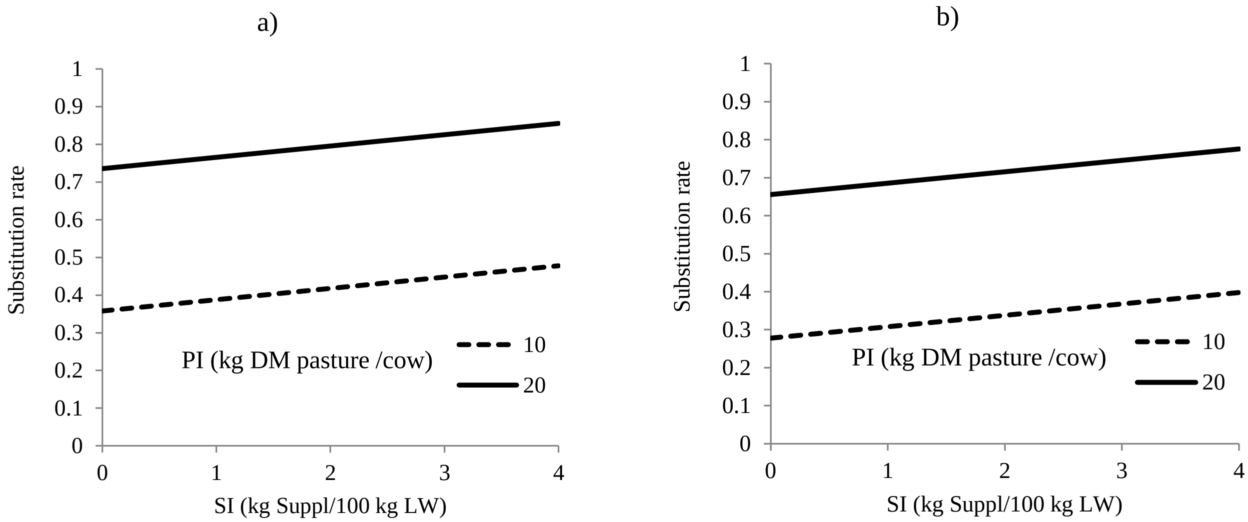

Figure A3: Substitution rate as a function of the supplementary feeding intake

(SI) for (a) silages and (b) concentrates. These relationships are computed for two levels of unsupplemented pasture intake (PI). Adapted from Stockdale (2000).

The substitution rate for turnips is $SR_t^T = 1$ (DairyNZ, 2010).

A2.5 Cow module

There are a total of 15,120 attribute combinations (cow types) that describe a large number of different types of cow. Cow types differ according to:

- $uf = [1, 2, ..., 6]$: These correspond to 0, 10, 20, 30, 40, and 50 per cent decreases, respectively, in the annual energy intake of a fully-fed cow. The energy intake of NZ dairy cows is typically reduced below potential for at least a proportion of the year, especially in the period prior to calving (Macdonald et al., 2008).
- $a = [1, 2, ..., 4]$: These represent cows that are 2, 3, 4, and 5+ years of age, respectively.
- $m = [1, 2, ..., 5]$: These represent the genetic merit of cows according to peak milk yield (kg day^{-1}).
- $cu = [1, 2]$: These represent standard cows ($cu = 1$) or those to be sold as culls after lactation is complete ($cu = 2$).

- $cd = [1, 2, ..., 9]$: These represent calving dates of 1 July, 15 July, 29 July, 12 August, 26 August, 9 September, 23 September, 7 October, and 21 October.
- $ll = [1, 2, ..., 7]$: These represent lactation lengths of 180, 210, 250, 265, 280, 295, and 310 days, respectively.

The number of cows with each attribute combination is denoted $C_{uf,a,m,cu,cd,ll}$. The total number of cows (*TC*) is thus defined:

$$TC = \sum_{uf=1}^{6} \sum_{a=1}^{4} \sum_{m=1}^{5} \sum_{cu=1}^{2} \sum_{cd=1}^{9} \sum_{ll=1}^{7} C_{uf,a,m,cu,cd,ll} \tag{16}$$

The total number of cull cows is:

$$TCU = \sum_{uf=1}^{6} \sum_{a=1}^{4} \sum_{m=1}^{5} \sum_{cd=1}^{9} \sum_{ll=1}^{7} C_{uf,a,m,cu=2,cd,ll} \tag{17}$$

The stocking rate (cows ha^{-1}) is the total number of cows divided by the total area of the farm. The number of cows in each age class is determined through:

$$\sum_{cu=1}^{2} C_{uf,a+1,m,cu,cd,ll} = C_{uf,a,m,cu=1,cd,ll} SV \ \ \forall a = [1,3] \tag{18}$$

where *SV* is the survival rate. The survival rate is the sum of the cull rate for disease in adult cows, the natural mortality rate of adult cows, and the empty rate. It is assumed that all empty cows are culled from the herd. The empty rate for a given cow type is computed based on the efficiency of reproductive management, cow health, rate of embryonic loss, and the number of heats exhibited during the mating period, which depends on age, changes in cow liveweight prior to mating, and the conception rate on each heat. These are described through the use of the reproduction management model of Beukes et al. (2010). All cull and dead cows are replaced each year.

The total number of female calves retained is calculated considering the empty rate, the gender ratio of calves, the natural mortality rate of calves, and the proportion of female calves sold. All male calves are sold; thus, all yearlings are female. The total number of yearlings retained is calculated considering the natural mortality rate of yearlings and the proportion of female yearlings sold.

