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# Total greenhouse gas emissions from farm systems with increasing use of supplementary feeds across different regions of New Zealand

SLMACC-AGR30624; Milestone 12

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# Total greenhouse gas emissions from farm systems with increasing use of supplementary feeds across different regions of New Zealand

## Report prepared for the Ministry for Primary Industries

**May 2015**

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# Executive Summary

Pastoral farms in New Zealand (NZ) have been intensifying and for dairy farms in particular this has involved the increased use of brought-in supplementary feeds. The objectives of this research project were to examine the effects of the integration of commonly-used supplementary feeds into dairy, or sheep and beef farm systems on total greenhouse gas (GHG) emissions, based on field and respiration chamber research studies and use of farm system analysis models. Results from the field and respiration chamber research studies were presented in previous reports and papers to MPI during this project. This report covers results from the use of farm system and life cycle assessment (LCA) models to evaluate the total GHG emissions from baseline dairy, and sheep and beef farm systems in NZ, and the effects of increased use of supplementary feeds, changes in supplementary feed types, GHG mitigation practices and measured feed-related GHG emission factors (from the field and respiration chamber studies) on these baseline farms.

**Dairy farms**: Survey data from dairy farms in four main regions of NZ (Waikato, Bay of Plenty, Marlborough/Canterbury, Otago/Southland) were obtained from the DairyNZ DairyBase (for 2010/11) covering low, medium and high farm system classes based on increased milksolids (MS) production per hectare through increased use of brought-in feed. The medium Waikato dairy farm was then also used to produce models of associated low and high feed-input farms using FARMAX modelling, where the level of brought-in feed was the only factor of difference between farms, except for changes in either cow stocking rate or MS production per cow. In all cases, intensification (e.g. with brought-in feed of up to 4.0 t dry matter/ha) was associated with an increase in total GHG emissions per on-farm hectare by up to 40%. However, across the survey farms there was no difference between low and high farm systems in total GHG emissions per kg MS (i.e. the carbon footprint of MS). For the modelled farm systems, the carbon footprint of MS increased by 5% between low and high supplementary feed input systems where this feed was used to increase MS/ha (i.e. no change in MS/cow), but it decreased by 8% where the feed was used to increase MS/cow with no change in cows/ha.

There was a wide variation in the total GHG emissions associated with production of different feeds from 0 to 0.51 kg $CO_2$-equivalents/kg dry matter (from wastes or by-products to the highest value for palm kernel expeller). Scenario analysis showed that the use of low carbon footprint feeds has the potential to reduce the average carbon footprint of MS from NZ farms by 12%.

The modelled dairy farm systems were used to evaluate the effects of a range of GHG mitigation practices. This analysis showed that the most sensitive options for reducing

total GHG emissions were feed conversion efficiency (FCE, i.e. feed requirement/kg milk) and MS/cow. However, when a range of realistic mitigation practices were evaluated, the largest single decrease in carbon footprint of MS of 7-9% was associated with ceasing use of nitrogen (N) fertiliser and replacing the reduced pasture growth with maize silage. Use of the realistic level of increase in FCE of 3% (based on NZ research) resulted in a 2% decrease in total GHG emissions. However, a combination of all of the mitigations examined corresponded to a decrease in carbon footprint of MS of 15-17% (excluding use of nitrification inhibitor which resulted in a total combined reduction of 15-19). Thus, there is significant potential to reduce total GHG emissions per kg milk and meat from the use of feeds with a low carbon footprint in combination with the use of mitigation practices on farm.

This project included several experimental studies where nitrous oxide ($N_2O$) emissions were measured from the establishment and production of a maize field crop and where enteric methane ($CH_4$) emissions were measured from sheep based on diets with different levels of maize silage or grain inclusion. The total measured $N_2O$ emissions from a maize crop were 51% of that calculated using the NZ GHG Inventory, and the effect of using these measured $N_2O$ emissions across the modelled dairy farm systems with low to high maize silage inputs was a 0.3-1.2% decrease in the carbon footprint of MS. Conversely, the $CH_4$ study indicated a higher enteric $CH_4$ emission factor with maize silage inclusion and represented a 0.5-2% increase in carbon footprint of MS. These were single studies (with the $CH_4$ study based on sheep and not cattle) and more research is required before such changes should be considered and reviewed for updating the NZ GHG Inventory.

**Sheep and beef farms**: Survey data were obtained from Beef+LambNZ for Class 4 (North Island hill country) and Class 6 (South Island finishing/breeding) sheep and beef farm systems for the year 2011/2012. The FARMAX model was used to link feed flows and animal productivity and define farm system scenarios with no on-farm crops and with addition of a summer rape crop for feeding and finishing lambs and/or a winter kale crop for feeding cattle (The effects of brought-in feed to sheep and beef farms were not evaluated since it is minimal relative to use of feed crops on-farm). Crop integration increased total GHG emissions/ha by 1-4%. However, while the brassica crops were estimated to increase animal productivity (by heavier lambs sold or more cattle carried) and provide some reduction in enteric $CH_4$ and excreta $N_2O$ per kg live-weight sold, this was largely countered by the increased GHG emissions associated with planting of the crop and the associated emissions from the crop inputs (particularly fertiliser).

This project included a field study where $N_2O$ emissions were measured from the establishment and production of a rape crop in winter in Waikato and these emissions were 78% higher than when estimated from the NZ GHG Inventory. This contrasts with results from the maize crop (outlined earlier) on a nearby site. Use of these measured emissions from the rape crop in the farm system analysis resulted in 1% higher GHG emissions/ha and a 1-2% higher carbon footprint of lamb compared to that using the Inventory methodology.

An allied SLMACC project (SLMACC-AGR30737) included studies where enteric $CH_4$ emissions from sheep were measured and showed a 13-28% lower emission factor (per kg dry matter intake) for a rape diet than for a ryegrass diet. Extrapolation of this to the farm system with lambs on a summer rape crop resulted in 1% lower GHG emissions/ha and a 1-2% lower carbon footprint of lamb compared to that using the Inventory methodology. While the measured crop $N_2O$ data was from a single field study and more data is required before any Inventory factors should be reviewed, the rape enteric emission factors were based on up to 7 studies and therefore much more confidence can be placed on a reduced enteric $CH_4$ emission factor for rape. This is important since enteric $CH_4$ is the single largest contributor to total GHG emissions from pastoral farms. However, the single sheep study showing an increased enteric emission factor from maize silage feeding (described earlier) needs further research using dairy cattle in view of the widespread use of maize silage on dairy farms and the much greater significance to NZ's GHG Inventory.

In conclusion, while crop integration on sheep and beef farms had a minor effect on total GHG emissions and the carbon footprint per kg product, the use of brought-in supplementary feeds on dairy farms had a much greater effect. When their use on dairy farms was associated with increased MS production per cow, this led to a decrease in the carbon footprint of milk. This analysis revealed that the integration of low carbon footprint feeds, in combination with practical mitigation options, have potential to decrease the carbon footprint of milk by up to 20%.

# 1. Introduction

Milk production in New Zealand (NZ) has been increasing over the past 50 years and since 1988/89 this has equated to a 9% increase per year (DairyNZ, 2014). This latter increase over 25 years has occurred through a combination of expansion of land area under dairying (+3%/year) and an increase in the milk production per hectare, the latter equating to 19 kg milksolids/ha/year (DairyNZ, 2014).

The increased use of supplementary feeds on farms in NZ has been important for intensification and increased productivity. DairyNZ classify farms into five farm system types according to level of brought-in feed used on farms (Hedley and Bird, 2006) and over a recent 10-year period, the proportion of both medium (dairy farm system 3) and high (dairy farm systems 4 and 5) feed-input farm systems has nearly doubled (Table 1).

**Table 1**. Changes in proportion of NZ dairy farms in different farm system categories reflecting the level of use of brought-in supplementary feeds (Greig, 2012).

| NZ dairy farm system* | 2000/01 | 2005/06 | 2009/2010 |
|---|---|---|---|
| System 1 | 41% | 15% | 10% |
| System 2 | 31% | 36% | 32% |
| System 3 | 17% | 32% | 36% |
| System 4 | 11% | 14% | 18% |
| System 5 | 1% | 3% | 4% |

**System 1 = all grass, self-contained, all stock on the milking platform*
*System 2 = Feed imported (~4-14%), either supplement or grazing off, fed to dry cows*
*System 3 = Feed imported (~10-20%) to extend lactation (typically autumn feed) and for dry cows*
*System 4 = Feed imported (~20-30%) and used at both ends of lactation and for dry cows*
*System 5 = Imported feed (~25-40%) used all year, throughout lactation and for dry cows*

On sheep and beef farms in NZ there is limited use of brought-in feed but there is significant use of forage crops on farm, such as forage brassicas (e.g. Bray and Gonzalez-Macauer, 2010). Over 300,000 ha of forage brassicas are planted each year on farms in NZ and their use has been increasing in recent years to provide additional high quality feed in summer, autumn or winter (Specialty seeds, 2014).

These supplementary feeds have greenhouse gas (GHG) emissions associated with their production and use, due to significant emissions from inputs of fertilisers and use of fossil fuels (e.g. Ledgard et al., 2007). This means that supplementary feeds have the potential to increase whole farm system GHG emissions when compared to farms based solely on grazed pasture. However, they may also provide opportunities, including higher production potential from some feed crops compared to that from pasture production, and greater environmental efficiency (e.g. via lower nitrogen concentrations in feed; Ledgard et al., 2009; Luo et al., 2015a). These supplementary feeds may be by-products of crops with other main uses (e.g. for oilseed production) or waste products (e.g. waste vegetables or fruit), and consequently have low or nil allocated emissions. Thus, it is important to examine the total GHG emissions associated with the production of animal products that involve the use of supplementary feeds and understand the potential for reducing whole-system emissions (i.e. using Life Cycle Assessment (LCA) methodology that accounts for all GHG emissions including from the production, transport and use of inputs for all on- and off-farm stages that contribute to milk/meat/fibre production; e.g. Hermansen and Kristensen, 2011; Ledgard et al., 2011).

The objectives of this research project were to examine the effects of the integration of commonly-used supplementary feeds into dairy (brought-in) or sheep and beef (grown on-farm) farm systems, on GHG emissions, based on field and respiration chamber research studies and use of farm system analysis models. Results from the field and respiration chamber research studies were presented in previous reports and papers (Jonker et al., 2015; Luo et al., 2015a; Wyatt et al., 2014). This report covers results from use of farm system and LCA models to evaluate the total GHG emissions from baseline dairy and sheep and beef farm systems in NZ, and the effects of increased use of supplementary feeds, changes in supplementary feed types, GHG mitigation practices and measured feed-related GHG emission factors.

## 2. Outline of full SLMACC project milestones

This SLMACC-AGR30624 project included 12 milestones and a brief outline of these and the outputs from them is given below:

**Milestone 1. Review of feeds used in New Zealand**. A review report (Ledgard and Boyes, 2013) was produced and submitted to MPI, which showed the ongoing increase in use of brought-in feed on NZ dairy farms and of forage crops grown on sheep and beef farms.

**Milestones 2 & 6. Update of feed carbon footprints**. The carbon footprints of a range of feeds used in NZ were determined. A report on the carbon footprint of brassica crops was produced (Falconer et al., 2014) and a summary of the updated values for the carbon footprint of a range of feeds is given later in this report (Table 10).

**Milestones 3 & 5. Nitrous oxide emissions from the production of maize**. A field study assessed the $N_2O$ emissions from a maize crop in the Waikato. A trial establishment report (Milestone 3; Luo et al., 2014) and a final trial report (Milestone 5; Wyatt et al., 2014) were produced and submitted to MPI.

**Milestones 4 & 7. Enteric methane emissions as affected by level of supplementary feeding**. A review report was produced and submitted to MPI, which indicated that feed type can influence enteric $CH_4$ emissions although the effects are complex (Jonker and Pacheco, 2014). A respiration chamber study with sheep showed that increasing levels of supplementation with maize silage or grain led to a quadratic response in enteric $CH_4$ emissions (Jonker et al., 2015).

**Milestones 5 & 9. Nitrous oxide emissions from the production of forage rape** (*Brassica napus* subspecies *biennis*). A field study assessed the $N_2O$ emissions from a forage rape crop in Waikato compared to continuous pasture and results were published in a report to MPI (Luo et al., 2015a).

**Milestones 8 & 10. Farm system analysis of the effects of differences in use of supplementary feeds**. Farm survey data was obtained from DairyNZ for dairy farms and from Beef+LambNZ for sheep and beef farms for different regions of NZ. This data was integrated into farm system models and LCA models and used to calculate total GHG emissions. A report on the base farms was provided to MPI (Ledgard and Falconer, 2014).

**Milestone 11. Carbon footprint analysis of farm system using forage rape**. Data from an allied project (SLMACC-AGR30737) on enteric $CH_4$ emissions from sheep fed on rape compared to sheep fed on ryegrass was obtained and used in farm system analysis, which is presented in this report.

**Milestone 12. Scenario analysis of effects of feed types and GHG reduction options**. This uses data from Milestones 8 & 10 for scenario analyses and the methods and results from these farm system analyses are presented in the remainder of this report.

# 3. Materials and Methods

## 3.1 Goal and Scope

### 3.1.1 General description

The project aim was to determine the total GHG emissions (carbon footprint) from pastoral farm systems and products (milk, meat, wool) with increasing farm system intensification due to integration of supplementary feeds. It involved use of Life Cycle Assessment (LCA) and farm system analysis models across a range of dairy and sheep and beef farm systems.

For dairying, two scenarios were used:

1) Survey data for the year 2010/11 from the DairyNZ DairyBase system for four regions of NZ for the five DairyNZ farm classes were used. These farm classes range from system 1 with no brought-in feed through to system 5 with about half of the total feed derived from brought-in supplementary feeds (Hedley and Bird, 2006). In this study, the five farm classes were grouped into low (farm class 1 and 2), medium (farm class 3) and high (farm class 4 and 5), because of the relatively small number of farms in systems 1 and 5. Farm production data and key farm input information (including amount and type of brought-in feeds) were used to calculate the total GHG emissions from these farm systems.

2) The medium Waikato dairy farm system outlined above was used specifically to model (using FARMAX), the effects of changes in the amount of brought-in feed on the carbon footprint per hectare and per kg of product. These farm systems were then evaluated for the effects of integration of a range of different feed types and mitigation practices.

For sheep and beef farm system analyses, farm survey data from Class 4 (North Island hill country) and Class 6 (South Island finishing/breeding) sheep and beef farm systems for the year 2011/2012 were obtained from Beef+LambNZ. The FARMAX sheep and beef model (Webby and Bywater, 2007) was used to link feed flows and animal productivity, in defining the farm system scenarios. The effects of incorporation of a summer and/or winter brassica crop were investigated.

### 3.1.2 System boundaries

#### 3.1.2.1 Dairy Farm Systems

The system boundary for the dairy farm systems was the "cradle-to-farm-gate" stages of the life cycle. The whole-system GHG emissions were calculated and expressed on a per-hectare (milking platform) or per-product unit basis. The calculated GHG emissions were allocated between the co-products milk and meat based on the physiological feed requirements of the animal to produce milk and meat (culled cows and surplus calves) using the IDF (2010) methodology. Thus, the functional units for these products were one kg milksolids or one kg live-weight (sold for meat).

The system boundary covered:

- Production of milk on-farm, including on-farm pasture production and utilisation (thus determining $CH_4$ and $N_2O$ from animals), use of farm equipment (representing diesel and petrol use) and milk extraction, farm dairy effluent management and water supply (determining electricity use).
- Production of supplementary feed.

- Off-farm pasture production for the dairy cow replacements.
- Wintering-off of non-lactating ("dry") cows, from South Island farms.
- Production and delivery of inputs to crops and pasture (e.g. fertilisers).

According to previous calculations (e.g. Basset-Mens et al., 2009), the above components account for at least 99% of the likely life cycle GHG emissions from cradle-to-farm-gate, thereby meeting one of the key requirements of the PAS 2050 (2011) methodology which states that at least 95% of all constituents should be included.

In this report (as recommended in the PAS 2050 (2011)), capital (or infrastructure, e.g. buildings, tractors etc.) was excluded from all calculations. A brief summary was carried out on the use of refrigerants (mainly associated with vats for chilling milk on farm prior to collection) after discussion with a local expert (D. Gray, NDA, *pers. comm*.). The estimate of emissions associated with the refrigerants HFCs and CFCs equated to 0.02 kg $CO_2$-equivalent/kg milksolids, although this can be highly variable. This represented only about 0.2% of the total carbon footprint and was included in all estimates for completeness.

This carbon footprint analysis used an attributional LCA approach (ISO, 2006) and therefore used average data for all processes.