Genetic merit for milk production impacts the relationship between cow intake and milk production. Thus, the distribution of genetic merit across the herd in an optimal solution must be consistent with those distributions observed on typical NZ dairy farms. Levels of peak milk are derived from data for 850,000 cows from the Livestock Improvement Corporation (Hamilton, New Zealand). The set of all levels of genetic merit to which a cow can belong is described $mw = [1, 2, ..., 5]$. The distribution is defined in each solution through:

$$TC \cdot me_{mw} = \sum_{uf=1}^{7} \sum_{a=1}^{4} \sum_{cu=1}^{2} \sum_{cd=1}^{9} \sum_{ll=1}^{7} C_{uf,a,m=mw,cu,cd,ll} \quad \forall mw \qquad (19)$$

where me_{mw} is the proportion of the cows in a standard herd that possess a given level of genetic merit for milk production *mw*.

The calving distribution must also approximate those distributions observed on real farms. The user can select a given calving date or the model can select the optimal calving date. The user can also select the proportion of the herd required to calve in each subsequent fortnight. Calving is assumed to take place over an 8-week period, spread over five fortnights, in the base line situation. 16, 37, 22, 11, and 14 per cent of the herd calve in the first, second, third, fourth, and fifth fortnights, respectively. This is drawn from unpublished DairyNZ data.

Total milk production is the sum of the annual milk production (t MS^{-1}) of each cow type multiplied by the number of cows of each type.

Integration module

The level of potential pasture intake, energy demand, and milk production for each cow type is computed outside of IDEA in a detailed optimisation model. This model is based on existing simulation models, described by NRC (2001), Johnson et al. (2008), and Freer et al. (2010). Use of an exogenous model to compute these quantities allows the thorough consideration of important processes, such as the dynamics of body condition gain and loss, while maintaining the tractability of IDEA.

Potential intake for a given type of cow specifies the maximum amount of feed (in kg pasture DM) that a cow can ingest in a given period when unrestricted access is given to a feed with a digestibility of at least 80 per cent. (This is measured in terms of pasture DM to ensure that intake substitution is accounted for.) The first integration constraint specifies that the total DM intake of the cow herd cannot be higher than the potential intake of the herd in period *t*. Supplement intake is converted into pasture DM equivalents through the use of substitution rates (eq. 14–15).

Metabolic energy is expended for gain in body condition, growth, lactation, maintenance, and pregnancy. Metabolic energy is obtained from the ingestion of feed and loss in body condition. The second integration constraint specifies that the total energy intake of the cow herd must be higher than the total energy demand of the cow herd in period *t*. The energy gained through supplement intake (MJ ME) is calculated through multiplication of the amount of each supplement fed (t DM) by its average energy content (MJ ME t DM^{-1}).

A2.6 Pad module

A farm can possess a feed pad and/or a stand-off pad. A stand-off pad involves standing cows on bark chips or other soft surfaces for a proportion of the day to reduce time on pasture. Cows are not fed on a stand-off pad, in contrast to a feed pad. Keeping cows off pasture is a key strategy for reducing soil compaction and reducing nitrate leaching and nitrous oxide emissions through decreasing the amount of urine that is deposited on agricultural soils.

The proportion of the day spent on the feed pad and stand-off pad are decision variables in the optimisation. A cow cannot spend more than half of the day on a stand-off pad unless a feed pad is present, as otherwise this will lead to detrimentally low levels of feed intake. Putting cows on pads reduces their capacity for pasture consumption, as depicted in Figure A4.

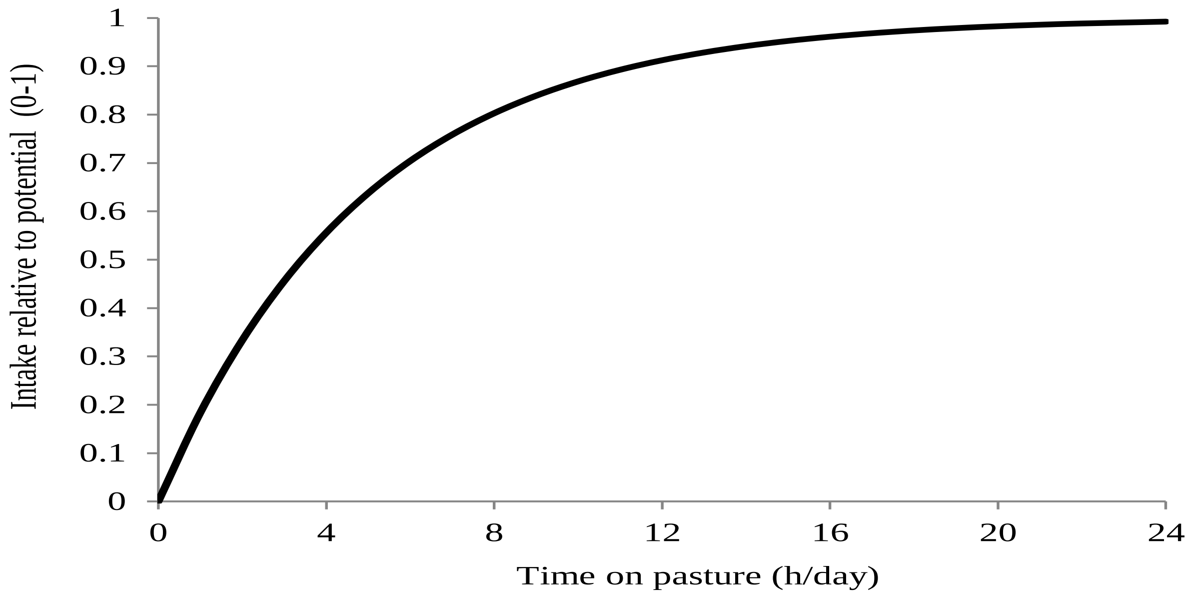

Figure A4: Effect of time on pasture on the intake of grazing cows.

Estimated using data from Clark et al. (2010).