#### 3.1.2.2 Sheep and Beef Farm Systems

The system boundary was the "cradle-to-farm-gate" stages of the sheep and beef farm systems. The whole-system GHG emissions were calculated and expressed on a per-hectare or per-product unit basis. For cattle, the live-weight sold off the farm was the only product, whereas for sheep the calculated GHG emissions were allocated between the co-products of live-weight (sold for meat) and wool based on the protein requirements of the animal to produce meat and wool using the LEAP (2014) methodology. Thus, the functional units for these products were one kg live-weight (sold for meat) or one kg greasy wool.

Data collected from Beef+LambNZ Economic Service's survey of sheep and beef farms in 2011/12 were used in FARMAX to model two main farm systems from the North and South Islands. These were an average Class 4 North Island Hill Country sheep and beef farm and an average Class 6 South Island Finishing - Breeding sheep and beef farm.

Expert modellers modified the average Beef+LambNZ farm systems in FARMAX to exclude; deer, goats, dairy animals brought on for grazing and land used for cash cropping. These activities were excluded to simplify the LCA modelling and to reduce uncertainty in some important inputs such as fertiliser and fuel. In addition, the animal numbers were kept constant across all crop scenarios for each farm class to simplify the interpretation of the LCA results.

The system boundary covered:

- Sheep and beef production on-farm, including on-farm pasture production and utilisation (thus determining $CH_4$ and $N_2O$ from animals).
- Production and use of supplementary feed (e.g. pasture silage/hay made on farm).
- Production and delivery of inputs to forage crops and pasture.

Farm GHG emissions from sheep and beef cattle were separated according to animal type where possible. The remaining on-farm emissions were allocated according to biological function (Cederberg and Mattson, 2000; Ledgard et al., 2008) and utilised the FARMAX estimates of feed dry matter (DM) intake for each of the animal types (Webby and Bywater, 2007).

## 3.2 Input data for Dairy Farm Systems

### 3.2.1 DairyBase Farm Systems

DairyBase categorises surveyed farms into five systems based on timing, purpose and amounts of imported feeds (Table 1). Examination of the 2010/11 survey sample numbers showed most regions had low sample numbers in some of the systems. Grouping the systems into low, medium and high improved the sample numbers but there were still some systems poorly represented in some regions. In smaller regions such as Northland, Westland and Taranaki, there were insufficient numbers of farms in these farm system groups to provide representative data for analysis and therefore they were excluded. Thus, the project analysis was reduced to 4 regions and 3 system groups (Table 2). The low group contains system 1 (all grass self-contained, with young stock off) and system 2 (dry cow feed purchased and includes grazing off (4-14% total feed)) farm classes. The medium group contains only system 3 (feed purchased to extend autumn lactation + dry cow feed (10-20% of total feed)). The high group contains systems 4 (feed purchased to extend both ends of lactation + dry cow feed (20-30% of total feed)) and system 5 (feed purchased for all year round (>30% of total feed)).

**Table 2**. Total number of farms in each of the low, medium and high intensity farm system groups, derived from the DairyBase database for 2010/2011.

| Region | Low | Medium | High | Total |
|---|---|---|---|---|
| Waikato | 34 | 41 | 32 | 107 |
| Bay of Plenty | 14 | 17 | 17 | 48 |
| Marlborough-Canterbury | 7 | 25 | 31 | 63 |
| Otago-Southland | 3 | 11 | 12 | 26 |
| Total | 92 | 126 | 114 | |

The regional Dairybase data provided by DairyNZ and LIC statistics were the two main sources of data used. These data were aggregated in order to match Dairybase regional categories with LIC district categories (Table 3). To overcome the possible bias of using one source of data for the output (milk production per ha) and another for the inputs of the system (e.g. kg N fertiliser per ha), the input data from Dairybase were normalised relative to LIC data on a "kg milksolids/ha" basis. Cow numbers, milk production, milk quality and size of farms were derived from LIC statistics while replacement rate, cow weight and key input data such as fertiliser-nutrients and feed supplements were obtained from the regional Dairybase databases (Table 4).

**Table 3**. Districts included in each regionally-adjusted category for this study.

| Waikato | Bay of Plenty | Marlborough + Canterbury | Otago + Southland |
|---|---|---|---|
| Manukau/Papakura<br>Franklin<br>Waikato<br>Western Uplands | Bay of Plenty<br>Central Plateau<br>East Coast | Marlborough<br>Kaikoura<br>Nth Canterbury<br>Sth Canterbury<br>Waitaki | Dunedin<br>Clutha<br>Central Otago<br>Southland |

### 3.2.2 Intake model for DairyBase Farm Systems

The animal feed intake model, used for the dairy farm systems, was that used in the Tier 2 approach of the NZ IPCC inventory (Clark et al., 2003). It is a comprehensive model that operates at a monthly time step and utilises data on livestock numbers, livestock performance and diet quality. Within the dairy category, the model subdivides a population into animal sub-categories such as dairy cows in milk, heifers from 0 to 1 year old and heifers from 1 to 2 years old. Dry matter intake was estimated by calculating the energy required to meet the assumed levels of performance (MJ metabolisable energy (ME) per day) and dividing this value by the energy concentration of the diet consumed (MJ ME per kg dry matter). For dairy cattle, energy requirements were calculated using the algorithms presented in the publication “Feeding standards for Australian livestock: Ruminants (CSIRO, 1990)”. These were chosen as they specifically include methods to estimate the energy requirements of grazing animals.

The intake model from the NZ GHG inventory described above was used for each scenario by entering data on milk production, milk quality and cow live-weight, and by adjusting the feed quality (ME, digestibility and N concentrations), on a monthly basis to account for all feed supplements used in addition to pasture.

#### 3.2.2.1 Off-farm grazing of replacements and wintering-off dry cows

Where there was off-farm grazing of replacements, an average beef farm was assumed to be used for grazing, based on the MPI Intensive Beef Monitor Farm. Distances for transport of animals that were grazed-off or wintered-off farm were based on data collected by surveying different experts from the consulting officers of DairyNZ and PGG Wrightson (PGGW). The practices of farmers in each region for the different aspects and distances of transportation for animals that were grazed-off farm were based on a survey of consulting officers from DairyNZ and experts from Westland Milk products and PGGW. Where cow wintering-off farm dominated in the eastern regions of the South Island, it was assumed that the feed was split between pasture silage (25%) and a brassica crop (75%).

#### 3.2.2.2 Supplementation with different feeds

In farm system scenarios where pasture was supplemented with feeds that were different from the base farm, the amount of new feed given was calculated by ensuring that the total MJME/ha from all supplements and pasture remained the same as that for the base farm. The amount of new feed was calculated by determining how much MJME/ha was required from that supplement by subtracting the pasture MJME/ha from the total MJME/ha needed. This figure was then divided by the MJME/kg DM for the proposed new supplement to determine the total kg DM required. All other inputs were kept the same as the base farms (Table 5).

**Table 4**. Technical description of key inputs from Waikato, Bay of Plenty, Marlborough + Canterbury and Otago + Southland dairy farms of low, medium and high intensity (year 2010/2011; farm data from DairyNZ DairyBase).