A2.7 Profit module

The objective function involves maximization of operating profit (OP_f) ($) for the farm. This is consistent with standard farm-level models (Cartwright et al., 2007; Kingwell, 2011). Solutions are equivalent to those obtained with the maximization of profit per ha (e.g. McCall et al., 1999), as $OP_f = c_{z1} OP_h$ where c_{z1} (farm size) is constant and OP_h is operating profit per ha. Profit per kg MS is also reported in each model solution and can be defined as the model objective

Operating profit at the farm level is calculated considering income from milk solids (fat plus protein), cull cows, cull calves, cull yearlings, grass silage that is sold, and maize silage that is sold. Costs include a fixed cost of production defined per ha, a variable cost of production defined per cow, cost of grass silage conservation, purchase of grass silage and maize silage, purchase of PKE, purchase and application of fertilisers (nitrogen and potassic superphosphate), grazing replacement female calves off-farm (grazing payment and transport), crop establishment, establishing and regrassing after crops or directly from pasture, and establishing and maintaining a feed pad and/or stand-off pad. The coefficients of the profit function are based on current market values in New Zealand and information from the DairyNZ Economic Survey (DairyNZ, 2011).

A3 RESULTS AND DISCUSSION

A3.1 Model runs

The Results and Discussion investigates the capacity of IDEA to predict data from the farmlet trial reported in Macdonald et al. (2008) (hereafter referred to as "MD08"). Moreover, output from a less-detailed LP model, based on the framework of McCall et al. (1999), is generated for comparative purposes. The last section in the Results and Discussion explores the capacity of IDEA to identify cost-effective responses to constraints imposed on greenhouse gas (GHG) emissions.

The LP model is constructed specifically for this analysis. It is less detailed than IDEA, incorporating around 7,000 equations and 4,500 decision variables, whereas IDEA has 30,000 constraints and 700,000 decision variables. The LP model incorporates fixed pasture growth, pasture residuals, pasture utilisation, potential intake, and substitution rates. Post-grazing mass is fixed according to the grazing strategy employed by MD08. For IDEA, the simulation model of pasture dynamics described above was used to estimate pasture growth and digestibility for the location and period of the MD08 study.

The IDEA and LP models are both calibrated to data generated from the 3.1 cows ha^{-1} treatment in the MD08 trial. Both models are then used to predict values for the 2.2 and 4.3 cows ha^{-1} treatments in the MD08 trial without further calibration. These stocking rates are the lowest and highest, respectively, of those used in MD08 and test the capacity of both models for meaningful prediction. Stocking rate is fixed in each model, in accordance with the experimental treatments used. Moreover, fixed rates of N fertiliser application are used. However, no further constraint addition is used for calibration, as this restricts the flexibility of the model to respond to perturbations. Following McCall et al. (1999), the objective in the optimisation for the validation exercise was to maximise milk production.

A3.2 Comparison of IDEA and LP with stocking rate treatment of 3.1 cows ha^{-1} in MD08

IDEA provides a meaningful description of the MD08 treatment incorporating 3.1 cows ha^{-1}. The broadest deviations from MD08 data differ little in absolute terms. First, the autumn grazing interval is 14% higher than trial data, but corresponds to a difference of only 5 days (Table A1). Second, the level of silage eaten is 8% lower than trial data, but corresponds to a difference of only 44 kg DM ha^{-1}. Last, the area of the farm topped is 10% lower than trial data, but corresponds to a difference of only 6% of farm area.

Table A1: Key farm characteristics recorded for a farmlet stocked at 3.1 cows ha^{-1} in Macdonald et al. (2008) (MD08) and the equivalent values predicted in IDEA and a linear programming (LP) model of the same farming system.

Variable	Unit	Source of output				
		MD08	IDEA	% diff.[1]	LP	% diff.[1]
Pre-grazing mass	kg DM ha^{-1}	3,355	3,228	-4	3,084	-9
Post-grazing mass	kg DM ha^{-1}	1,985	1,880	-6	2,038	+3
Grazing interval						
Winter	Days	70	67	-4	72	+2
Spring	Days	30	30	0	34	+12
Summer	Days	25	24	-4	25	0
Autumn	Days	30	35	+14	31	-3
Pasture eaten	kg DM ha^{-1}	14,322	14,771	+3	15,206	+6
Silage conserved	kg DM ha^{-1}	806	813	+1	1,172	+45
Silage eaten	kg DM ha^{-1}	562	518	-8	1,172	+109
Farm topped	%	65	59	-10	60	-8
OM digestibility	% DM	78	78	0	76	-3
Pasture ME	MJ ME/kg DM	11.3	11.25	-1	11	-3
Lactation length	Days	258	260	+1	247	-4
Annual milk production	kg cow^{-1}	4,128	4,105	-1	4,124	-1
Annual milk production	kg ha^{-1}	12,796	12,726	-1	12,784	-1

[1] Percentage difference between the value of the farm characteristic in Macdonald et al. (2008) and the model prediction.

The majority of model output fits trial data well (Table A1). Pre- and post-grazing pasture mass are around 5% below the trial data. This stimulates pasture growth—hence pasture eaten is higher by 3% in IDEA—as lower grazing residuals improve light interception and photosynthetic efficiency in perennial-ryegrass swards (Chapman and Lemaire, 1993). IDEA provides an accurate prediction of organic matter (OM) digestibility and pasture ME, reinforcing the value of representing residual length as a decision variable in a model of a dairy farm (Table A1). The detailed cow model also provides high precision in terms of lactation length and milk production.

The LP framework also provides a meaningful description of the MD08 treatment incorporating 3.1 cows ha^{-1}. The LP model fits the trial data for grazing interval as well as IDEA does. Moreover, milk production in the LP matches trial data more closely than IDEA, although lactation length is 11 days (4%) below the MD08 levels. Pasture eaten is 884 kg DM ha^{-1} (6%) above trial data—around twice the magnitude of the deviation reported for IDEA (Table A1)—since pasture growth is constant and there is no relationship between cow intake and herbage allowance. These factors also drive large deviations relating to feed conservation. Silage production and feeding are 45% and 109% above trial data, respectively.

Silage conservation and feeding were also the factors that deviated the most from reported outcomes when LP output was compared to trial data in McCall et al. (1999). This difficulty in LP models of dairy farms occurs for a number of reasons. First, use of fixed pasture growth rates fails to account for ryegrass growth dynamics (especially senescence) in paddocks spelled for silage conservation, especially at high levels of pasture mass. Second, use of a fixed residual for silage production in a LP model reduces the flexibility with which silage making can be used in the grazing rotation.

A3.3 Comparison of IDEA and LP with stocking rate treatment of 2.2 cows ha^{-1} in MD08

The IDEA model also provides a very good representation of the low stocking rate (2.2 cows ha^{-1}) system in MD08. Pre-grazing biomass differs from trial data by 1%, but post-grazing pasture mass is 162 kg DM ha^{-1} (8%) lower. Grazing intervals are also longer in IDEA, though only by 1–3 days (Table A2). A lower post-grazing biomass and longer grazing intervals stimulate greater pasture growth, by maintaining the sward closer to the optimum state, on average (Parsons et al., 1988). Accordingly, pasture eaten is higher by 3% and silage production is higher by 211 kg DM ha^{-1} (14%) (Table A2). Intensive silage production and mowing is necessary given the low stocking rate in this treatment. Silage feeding is also 150 kg DM ha^{-1} (29%) higher in IDEA relative to trial data, as this supplement is used to extend grazing intervals and hence promote pasture accumulation. IDEA predicts OM digestibility and energy content exactly, while lactation length and milk production are estimated within a 1% margin of error.

Table A2: Key farm characteristics recorded for a farmlet stocked at 2.2 cows ha-1 in Macdonald et al. (2008) (MD08) and the equivalent values predicted in IDEA and a linear programming (LP) model of the same farming system.

Variable	Unit	Source of output				
		MD08	IDEA	% diff.[1]	LP	% diff.[1]
Pre-grazing mass	kg DM ha^{-1}	3,300	3,262	-1	3,017	-9
Post-grazing mass	kg DM ha^{-1}	2,265	2,103	-8	2,038	-11
Grazing interval						
Winter	Days	58	60	+3	74	+21
Spring	Days	31	32	+3	30	-3
Summer	Days	23	26	+12	26	+12
Autumn	Days	26	29	+10	26	0
Pasture eaten	kg DM ha^{-1}	12,098	12,493	+3	12,728	+5
Silage conserved	kg DM ha^{-1}	1,257	1,468	+14	421	-199
Silage eaten	kg DM ha^{-1}	354	504	+29	421	+16
Farm topped	%	90	93	+3	80	-13
OM digestibility	% DM	76	76	0	76	0
Pasture ME	MJ ME/kg DM	11	11	0	11	0
Lactation length	Days	291	287	-1	309	+6
Annual milk production	kg cow^{-1}	5,032	5,029	-1	5,269	+4
Annual milk production	kg ha^{-1}	11,071	11,063	-1	11,592	+4

[1] Percentage difference between the value of the farm characteristic in Macdonald et al. (2008) and the model prediction.

The LP results for the low stocking rate treatment demonstrate that its inherent rigidity reduces its ability to accurately predict meaningful outcomes when moving away from calibrated scenarios. Post-grazing pasture mass is lower (11%) than reported in trial data, as residuals are not determined during optimisation of grazing management. Grazing intervals are 12% and 21% higher in summer and winter, respectively. Pasture eaten is 5% higher, but silage conservation is around 200% lower. Moreover, with the low stocking rate treatment, lactation length is 18 days (6%) longer in the LP, as the presence of substantial inflexibility in the feed component of the LP (e.g. fixed pasture growth and digestibility) means that cow management is altered to a greater extent, relative to IDEA, to maximise production.

Primary reasons for large deviations with silage management in the LP model are discussed above. However, an additional driver here is that silage production confers no benefit for subsequent pasture growth or quality in the LP model. Accordingly, all silage conserved is eaten in each scenario for the LP model (Tables A1–A2). In contrast, optimisation of pasture residual mass in IDEA allows defoliation through silage production to confer benefits for subsequent pasture growth and the digestibility of this biomass. Thus, the amount of silage conserved is greater than the amount of silage eaten in the IDEA solutions for the 2.2 cows ha^{-1} (Table A2) and 3.1 cows ha^{-1} (Table A1) systems, as identified by MD08. The same effect reduces the incentive to mow pasture in the LP model to improve pasture quality within the 2.2 cows ha^{-1} treatment (Table A2).

A3.4 Comparison of IDEA and LP with stocking rate treatment of 4.3 cows ha^{-1} in MD08

IDEA also provides a good prediction of trial data for the high stocking rate treatment from MD08. Pre- and post-grazing biomass levels are lower by 4% and 5%, respectively. These negative deviations reflect that the maintenance of lower post-grazing residual levels under this treatment promote pasture growth due to reduced shading and hence less impairment of photosynthetic efficiency. This effect is present in the MD08 trial data and captured in IDEA through the incorporation of output from the detailed pasture simulation model. Pasture eaten is predicted with good precision, but silage production is overestimated by 66%, though the deviation is low in absolute terms (41 kg DM ha^{-1}) (Table A3). The incorporation of output from the detailed pasture simulation model in IDEA also allows the relationship between lower post-grazing residuals and improved OM digestibility observed in the high stocking rate treatment in MD08 to be well captured (Table A3). Moreover, cow attributes are predicted accurately, with lactation length and milk production within 1% of trial data.