| Region | Waikato | | | Bay of Plenty | | | Marlborough + Canterbury | | | Otago + Southland | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm System | 1-2 | 3 | 4-5 | 1-2 | 3 | 4-5 | 1-2 | 3 | 4-5 | 1-2 | 3 | 4-5 |
| Group | Low | Medium | High | Low | Medium | High | Low | Medium | High | Low | Medium | High |
| On-farm area, ha | 130 | 137 | 203 | 126 | 132 | 156 | 223 | 252 | 266 | 198 | 205 | 225 |
| Cow weight, kg | 453 | 473 | 550 | 505 | 525 | 550 | 453 | 473 | 498 | 453 | 473 | 498 |
| Dairy cows/ha | 2.81 | 2.91 | 2.81 | 2.84 | 3.03 | 3.44 | 3.00 | 3.27 | 3.62 | 2.63 | 2.71 | 2.85 |
| Replacement rate | 0.20 | 0.19 | 0.23 | 0.22 | 0.22 | 0.22 | 0.18 | 0.22 | 0.21 | 0.21 | 0.24 | 0.23 |
| kg milksolids/ha | 915 | 1083 | 1184 | 921 | 1011 | 1268 | 1237 | 1456 | 1563 | 969 | 1180 | 1285 |
| Butterfat%[a] | 4.97 | 4.94 | 4.73 | 4.91 | 4.84 | 4.73 | 5.19 | 4.96 | 4.81 | 5.00 | 4.75 | 4.80 |
| Protein%[a] | 3.68 | 3.67 | 3.62 | 3.63 | 3.60 | 3.52 | 3.72 | 3.75 | 3.74 | 3.78 | 3.67 | 3.68 |
| kg milksolids/cow | 325 | 372 | 422 | 324 | 334 | 369 | 413 | 445 | 431 | 369 | 436 | 451 |
| kg fertiliser N/ha | 121 | 151 | 164 | 120 | 161 | 182 | 185 | 236 | 231 | 149 | 152 | 137 |
| kg fertiliser P/ha | 37 | 39 | 52 | 27 | 39 | 35 | 34 | 27 | 37 | 39 | 37 | 40 |
| kg fertiliser K/ha | 42 | 40 | 45 | 52 | 52 | 43 | 23 | 27 | 25 | 19 | 17 | 19 |
| kg lime /ha | 113 | 173 | 105 | 74 | 70 | 64 | 54 | 75 | 53 | 48 | 54 | 57 |
| Brought-in feeds (kg DM/ha): | | | | | | | | | | | | |
| Maize silage | 276 | 683 | 1209 | 442 | 878 | 1600 | 95 | 279 | 371 | - | - | 200 |
| Grass silage & hay | 160 | 116 | 100 | 73 | 151 | 67 | 270 | 360 | 308 | 182 | 320 | 440 |
| Hay | 52 | 65 | 10 | - | 2 | 30 | 70 | 10 | 10 | - | 11 | 5 |
| Concentrate | - | 258 | 258 | - | - | 824 | 350 | 650 | 750 | 700 | 900 | 900 |
| PKE | 500 | 900 | 2100 | 400 | 650 | 1000 | - | 100 | 460 | - | - | 100 |
| Grain (barley, maize) | 7 | - | 20 | - | 90 | - | - | 200 | 470 | - | 150 | 385 |
| Brewers grain | - | 1 | 60 | - | - | 10 | - | - | 26 | - | - | 8 |
| Cereal silage | - | - | - | - | - | - | - | 30 | 55 | - | 200 | 71 |
| Cereal straw | 5 | - | 5 | - | 6 | - | 200 | 50 | 40 | - | - | 21 |
| Molasses | 9 | 7 | 20 | 4 | 50 | - | 26 | 20 | 30 | - | 30 | 159 |
| Proliq | - | 27 | 60 | - | - | - | - | - | - | - | - | 114 |
| Soyabean meal | - | - | 3 | - | - | - | - | - | - | - | - | - |
| Other[b] | 22 | 92 | 185 | 26 | 110 | 118 | 30 | 150 | 126 | - | 20 | 20 |

[a] Where % is mass/mass, [b] Where Other represents feeds like Broll, Tapioca, Fruit and Vegetables

**Table 5**. Summary of the amounts of brought-in supplementary feeds (kg DM/ha) used for farms across 4 regions and in the 3 different intensity farms from DairyBase for 2010/11. Quantities of feed used in scenarios involving maize silage, Brewers grain and PKE are also given.

| Region | Waikato | | | Bay of Plenty | | | Marlborough + Canterbury | | | Otago + Southland | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm System | 1-2 | 3 | 4-5 | 1-2 | 3 | 4-5 | 1-2 | 3 | 4-5 | 1-2 | 3 | 4-5 | Scenario |
| Group | Low | Medium | High | Low | Medium | High | Low | Medium | High | Low | Medium | High | |
| Maize silage | 276 | 683 | 1209 | 442 | 878 | 1600 | 95 | 279 | 371 | - | - | 200 | |
| Grass silage & hay | 160 | 116 | 100 | 73 | 151 | 67 | 270 | 360 | 308 | 182 | 320 | 440 | |
| Hay | 52 | 65 | 10 | - | 2 | 30 | 70 | 10 | 10 | - | 11 | 5 | |
| Concentrate | - | 258 | 258 | - | - | 824 | 350 | 650 | 750 | 700 | 900 | 900 | |
| PKE | 500 | 900 | 2100 | 400 | 650 | 1000 | - | 100 | 460 | - | - | 100 | |
| Grain (barley, maize) | 7 | - | 20 | - | 90 | - | - | 200 | 470 | - | 150 | 385 | |
| Brewers grain | - | 1 | 60 | - | - | 10 | - | - | 26 | - | - | 8 | Base Farm |
| Cereal silage | - | - | - | - | - | - | - | 30 | 55 | - | 200 | 71 | |
| Cereal straw | 5 | - | 5 | - | 6 | - | 200 | 50 | 40 | - | - | 21 | |
| Molasses | 9 | 7 | 20 | 4 | 50 | - | 26 | 20 | 30 | - | 30 | 159 | |
| Proliq | - | 27 | 60 | - | - | - | - | - | - | - | - | 114 | |
| Soyabean meal | - | - | 3 | - | - | - | - | - | - | - | - | - | |
| Other[a] | 22 | 92 | 185 | 26 | 110 | 118 | 30 | 150 | 126 | - | 20 | 20 | |
| Maize silage | 1101 | 2404 | 4520 | 1005 | 2079 | 4162 | 1127 | 2209 | 3220 | 1185 | 2065 | 3053 | Maize silage only |
| Brewers grain | 796 | 1739 | 3270 | 727 | 1504 | 3010 | 815 | 1598 | 2329 | 857 | 1494 | 2208 | Brewers grain only |
| PKE | 814 | 1779 | 3344 | 744 | 1538 | 3079 | 833 | 1634 | 2382 | 877 | 1528 | 2258 | PKE only |

[a]Where Other represents feeds like Broll, Tapioca, Fruit and Vegetables

### 3.2.3 Modelled dairy farms using FARMAX

An average DairyBase medium group Waikato farm was used as a base farm to be modelled in FARMAX and different scenarios were set up to examine the effects of changing the intensification on this farm. This was attained by two methods: 1) changing cow productivity (with cows/ha held constant) and 2) changing cow numbers per hectare (with milksolids/cow held relatively constant) (Table 6). In the first instance, improved cow productivity was achieved by increasing the amount of brought-in supplements. In the second instance, intensification occurred by increasing the number of dairy cows per hectare and subsequently the amount of brought-in feed.

**Table 6**. Technical description of key inputs used in the FARMAX-modelled dairy farm systems (year 2010/2011).

| All per on-farm ha unless specified | Cow productivity | | | Cow numbers | | |
|---|---|---|---|---|---|---|
| | Low | Medium | High | Low | Medium | High |
| On-farm area, ha | 150 | 150 | 150 | 150 | 150 | 150 |
| Cow weight, kg | 438 | 443 | 453 | 441 | 443 | 437 |
| Dairy cows | 2.60 | 2.60 | 2.60 | 2.30 | 2.60 | 2.90 |
| Replacement rate | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Kg milksolids | 828 | 1047 | 1159 | 919 | 1047 | 1153 |
| Annual milk yield[a] | 3962 | 4977 | 5506 | 4944 | 4977 | 4916 |
| Butterfat%[b] | 4.45 | 4.47 | 4.45 | 4.46 | 4.47 | 4.47 |
| Protein%[b] | 3.59 | 3.62 | 3.65 | 3.62 | 3.62 | 3.62 |
| Kg milksolids/cow | 318 | 403 | 446 | 400 | 403 | 398 |
| Kg fertiliser N | 121 | 121 | 121 | 121 | 121 | 121 |
| Kg fertiliser P | 44 | 41 | 38 | 45 | 41 | 37 |
| Kg DM maize silage | 468 | 1694 | 2202 | 363 | 1694 | 1967 |
| Kg DM pasture silage | - | - | - | - | - | - |
| Kg DM concentrate | - | - | - | - | - | - |
| Kg DM PKE | 322 | 857 | 1733 | 284 | 857 | 2120 |

[a] litres/cow; [b] % mass/mass

#### 3.2.3.1 Effects of supplementation with different feeds

In farm systems where scenario analyses of supplementation with different feeds were carried out, the amount of new feed given was calculated by ensuring that the total MJME/ha from all supplements and pasture remained the same as that for the base farm. The amount of new feed was calculated by determining how much MJME/ha was required from that supplement by subtracting the pasture MJME/ha from the total

MJME/ha needed. This figure was then divided by the MJME/kg DM for that supplementary feed to determine the total kg DM required. All other inputs were kept the same as the base farms (Table 7).

**Table 7**. Summary of the amounts of different brought-in supplementary feeds (kg DM/ha) used in the scenario analyses of the FARMAX-modelled dairy farm systems (year 2010/11).

| kg DM/ha | Cow Productivity | | | Cow Numbers | | | Scenario |
|---|---|---|---|---|---|---|---|
| | Low | Medium | High | Low | Medium | High | |
| Maize silage | 468 | 1694 | 2202 | 363 | 1694 | 1967 | Base farm |
| PKE | 322 | 857 | 1733 | 284 | 857 | 2120 | |
| Maize silage | 806 | 2592 | 4017 | 660 | 2592 | 4192 | Maize silage only |
| Brewers grain | 639 | 2177 | 3375 | 555 | 2177 | 3521 | Brewers grain only |

#### 3.2.3.2 Effects of mitigation practices

A range of different mitigation practices were evaluated to determine what effect they would have on the GHG emissions relative to the base farm systems. These were split between fixed and realistic levels of integration of mitigations. A fixed 15% change for each mitigation was used so that the relative effects of different mitigations could be compared. Realistic levels of integration of mitigation were based on relatively large changes that were considered to be feasible to apply in practice and were based on discussion with industry experts. The mitigation practices evaluated for a fixed 15% change were decreasing the cow replacement rate, the electricity use or amount of N fertiliser applied, or increasing the feed conversion efficiency (FCE) or milksolids/cow. The realistic mitigation practices evaluated were a decrease in the cow replacement rate (by 18%; based on a 19% replacement rate as a realistic low target), reduced electricity use (by 28%; based on Fonterra 2011), decreased amount of N fertiliser applied (to nil N, and assuming reduced pasture growth was replaced by brought-in maize silage), an increase in FCE (by 3%; based on Macdonald et al. 2014), a change in brought-in feed to only maize silage, or use of the nitrification inhibitor dicyandiamide (DCD; e.g. Gillingham et al., 2012). Additionally, a realistic option based on a combination of all of these mitigations with or without DCD use was tested.

#### 3.2.3.3 Scenario analysis: Measured versus Inventory emission factors for use of maize silage

Two scenario analyses were conducted using the range of modelled dairy farm systems (i.e. low, medium or high feed inputs with changes in cow productivity or stocking rate) and based on maize silage as the only source of brought-in feed.

#### 3.2.3.1 Effect of measured $N_2O$ emissions from a maize silage crop

This scenario compared the effects of using the NZ GHG Inventory for $N_2O$ emissions associated with the production of maize silage (including spraying out pasture, cultivation of soil, planting maize, use of N fertiliser and pesticides, harvesting maize, effects of crop residues and direct-drilling with new pasture) relative to $N_2O$ emissions that were measured in a Waikato field trial (Wyatt et al., 2014; Milestone 3 of this project).

#### 3.2.3.2 Effect of measured enteric methane emission factors for different levels of maize silage supplementation

This second scenario examined the effects of enteric $CH_4$ emission factors from feeding of different levels of maize silage in a cow's diet. Results from the study of Jonker et al. (2015; Milestones 7 and 9 of this project), involving testing of the effects of different levels of supplementation with maize silage, were used to derive values for changes in the enteric $CH_4$ emission factor for the total diet across the different dairy farm systems. This was compared with analyses based on a single common enteric $CH_4$ emission factor for a cow's diet of 21.6 g $CH_4$/kg DM intake (independent of diet constituents) based on the NZ GHG Inventory (MfE, 2014).

## 3.3 Input data for Sheep and Beef Farming Systems

Animal data for average Class 4 and Class 6 B+LNZ farm systems were obtained from Beef+LambNZ (2014) and were entered into the FARMAX model. This was then modified to create 'equilibrium' farm systems with the same animal numbers and weights at the start and end of the year (in practice, some farm class data were associated with changes in core sheep numbers over time). The model was also used to obtain realistic estimates of the monthly timing of sales of different animal classes to match annual records from B+LNZ data. This is an important requirement in estimating total feed intake (calculated using FARMAX) and $CH_4$ emissions (the longer an animal takes to reach sale weight the greater the intake and $CH_4$ emissions).

FARMAX data was also used in estimating the relative feed intake from pasture, silage/hay or fodder crop. Base farm systems were set up that used no forage crops, while scenarios with or without the integration of summer and/or winter forage crops were also developed. The area for the summer and winter forage crops was based on calculations of the total amount of crop required to feed all the lambs 75% of their diet during the 3 month summer period of Jan–Mar, and the amount of feed required to feed the cattle 75% of their diet during the winter months of Jun–Aug. A breakdown of the areas estimated for use for different farm activities is given in Table 8. Pasture silage/hay that was made on farms was assumed to be used mainly for cattle, with limited use for ewes (B+LNZ staff, *pers. comm.*).

**Table 8**. Technical description of farm information for the Class 4 and Class 6 Sheep and Beef farms for 2011/2012, including areas and inputs for the summer and winter forage crops.

| | Class 4 | Class 6 |
|---|---|---|
| Effective farm area, ha | 433 | 485 |
| Area (ha) for farm operations: | | |
| Hay/silage area | 10 | 38 |
| Summer forage crop area | 41.3 | 24.8 |
| Winter forage crop area | 7.7 | 4.7 |
| Fertiliser and lime use on pasture: | | |
| N fertiliser kg N/ha/year | 3.9 | 5.4 |
| P fertiliser kg P/ha/year | 12.5 | 10.1 |
| K fertiliser kg K/ha/year | 6.3 | 1.4 |
| Lime kg/ha/year | 102 | 355 |
| Fertiliser use on forage crops: | | |
| N fertiliser kg N/ha/year | 10.2 | 118.7 |
| P fertiliser kg P/ha/year | 8.2 | 57.6 |
| K fertiliser kg K/ha/year | 4.1 | 10.2 |

### 3.3.1 Addition of brassica crops

A summer forage rape crop was assumed to be used solely for lamb finishing while a winter kale crop was assumed to be used solely for cattle (B+LNZ staff, *pers. comm.*). The increase in feed intake and product sold for each animal class as a result of the addition of the different feed crop scenarios is shown in Table 9.

**Table 9**. Summary of the changes to the dry matter intake (DMI), product sold, and kg DMI/kg product sold from each farm class for crop scenarios with or without summer and/or winter forage brassicas.

| | No crop | Summer crop | Winter crop | Both crops |
|---|---|---|---|---|
| **Class 4:** | | | | |
| Sheep kg DMI | 1,486,619 | 1,495,625 | 1,476,010 | 1,485,017 |
| Lamb kg DMI | 349,474 | 329,050 | 349,474 | 329,574 |
| Cattle kg DMI | 622,524 | 616,072 | 688,639 | 682,057 |
| % DMI sheep | 75% | 75% | 73% | 73% |
| % DMI cattle | 25% | 25% | 27% | 27% |
| Lamb sold (kg LW) | 78,791 | 83,822 | 78,791 | 83,822 |
| Mutton sold (kg LW) | 38,429 | 38,429 | 38,429 | 38,429 |
| Greasy wool (kg) | 16,764 | 16,328 | 16,443 | 16,328 |
| Beef (kg LW) | 32,349 | 32,349 | 35,864 | 35,864 |
| Lamb kg DMI/kg LW sold | 4.44 | 3.93 | 4.44 | 3.93 |
| Sheep kg DMI/kg LW sold | 38.7 | 38.9 | 38.4 | 38.6 |
| Beef kg DMI/kg LW sold | 19.2 | 19.0 | 19.2 | 19.0 |
| **Class 6:** | | | | |
| Sheep kg DMI | 1,467,465 | 1,474,691 | 1,464,458 | 1,471,684 |
| Lamb kg DMI | 317,045 | 302,737 | 315,590 | 301,282 |
| Cattle kg DMI | 504,400 | 500,035 | 541,255 | 536,890 |
| % DMI sheep | 78% | 78% | 74% | 77% |
| % DMI cattle | 22% | 22% | 26% | 23% |
| Lamb sold (kg LW) | 85,456 | 89,079 | 85,456 | 89,089 |
| Mutton sold (kg LW) | 28,243 | 28,243 | 28,243 | 28,243 |
| Greasy wool (kg) | 17,182 | 17,333 | 17,182 | 17,332 |
| Beef (kg LW) | 27,089 | 27,089 | 29,346 | 29,346 |
| Lamb kg DMI/kg LW sold | 3.71 | 3.40 | 3.69 | 3.38 |
| Sheep kg DMI/kg LW sold | 52.0 | 52.2 | 51.9 | 52.1 |
| Beef kg DMI/kg LW sold | 18.6 | 18.5 | 18.4 | 18.3 |

### 3.3.2 Scenario analysis: Measured versus Inventory emission factors for use of a forage rape crop

Two scenario analyses were conducted based on the Class 4 and 6 farms with the use of a summer forage rape crop. These scenario analyses compared the effects of NZ GHG Inventory and measured emission factors on $N_2O$ and $CH_4$ emissions.