Table A3: Key farm characteristics recorded for a farmlet stocked at 4.3 cows ha-1 in Macdonald et al. (2008) (MD08) and the equivalent values predicted in IDEA. A linear programming (LP) model of the same farming system was infeasible in this scenario.

Variable		**Source of output**		
	Unit	**MD08**	**IDEA**	**% diff.**
Pre-grazing mass	kg DM ha^{-1}	3,530	3,402	-4
Post-grazing mass	kg DM ha^{-1}	1,767	1,677	-5
Grazing interval				
Winter	Days	77	75	-3
Spring	Days	32	37	+13
Summer	Days	30	32	+6
Autumn	Days	35	38	+8
Pasture eaten	kg DM ha^{-1}	16,597	16,633	+1
Silage conserved	kg DM ha^{-1}	65	106	+66
Silage eaten	kg DM ha^{-1}	876	809	-8
Purchased silage	kg DM ha^{-1}	812	703	-13
Farm topped	%	0	0	0
OM digestibility	% DM	79	78	-1
Pasture ME	MJ ME/kg DM	11.4	11.4	0
Lactation length	Days	221	224	+1
Annual milk production	kg cow^{-1}	3,448	3,462	+1
Annual milk production	kg ha^{-1}	14,828	14,889	+1

[1] Percentage difference between the value of the farm characteristic in Macdonald et al. (2008) and the model prediction.

In contrast, the LP model was infeasible with a stocking rate of 4.3 cows ha^{-1}. This reinforces how the rigid structure of a less-detailed LP model of a dairy farm restricts its ability to flexibly represent alternative farm plans, particularly relative to IDEA.

A3.5 Use of IDEA to generate cost-effective responses to constraints on GHG load

New Zealand dairy farms account for around 17 per cent of this nation's greenhouse gas emissions (GHG-e) (MfE, 2010). A focus towards reducing GHG-e on these farms is consistent with the Climate Change Response (Moderated Emission Trading) Amendment Act 2009. The

IDEA model is used to identify how farm management should change in response to simulated reductions in baseline GHG-e of 10, 20, and 30 per cent. This range of reductions is simulated given potential heterogeneity in the amount of mitigation required across farms and to demonstrate the flexibility of the model.

The characteristics of a representative Waikato farm are drawn from information for Waikato farms in the DairyBase database for the 2009–10 milking season. Prices and costs for this milking season are also used. This farm has medium-input intensity, importing between 10 and 20 per cent of feed. The IDEA model was modified to incorporate GHG-e through the addition of IPCC methodology calculations (IPCC, 2006) and emission factors specific for NZ obtained from MfE (2008).

Two types of mitigations are incorporated in the simulations to sharpen the focus on appropriate management response. A Type 1 mitigation (T1M) involves de-intensification. T1Ms in the model are reductions in stocking rate, supplement, and/or nitrogen fertiliser application. A Type 2 mitigation (T2M) is an abatement strategy that does not explicitly require de-intensification. T2Ms in the model are the use of improved reproduction, turnip (*Brassica rapa*) crops, nitrification inhibitors, and restricted grazing regimen incorporating a feed pad or a stand-off pad (Eckard et al., 2010).

Table A4 presents key farm system output computed in IDEA for the simulated reductions in GHG-e. The "Base" scenario reports the model solution calibrated to survey data, with no T2Ms available. T2Ms are available in all other scenarios. IDEA output indicates that de-intensification is a key strategy to reduce GHG-e (Table A4). Stocking rate decreases by 9, 17, and 26 per cent at simulated reductions of 10, 20, and 30 per cent, respectively (Table A4). Also, nitrogen fertiliser application falls by 17, 54, and 97 per cent at simulated reductions of 10, 20, and 30 per cent, respectively (Table A4). Moreover, the level of purchased supplement (Palm Kernel Expeller or PKE) falls as more abatement is required, since stocking-rate reductions decrease feed demand (Table A4). The availability of T2Ms increases farm profit by \$13 ha^{-1} in the baseline solution (Table A4). This involves the use of improved reproductive management, which reduces the cost of managing more young stock through decreasing the replacement rate (Table A4), but adds costs associated with improved heat detection and increased body condition at calving. Improved reproduction is the only T2M used in any simulated scenario.

Table A4: Key farm system output from IDEA for simulated reductions in GHG emissions of 0 (Base), 10, 20, and 30 per cent for a representative Waikato dairy farm.

Variable	Units	Baseline scenarios		GHG-e reduction (%)		
		Base[1]	Base+T2M[2]	10	20	30
Farm profit	$ ha^{-1}	1,257	1,270	1,209	1,077	903
Farm profit	$ kg MS^{-1}	1.21	1.22	1.25	1.22	1.14
Stocking rate	cows ha^{-1}	3	3	2.73	2.48	2.23
Milk production	kg MS cow^{-1}	346	347	354	356	356
Milk production	kg MS ha^{-1}	1,038	1,041	966	881	794
Lactation length	Days	278	277	288	290	290
Grazed pasture eaten	t DM ha^{-1}	12.58	12.61	11.82	10.75	9.59
Grass silage eaten	t DM ha^{-1}	0.64	0.61	0.32	0.17	0.26
Maize silage eaten	t DM ha^{-1}	0.37	0.37	0.37	0.37	0.37
PKE eaten	t DM ha^{-1}	1.54	1.54	1.41	1.27	1.16
N fertiliser applied	kg N ha^{-1}	112	112	93	52	3
Crop area	% area	2.5	2.5	2.5	2.5	2.5
Replacement rate	%	23.3	18.3	17.8	17.5	17.5
Methane emissions	kg CH_4 ha^{-1}	295.08	295.69	274.04	247.64	220.8
N_2O emissions	kg N_2O ha^{-1}	8.68	8.64	7.79	6.49	5.09
GHG emissions	kg CO_2-eq ha^{-1}	12,745	12,546	11,471	10,196	8,922
Mitigation practices used	-	-	Improved repro.	Improved repro.	Improved repro.	Improved repro.