#### 3.3.2.1 Effect of measured $N_2O$ emissions from a forage rape crop

This scenario compared the effects of using the NZ GHG Inventory for $N_2O$ emissions associated with the production of a summer forage rape crop (including spraying out pasture, cultivation of soil, crop planting, use of N fertiliser and pesticides, cutting the crop, effects of crop residues and direct-drilling with new pasture) relative to $N_2O$ emissions that were measured in a Waikato field trial (Luo et al. 2015a; Milestone 5 and 9 of this project). The cutting option from the field trial study was used because the grazing treatment of the rape field trial was by cows in winter and was deemed to be non-comparable to that for summer grazing by sheep.

#### 3.3.2.2 Effect of changes in lamb enteric methane factor when fed forage rape

Various research experiments, including that in a separate SLMACC project on the effects of rape on $CH_4$ and $N_2O$ emission factors (SLMACC-AGR30737), were summarised by Drs Pacheco and Sun (unpublished data). This summary included a meta-analysis of all sheep $CH_4$ experiments comparing rape and ryegrass diets and concluded that on average the $CH_4$ emission factor (kg $CH_4$/kg DM intake) for rape was 72% of that for ryegrass. However, two trials used summer rape crops and their average $CH_4$ emission factor relative to ryegrass was 87%. Thus, these two factors were used in a sensitivity analysis examining the effects of inclusion of a $CH_4$ emission reduction factor from rape feeding. The SLMACC-AGR30737 research also included assessment of the effects of a rape diet on the $N_2O$ emission factor for urine from sheep fed rape compared to ryegrass. While an initial study indicated a decrease in $N_2O$ emission factor from urine from a rape diet (Luo et al., 2015b), subsequent repeat studies have shown variable results and the overall conclusion currently is that there is no specific effect of rape in the diet on $N_2O$ emission factor (David Pacheco, *pers. comm.*). Thus, no change in $N_2O$ emission factor was used in this sensitivity analysis. However, any effects of the N concentration in rape relative to that in pasture are accounted for in all modelling work with sheep and beef fed rape as part of their diet in this study.

## 3.4 Additional input data

### 3.4.1 Electricity

The NZ electricity inventory was based on the breakdown between different NZ electricity sources (thermal including coal, natural gas and oil, hydro, and geothermal) according to MED (2011). The inventory for crude oil included the different origins of oil used in NZ according to the NZRC (2013) annual report.

#### 3.4.1.1 Dairy farms

Electricity consumption was calculated as a function of cow numbers based on a NZ study by Sims et al. (2005) and as a function of irrigation based on a summary of types of irrigation systems, amount of irrigation water applied and typical depth of pumping.

#### 3.4.1.2 Sheep and Beef farms

Electricity use was based on the average consumption from two small surveys carried out by AgResearch (Ledgard, unpublished) and by AgriLink (Barber, unpublished). An attempt to use B+LNZ data on expenditure on electricity was unsuccessful because of difficulty in defining line and meter charges and the average number of meters per farm.

### 3.4.2 Fertilisers

The carbon footprint calculations for the manufacturing of fertilisers were based on the NZ study of Ledgard et al. (2011).

#### 3.4.2.1 Dairy Farms

Average fertiliser application rates were derived from the DairyBase survey statistics. Data on the distances of fertiliser transportation for each region were provided by experts from fertiliser companies Ballance Agri-Nutrients® and Ravensdown®).

#### 3.4.2.2 Sheep and Beef Farms

Estimated rates of nutrient application on pasture and forage crops and data on relative amounts of fertiliser and lime applied by air or by ground-spreading, and on the distance fertiliser was carted from fertiliser plants to farms, were obtained from B+LNZ statistics for the two farm classes.

### 3.4.3 Fuel

#### 3.4.3.1 Dairy Farms

The fuel consumption for all agricultural components including cow management, pasture production, supplementary feed production and delivery, was calculated from the analysis of all single operations needed specifically for each scenario and parameterised in the LCA model – SimaPro (PRé Consultants, 2014).

#### 3.4.3.2 Sheep and Beef

Fuel is used for a wide range of farm operations including fertiliser application, hay/silage making and feeding out, crop establishment and inputs, stock cartage, herbicide application, and travel by veterinarians (assumed for cattle only) and shearers. The fuel use on farm was estimated from B+LNZ economic data on farm expenditure on fuel in combination with data from the two surveys by Ledgard and Barber (unpublished reports) on the proportion of total fuel use as diesel versus petrol. However, this only provided an estimate of actual farm operations carried out by the farmer and excludes fuel use by contractors. Thus, a list of operations carried out by contractors was defined and expert opinion on the proportion of operations by contractors versus farmers was obtained from B+LNZ field staff. These estimates were used in conjunction with data on the area used for the various operations (e.g. see Table 8) and average data on fuel use for the range of specific operations (using some data from large contractors such as for fertiliser and lime application; otherwise it was obtained from Wells 2001). Indirect fuel use for pasture seed production for pasture renovation was included based on data from a separate LCA study done on total energy use and emissions from the production of grass and clover seed (Boyes et al., unpublished). Aerial topdressing is a specific method for applying fertilisers and lime on NZ sheep and beef farms and can represent a significant amount of fuel use especially for the taking off and landing of the small planes used for these operations. Fuel use data for aerial topdressing were obtained from Superair, a New Zealand company providing this service to farmers.

### 3.4.4 Pesticides

Data on total use of herbicides and pesticides were obtained from the national summary of Manktelow et al. (2005). Expert opinion (Trevor James, AgResearch, *pers. comm.*) was used to estimate the main forms of agrichemicals, the rate of application and therefore the areas treated. The use of fuel for transport and application of the agrichemicals was then calculated from this data. Emissions associated with agrichemical production were obtained using the Ecoinvent database v3.1 (Ecoinvent 2014).

### 3.4.5 Supplementary Feeds

The carbon footprint models of different brought-in feed sources were based on updated feed carbon footprints carried out in Milestone 6 of this study (Table 10). Transportation distances to the farm for brought-in-feed supplements were obtained from experts from Pioneer, DairyNZ and PGGW for dairy farms. There was no brought-in feed on the sheep and beef farms, where all feed was assumed to be grown on-farm.

**Table 10**. Carbon Footprint for the production of various supplementary feeds used on farm (excluding transport to the farm and feeding out on the farm).

| Supplementary Feed | kg $CO_2$-equivalent /kg DM |
|---|---|
| PKE | 0.506 |
| Barley grain | 0.355 |
| Concentrate | 0.355 |
| Rape (single grazing) | 0.328 |
| Turnips (bulb) | 0.264 |
| Pasture Silage (baled) | 0.201 |
| Kale | 0.192 |
| Maize silage - contract grower | 0.188 |
| Cereal silage | 0.185 |
| Hay | 0.182 |
| Molasses | 0.079 |
| Brewers grain | 0.004 |
| Others* | 0.000 |

*Others are usually classified as by-products or waste and only have transport emissions (waste fruit and vegetables).

## 3.5 Inventory-based greenhouse gas emissions

The inventory of GHG emissions covering $CH_4$ from enteric fermentation by cows, $CH_4$ and $N_2O$ from excreta deposited on pasture and from effluents, and carbon dioxide ($CO_2$) emissions from lime and urea application were based on IPCC and IPCC-NZ methodologies (Clark, 2001; IPCC, 2006; MfE, 2014).

### 3.5.1 N excreted

Calculation of the N excreted by animals used the NZ inventory methodology, which was based on principles in the OVERSEER® model (Wheeler et al., 2003). Dry matter intake was based on the various farm system models used, i.e. NZ inventory for DairyBase farms and FARMAX for the modelled dairy farms and the sheep and beef farms. This was then multiplied by the average NZ pasture N concentration (from a review of data for the NZ inventory) to calculate N intake. For all brought-in feed sources, N concentrations were based on the mean of samples submitted to NZ laboratories and reported by DairyNZ (2012) in a document entitled Facts and Figures. The N in milk and meat products (based on the NZ inventory) was subtracted from total N intake in order to calculate the amount of N excreted. The equation $N_{urine}$ (% of excretal N) = 11.0 x %N in diet + 31.8 was used to calculate the portion of the N excreted going to urine (Ledgard et al., 2003). In the IPCC-NZ inventory, 95% of the excreted N is assumed to be applied onto pastures during grazing and 5% to be processed as Farm Dairy Effluent (FDE) for dairy farms. For FDE management on farms, we assumed that all FDE was spread onto land on a daily basis.

### 3.5.2 Methane emissions

Methane emissions from enteric fermentation were calculated from the product of energy and dry matter intake by animals using the NZ Inventory model and the IPCC-NZ emission factors. Methane emissions due to waste management were calculated by multiplying faecal dry matter (1- digestibility of feed) by specific emission factors according to MfE (2014) for faecal dry matter deposited on pastures.

### 3.5.3 Nitrous oxide emissions

Direct $N_2O$ emissions were calculated by multiplying N inputs by specific NZ emission factors corresponding to the fraction emitted to the atmosphere as $N_2O$ (de Klein et al., 2001). In particular, the NZ emission factors for $N_2O$ from urine-N and dung-N on grazed pasture of 1% and 0.25% respectively (MfE, 2014) were used. Indirect $N_2O$ emissions were calculated using the IPCC-NZ N source and emission factors, which were developed from research and reviews carried out by NZ researchers.

### 3.5.4 $CO_2$ emissions from lime and urea application

Direct $CO_2$ emissions from lime and urea application to soils were calculated according to the default IPCC emission factors (IPCC, 2006). The $CO_2$ absorbed by plants was not taken into account since it was assumed to be in equilibrium with losses from the grazing cycle and plant respiration.

## 3.6 Carbon footprint calculation

The carbon footprint (equivalent to Global Warming Potential; GWP) for a 100 year time horizon ($GWP_{100}$) was calculated according to the recent widely-used IPCC (2006) reference in kg $CO_2$-equivalent (subsequently expressed as kg $CO_2$-eq), i.e. with multiplication factors of $CO_2$ 1, $N_2O$ 298, $CH_4$ 25 (however, note that these have recently been reviewed and modified). GWP corresponds to the impact of emissions on the heat radiation absorption of the atmosphere.

# 4. Results

## 4.1 DairyBase Farms

### 4.1.1 DairyBase base farms

The total annual GHG emissions per on-farm hectare were least from the low intensity farms and highest from the high intensity farms in each region (Table 6). The increase from high intensity farms relative to low intensity farms ranged from 22% in Otago/Southland to 40% in Bay of Plenty. However, the amount of product (milksolids and live-weight sold) generated per hectare increased with increased farm system intensity and therefore it is appropriate to also assess it on a per product unit basis.

**Table 11**. Summary of total annual GHG emissions (kg $CO_2$-eq) on a per-hectare (on-farm area only) basis, and the carbon footprint of milksolids (MS) and live-weight (LW) sold off farm for the 4 regions and 3 different intensity farms from DairyBase for 2010/11.

| Region | Intensity | Base farm | | |
|---|---|---|---|---|
| | | kg $CO_2$-eq /ha (on-farm) | kg $CO_2$-eq /kg MS | kg $CO_2$-eq /kg LW |
| Waikato | Low | 10,954 | 10.08 | 5.16 |
| | Med | 12,661 | 10.04 | 5.06 |
| | High | 14,570 | 10.32 | 5.46 |
| Bay of Plenty | Low | 11,613 | 10.29 | 5.42 |
| | Med | 13,464 | 10.62 | 5.79 |
| | High | 16,217 | 10.39 | 5.65 |
| Marlborough + Canterbury | Low | 13,680 | 9.82 | 4.62 |
| | Med | 16,299 | 9.78 | 4.79 |
| | High | 17,857 | 9.91 | 4.97 |
| Otago + Southland | Low | 11,366 | 10.05 | 5.02 |
| | Med | 12,850 | 9.32 | 4.83 |
| | High | 13,879 | 9.27 | 4.76 |

The carbon footprint (cradle-to-farm-gate) of milksolids (MS) for the surveyed regional high, medium and low DairyBase farms ranged from 9.3 to 10.6 kg $CO_2$-eq/kg MS (Table 11). There was some variation across the regions with the highest values for Bay of Plenty and lowest for Otago + Southland. However, the variation between the four regions was relatively small (9.3-10.6 kg $CO_2$-eq/kg MS). There were different trends within each region, with high intensity farms having a higher carbon footprint than the low intensity farms for all regions except Otago + Southland. The medium intensity Bay of Plenty farm had the highest carbon footprint whilst the Otago + Southland high intensity farm had the lowest (Table 11).

Dairy farms also produce live-weight which is sold for meat and the total GHG emissions were allocated between MS and LW. Over all farm systems there was little variation in the GHG allocation to milk at 81-86% (data not presented), with the remainder going to LW (i.e. 14-19%). Thus, the carbon footprint of the LW sold showed the same pattern within and between regions as that for MS, and varied between 4.6 and 5.8 kg $CO_2$-eq/kg LW (Table 11). In view of the dominance of MS as the main product and the same pattern in carbon footprint for MS and LW, the remainder of the results are presented for MS only.

The relative contributions from various on-farm (dairy platform) and off-farm (replacement animals, cows wintered off-farm, brought-in feeds) sources to the total carbon footprint of MS are given in Table 12. The average on-farm emissions constituted 83% of the total carbon footprint. Of the average off-farm emissions, the contribution from replacement animals to the total carbon footprint ranged from 8.8-13.3%, while the cows that were wintered off-farm in the South Island contributed 3.0-4.2%. The contribution from the feeds (production, indirect land use change and transport) brought-in to the dairy platform ranged from 1.6–10.0% of the total carbon footprint.

At the on-farm (dairy platform) level, the relative contribution of gases (in $CO_2$-equivalents) to the carbon footprint of MS were 67-71% from $CH_4$, 21-24% from $N_2O$, 8-10% from $CO_2$ (Table 13) and 0.01-0.3% from refrigerant loss (from milk-chilling vats; not included in Table 13). Of the $CH_4$ production, 99% was from enteric production from the animal rumen and 1% from dung and FDE. For $N_2O$, 49-65% was from animal excreta, 29-40% from N fertiliser, 4-13% from FDE and 0-2% from crop residues. For $CO_2$, the main sources were N fertiliser (59-72%), non-N fertilisers (8-18%), lime (2-8%), electricity (13-19%) and fuel use (2-3%). The large difference between $N_2O$ from animal excreta and FDE was mainly due to the use of feed pads in medium and high intensity farms.

**Table 12**. The contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the surveyed base regional farm groups for 2010/11.

| Region | Waikato | | | Bay of Plenty | | | Marlborough + Canterbury | | | Otago + Southland | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm system | Low | Med | High | Low | Med | High | Low | Med | High | Low | Med | High |
| On-farm: | | | | | | | | | | | | |
| Cow $CH_4$ | 5.84 | 5.67 | 5.48 | 5.95 | 5.88 | 5.71 | 5.61 | 5.36 | 5.41 | 5.60 | 5.16 | 5.22 |
| Cow excreta+FDE $N_2O$ | 1.34 | 1.24 | 1.12 | 1.37 | 1.35 | 1.26 | 1.24 | 1.14 | 1.13 | 1.17 | 1.06 | 1.05 |
| N fertiliser ($N_2O$ + $CO_2$) | 1.04 | 1.12 | 1.09 | 1.00 | 1.20 | 1.10 | 1.24 | 1.32 | 1.20 | 1.23 | 1.03 | 0.85 |
| Others[a] | 1.43 | 1.52 | 1.46 | 1.34 | 1.53 | 1.37 | 1.66 | 1.71 | 1.57 | 1.55 | 1.31 | 1.13 |
| Off-farm: | | | | | | | | | | | | |
| Replacements $CH_4$ | 0.81 | 0.74 | 0.89 | 0.97 | 1.01 | 0.95 | 0.62 | 0.71 | 0.73 | 0.76 | 0.78 | 0.78 |
| Repl. excreta $N_2O$ | 0.25 | 0.22 | 0.27 | 0.30 | 0.31 | 0.29 | 0.19 | 0.21 | 0.22 | 0.23 | 0.24 | 0.24 |
| Repl. Others | 0.07 | 0.07 | 0.08 | 0.09 | 0.09 | 0.09 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 |
| Cows wintered off | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.29 | 0.30 | 0.32 | 0.42 | 0.36 | 0.35 |
| Brought-in feeds[b] | 0.33 | 0.58 | 1.03 | 0.27 | 0.46 | 0.73 | 0.16 | 0.29 | 0.45 | 0.25 | 0.34 | 0.44 |
| TOTAL | 10.08 | 10.04 | 10.32 | 10.29 | 10.62 | 10.39 | 9.82 | 9.78 | 9.91 | 10.05 | 9.32 | 9.27 |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b] Includes all GHG emissions associated with the production and transportation of brought-in feeds