[1] This is the baseline level of production with T2Ms unavailable.

[2] This is the baseline level of production with T2Ms available.

A4 CONCLUSIONS

Optimisation models are valuable tools for evaluating optimal responses to new policies, prices, and technologies in complex pasture-based dairy systems. A detailed nonlinear optimisation model of a New Zealand dairy farming system is described. This framework is notable for its inclusion of pasture residual mass, intake regulation, and pasture utilisation as key decision variables.

Validation of the model shows that the detailed representation of key biophysical relationships in IDEA has two key benefits relative to a less-detailed LP model. First, the model has an enhanced capacity to provide reasonable predictions outside of calibrated scenarios. Second, the flexibility of management plans in IDEA helps avoid the infeasibility of the model when significant perturbations to calibrated scenarios are simulated.

Model output demonstrates that IDEA can be used to determine pragmatic strategies to reduce GHG emissions. De-intensification is a key strategy, with reductions in nitrogen fertiliser, stocking rate, and supplement use required under optimal management. Moreover, the use of improved reproductive management is highly favorable.

The IDEA model provides an ideal platform for further research regarding New Zealand dairy systems. Key issues that IDEA could help investigate are the cost-effective mitigation of nitrogen leaching, profitability of improved reproductive management, and determining the marginal value of feed across time. Interesting extensions of the model include the incorporation of tactical decision making (Pannell, 1996) and the representation of dairy farms in different regions of New Zealand. However, the IDEA framework could benefit from further biophysical research. Key issues are the relationship between pasture growth and quality and different post-grazing residuals within New Zealand's key dairy regions and the association between time off pasture and cow intake.

Overall, this paper demonstrates that the inclusion of greater detail in optimisation models of dairy systems promotes their capacity to meaningfully predict outcomes outside of sample data used for calibration.

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Appendix 2

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

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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 which was 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.

A6 Introduction

Dairy farming in New Zealand (NZ) accounts for about 17% of the total country's GHG-e and, as a whole, NZ agriculture has increased GHG-e by around 10% since 1990 (MfE 2008). The Climate Change Response (Moderated Emission Trading) Amendment Act 2009 (Anonymous 2009) states that farmers will begin to pay for their GHG-e from 2015. Initially they will be granted credit for 90% of their GHG-e, from some yet to be established baseline. Therefore, it is probable that New Zealand dairy farmers will face pressure to either reduce, or pay for their GHG-e.

Methane (CH_4) emissions are an inevitable consequence of ruminant digestion. Nitrous oxide (N_2O) emissions have risen over the last decade following increases in production intensity on NZ dairy farms, especially through increases in application of nitrogen (N) fertiliser and stocking rate (NZ GHG Inventory 2008). One way of reducing methane emissions is to reduce the number of animals on any given farm to reduce total feed intake, but this strategy can lead to a reduction in productivity and also reduced profit if feed efficiency is not increased and the whole farm system is not adapted (Beukes et al., 2011). N_2O emissions can be lowered through reducing nitrogen fertiliser application and stocking rate, but also through the use of other mitigation options, such as stand-off pads, feed pads, and the application of nitrification inhibitors (de Klein et al., 2008). This highlights that cost-effective mitigation may require substantial changes to many interdependent management variables within a farming system. Computer modelling is highly suited to evaluate alternative strategies given its capacity to represent and consider these interdependencies simultaneously.

The influence of cow genetics across different feeding systems was tested for profit and GHG-e by O'Brien et al. (2010), using simulation modelling. They found that generally GHG-e per ha increased with higher stocking rate or more concentrate feeding and profitability was higher for the New Zealand strain in high stocking rate grazing systems, compared to control and high concentrates feeding systems. This demonstrates that less-intensive grass-based systems can achieve high profitability and decrease GHG-e simultaneously.

Basset-Mens et al. (2009) studied the effect of intensification of New Zealand dairy farms using life cycle assessment to compare an average NZ dairy farm system (season 2004-2005) with those of three dairy experimental systems (Jensen et al. 2005) representing a range of intensification systems: low input (no N fertiliser, no brought-in feed supplement, stocking rate 2.3 cows per ha) N fertilised farm (170 kg per ha of N fertiliser, 3 cows per ha) and N fertiliser and maize silage supplemented system (170 kg N fertiliser, 13 t DM maize silage per ha per year, 5.2 cows per ha). These authors found that the low input system had the lowest global warming potential per kg of milk and also the emissions per ha were very similar to those of the average NZ farm which had the lowest emissions per ha of the four systems compared.

The economics of different mitigation options have been studied using a mechanistic model (WFM) and inventory tools like OVERSEER® (Beukes at al. 2011; Beukes at al. 2010). However, in those studies, mitigation options were implemented by the modeller at one pre-established level, and GHG-e reduction and profit were calculated afterwards for the different scenarios. This is a time consuming process and requires a great deal of ability and farm system knowledge from the modeller to achieve the best possible use of resources. In contrast, for this paper a detailed optimisation model—the Integrated Dairy Enterprise Analysis (IDEA) framework—was employed to identify the best combination of mitigation options, and "level" for each mitigation, that maximises operating profit while reducing total GHG-e of the farm by 10%. Given the absence of better information regarding GHG-e goals, the 10% is based on the level defined by the Climate Change Response (Moderated Emission Trading) Amendment Act 2009 (Anonymous, 2009).

The objective of this study was to determine the cost associated with a 10% reduction in GHG-e and at the same time identify the required changes to the farming system that will achieve this reduction whilst maximising operating profit.

A7 Method

Model description

IDEA is a nonlinear optimisation model that provides a detailed description of management within a New Zealand dairy farming system. The model is defined over 26 fortnights to provide comprehensive insight into feed allocation across a typical management year. Use of optimisation allows interdependencies between system elements to be considered when exogenous shocks, such as changes in price or government policy, are simulated.

IDEA incorporates the basic structure of the model introduced by McCall et al. (1999). However, this framework is extended in various ways to provide a closer description of real systems. Firstly, grazing strategies involve both rotation length and post-grazing residual herbage mass as decision variables. Secondly, rotation length and post-grazing residual herbage mass impact the growth and digestibility of pasture. Thirdly, cows can be fed below potential capacity to varying degrees. Fourthly, cow condition influences intake, milk production, and conception rate. Finally, pasture utilisation is conditional on stocking rate.

IDEA identifies the feeding strategy that maximises annual profit. Feed supply is based on grazing management that allocates pasture to stock, while silage can be produced during periods of surplus grass production. Dairy meal, maize silage, and palm kernel expeller can be purchased, while maize silage can also be produced on-farm. Kale and turnips can be grown as forage crops. Age structure, calving date, and culling policy affect temporal energy requirements. Also, individual cow attributes, such as body condition, lactation length and milk production level, influence feed demand. The genetic merit of cows is also represented in the IDEA model. Cows with high genetic merit have a mean peak milk yield one standard deviation above that of standard New Zealand cows. The levels of peak milk yield for the standard set of cows represented in IDEA are generated using data from 850,000 cows from the LIC database. IDEA is solved using the General Algebraic Modelling Systems (GAMS) (Brooke et al., 2008).

Model runs

DairyNZ classifies dairy farm systems on a scale of 1 to 5 according to the level of imported supplements, ranging from no imported supplements (system 1) to between 25 and 40% of the total feed requirements consisting of imported supplements (system 5; DairyNZ, 2010). The analysis presented here is based on the simulation of four scenarios for the intermediate production system 3 farm. Typically, between 10 and 20 per cent of the total feed is imported in these kinds of farms to extend lactation in early spring or as autumn feed and for dry cows. The representative farm is based on means (n=30) of survey information from system 3 farms in the Waikato-Bay of Plenty region extracted from the DairyBase database for the 2008-09 season (dairybase.co.nz). This representative system 3 farm (Table A7 scenario 1) was modelled in Farmax, a complex simulation model of a NZ dairy system (Bryant et al., 2010), which was used to create a complete set of farm output beyond what is recorded in DairyBase. Comparison of Farmax and IDEA output was used to assess if IDEA provides a meaningful description of the farming system being studied. Table A5 show that IDEA provides a close description of the farming system described by this Farmax output (Table A5). This allows some validation of IDEA output as Farmax also provides a system-level description of a dairy farming system, albeit not in an optimisation environment. There is less than 1 per cent difference between stocking rate and milk production reported for each model. However, some deviations occur with respect to "grazed pasture eaten" and the related level of "N fertiliser applied" (Table A5). These deviations are deemed acceptable given that the Farmax runs were conducted for smaller cows, which have a lower optimal intake than the Friesian cows represented in IDEA, and because the utilisation of grass is user-defined in Farmax, while in IDEA it is a consequence of management decisions. Furthermore, GHG-e of the baseline farm are in line with standard figures reported in Beukes et al. (2011) and with OVERSEER®(Wheeler et al. 2003) model output for the system 3 farm. This provided some validation that the IDEA model was predicting GHG-e within an acceptable range.

The four scenarios evaluated in the model are shown in Figure A5. These scenarios differ in whether a cap is present that requires producers to reduce GHG-e by 10% and the possibility to implement recommended strategic mitigation practices. The mitigation practices available to the

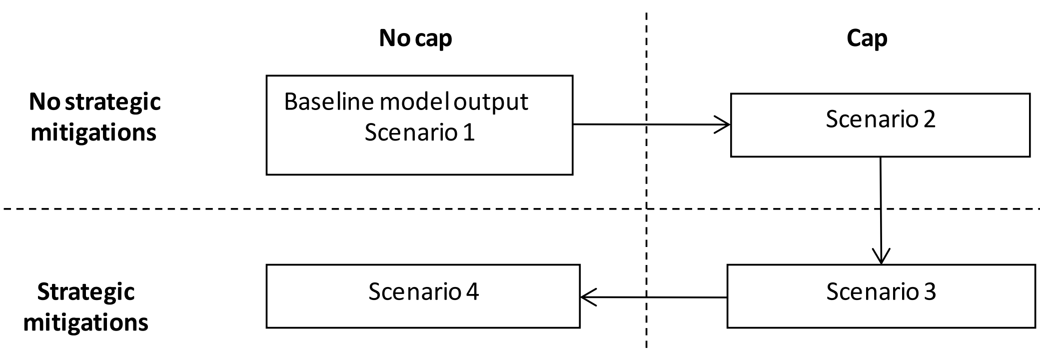

Figure A5: Four modelling scenarios investigated with the nonlinear optimisation model. Cap = GHG-e constraint of 10% reduction.

The arrows show the sequence of the modelling

Table A5: Comparison of model output from Farmax and IDEA.

Variable	Units	Farmax	IDEA	Diff. (%)
Farm profit	$ ha^{-1}	1098	1053	-4.27
Stocking rate	cows ha^{-1}	3.07	3.08	0.33
N fertiliser applied	kg N ha^{-1}	105	119	13.33
Milk production	kg MS cow^{-1}	328	331	0.91
Lactation length	Days	271	277	2.21
Grazed pasture eaten	t DM ha^{-1}	9.79	11.76	20.12
Supplement eaten	t DM ha^{-1}	2.05	2.33	13.66
Crop area	type,% area	maize, 2.16	maize, 2	-8
Silage conserved	t DM ha^{-1}	0.46	0.43	-6.5
Replacement rate	%	23	21.3	-7.39

"No strategic mitigation farmer" are restricting stocking rate, nitrogen fertiliser application, and use of a stand-off pad. These strategies represent the abatement methods a standard producer can use without the adoption of additional innovations. The abatement practices available to the "Strategic mitigation farmer" include the use of high genetic merit cows, application of nitrification inhibitors, and use of forage crops grown on farm (Beukes et al., 2011).

The baseline situation in Figure A5 provides a benchmark for the other scenarios. No additional pasture growth was assumed to be obtained with the application of nitrification inhibitors, consistent with experiments conducted on NZ dairy farms (Macdonald et al., 2010). Improved herd reproduction is also a potential mitigation strategy, but this was not modelled because it still has to be satisfactorily represented in IDEA.

Parameter values

The milk pay out for this exercise was fixed at $5.5/kg of milk solids and the relevant prices used in the simulations are listed in Table A6.

Table A6: Relevant prices used in this application of IDEA.

Cost	Units	Amount
Fixed	$ ha^{-1}	900
Variable	$ cow^{-1}	500
Concentrates	$ tDM^{-1}	350
N Fertiliser	$ t $Urea^{-1}$	500
Maize silage	$ ha^{-1}	3300
Re-grassing	$ ha^{-1}	1000
Nitrification inhibitors	$ ha^{-1}	150
Dairy meal	$ tDM^{-1}	650

A8 Results and Discussion

A profit reduction of $79 ha^{-1} or 8% was found when reduction in GHG-e/ha of 10% was imposed without strategic mitigation options available (scenario 2; Table A7). Two of the observed changes to the system were more important than the others: first a 58% reduction in nitrogen fertiliser input, and second a 7% reduction in stocking rate. These changes show that adaptation of the farm system to achieve a reduction in GHG-e is reliant on reducing production intensity given the unavailability of more strategic options such as high genetic merit cows, application of nitrification inhibitors, and use of forage crops, which imply further farm system changes. These results are in line with those of Basset-Mens et al. (2009). They found that GHG-e per ha increases with the intensification of the farming system in New Zealand, and GHG-e per kg of milk solids was least for the low input system and intermediate for the higher input systems.

Introducing strategic mitigation practices with the cap imposed (Scenario 3) increased profit relative to the baseline situation by 5%. This occurred because although stocking rate and total feed eaten decreased by 9 and 8% respectively relative to the baseline situation, milk production per cow increased by 4% given the use of cows with higher genetic merit. Cows with higher genetic merit can achieve better economic performance and reduce GHG-e at the same time. In the same way, when the cap was removed and strategic mitigation options were available (Scenario 4), profit increased by 13% relative to the baseline. In this scenario, a reduction of 2%

Table A7: IDEA model output for the four scenarios.

Variable	Units	Scenario[ϕ]			
		1	2	3	4
Farm profit	$ ha^{-1}	1053	974	1106	1191
Stocking rate	cows ha^{-1}	3.08	2.87	2.81	3.01
N fertiliser applied	kg N ha^{-1}	119	50	51	118
Milk production	kg MS cow^{-1}	331	331	344	344
Milk production	Kg MS ha^{-1}	1019	950	967	1035
Lactation length	days	277	277	278	277
Pasture eaten	t DM ha^{-1}	11.76	10.64	10.76	11.81
Supplement eaten	t DM ha^{-1}	2.33	2.18	2.16	2.31
Total feed eaten	t DM ha^{-1}	14.52	13.32	13.37	14.51
Methane emissions	kg CH_4 ha^{-1}	347.68	323.04	322.5	346.6
N_20 emissions	kg N_20 ha^{-1}	13.68	11.63	11.67	13.67
GHG emissions	kg CO_2-eq ha^{-1}	11,543	10,389	10,389	11,517
Mitigation practices	-	-	-	Cows with high genetic merit	Cows with high genetic merit

[ϕ] Scenario description: 1. Baseline situation. 2. 10 per cent reduction in baseline emissions without strategic mitigation options. 3. 10% reduction in baseline emissions with strategic mitigation options. 4. No reduction in baseline emissions with strategic mitigation options.

in stocking rate occurred to compensate for the higher potential intake of the high genetic merit cows and GHG-e per ha was about the same as the baseline.

Profit does not decrease much with the cap in Scenario 2 and Scenario 3 for two reasons. First, the 10% reduction in emissions proposed by the cap is significant, but not large. Secondly, the use of strategic mitigations other than cows with high genetic merit introduces additional costs that are unwarranted at the 10% cap. For example, nitrification inhibitors would only be used in the optimal plan in Scenario 3 if their cost falls by 13% to $131 ha^{-1}. For that reason, if high genetic merit cows are removed as an option, then optimal management in Scenario 3 would be identical to optimal management in Scenario 2.

The emissions profile changed in the mitigated systems. Most abatement occurs through a reduction in N_2O, which decreases by 15 per cent. However, CH_4 abatement is also important, as it falls by around 7 per cent. These results are in line with those reported by Beukes et al. (2010, 2011)

A9 Conclusions

The IDEA model provides a meaningful description of a production system 3 dairy farm parameterised using survey data from the DairyBase database and Farmax simulations. Optimisation of the farming system using IDEA provides a consistent and flexible means to consider its many interdependent elements while seeking to identify systems that cost-effectively reduce greenhouse gas emissions.

Reducing N fertiliser is the cheapest way to reduce GHG-e from dairy farms in the Waikato-Bay of Plenty. This option will affect both nitrous oxide and methane emissions as less feed is available for the cows. This reduction in available feed not necessarily results in a reduction in profit of the same magnitude because feed efficiency gains can be achieved by increased individual cow performance, e.g. through using high merit cows, resulting in lower number of cows and associated costs. This partially compensates for the lower total herd intake.

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