**Table 13**. Percentage contribution from various gases and sources to the on-farm (milking platform) carbon footprint of milksolids for the surveyed base regional farm groups for 2010/11.

| Region | Waikato | | | Bay of Plenty | | | Marlborough + Canterbury | | | Otago + Southland | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm system | Low | Med | High | Low | Med | High | Low | Med | High | Low | Med | High |
| Methane | 68% | 68% | 68% | 69% | 67% | 69% | 67% | 67% | 68% | 68% | 69% | 71% |
| Nitrous oxide | 23% | 23% | 22% | 23% | 24% | 23% | 24% | 24% | 23% | 23% | 22% | 21% |
| Carbon dioxide | 9% | 9% | 9% | 8% | 9% | 8% | 9% | 10% | 9% | 9% | 9% | 8% |
| Sources of methane: | | | | | | | | | | | | |
| Enteric rumen | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% | 99% |
| Dung and FDE | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 1% |
| Sources of nitrous oxide: | | | | | | | | | | | | |
| Excreta | 64% | 53% | 49% | 65% | 55% | 53% | 59% | 50% | 50% | 58% | 54% | 55% |
| N fertiliser | 31% | 34% | 35% | 29% | 34% | 33% | 37% | 40% | 38% | 38% | 36% | 32% |
| Crop residues | 1% | 2% | 2% | 1% | 0% | 0% | 0% | 0% | 0% | 1% | 1% | 0% |
| Farm dairy effluent | 4% | 11% | 13% | 4% | 11% | 13% | 4% | 9% | 12% | 4% | 10% | 13% |
| Sources of carbon dioxide: | | | | | | | | | | | | |
| N fertiliser | 59% | 61% | 61% | 61% | 65% | 67% | 69% | 72% | 70% | 67% | 66% | 61% |
| P,K,S fertilisers | 18% | 15% | 17% | 16% | 16% | 13% | 11% | 8% | 10% | 14% | 12% | 14% |
| Lime | 6% | 8% | 4% | 4% | 3% | 3% | 2% | 2% | 2% | 2% | 3% | 3% |
| Electricity | 15% | 14% | 14% | 15% | 13% | 15% | 15% | 15% | 16% | 14% | 17% | 19% |
| Fuel | 3% | 3% | 2% | 3% | 3% | 3% | 3% | 2% | 3% | 3% | 3% | 3% |

### 4.1.2 DairyBase Farms – Effect of change in feed type

The increase in amount of brought-in supplementary feed on high intensity farms relative to low intensity farms was 2.9-fold in North Island regions and approximately 1.7-fold in South Island regions (Table 5). Across all regions, the brought-in feed equated to 6-8%, 11-15% and 15-23% of total feed intake for the low, medium and high intensity farm categories (data not shown).

These supplementary feeds have GHG emissions associated with their production and use (due to significant inputs from fertilisers and fossil fuels), which means they have the potential to change a whole-farm system carbon footprint. Three scenarios were investigated whereby all the brought-in feed was attributed to maize silage, Brewers grain or PKE (Figure 1, Table 14).

The scenario examining the replacement of all brought-in feed sources with maize silage resulted in an average decrease in the GHG emissions per on-farm hectare across regions of 1.3%, where the carbon footprint ranged from 9.3 to 10.6 kg $CO_2$-eq/kg MS (Table 14). However, this effect was mainly concentrated in the North Island regions with an average decrease of 2.5%, whereas for the South Island farms only a 0.17% decrease occurred. This is a result of using maize silage to replace the high amount of PKE used on the North Island farms (Table 4), which has a higher carbon footprint than maize silage (Table 10).

The replacement of all brought-in feed with a very low carbon footprint supplementary feed like Brewers grain (Table 10) resulted in an average decrease across regions of 11.6% in GHG emissions per on-farm hectare. The carbon footprint of MS for the farms ranged from 7.9 to 9.6 kg $CO_2$-eq/kg MS (Table 14). The biggest decrease in the carbon footprint of MS occurred in the high intensity farms (12.2-23.7%), whilst the lowest decreases occurred in the low intensity farms (5.3-7.9%).

The replacement of all brought-in feed with PKE, which has one of the highest carbon footprints (Table 10), resulted in an increase in GHG emission per on-farm hectare across all farms, but particularly in the high intensity farms where an average 6% increase was calculated. The carbon footprint of MS for the farms with PKE as the only brought-in feed ranged from 9.7 to 11.0 kg $CO_2$-eq/kg MS (Table 14).

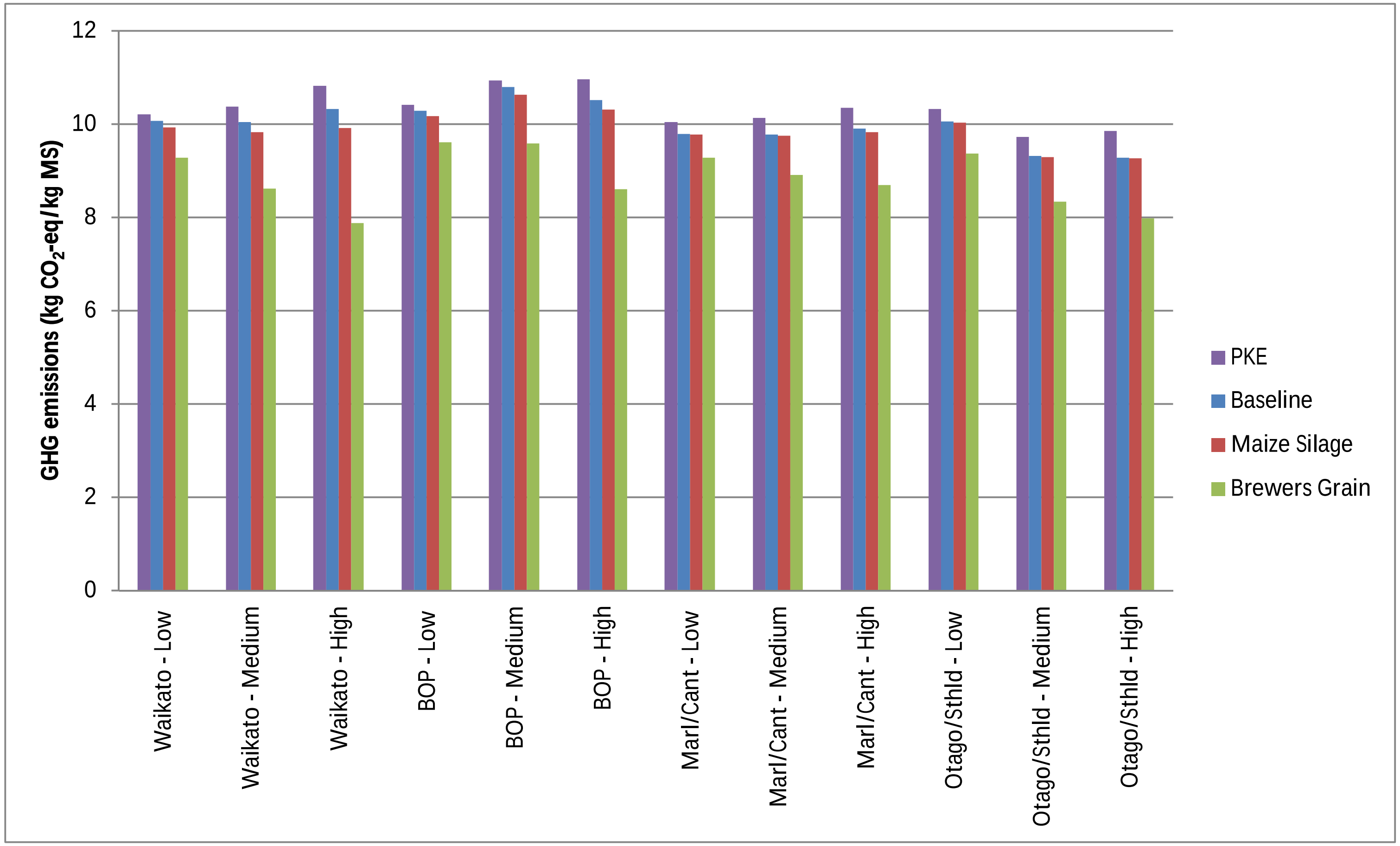


**Figure 1**. Summary of the effects of replacing all brought-in feed with either maize silage, Brewers grain or PKE, on the carbon footprint of milksolids (MS) for the 4 regions and 3 different intensities (low, medium or high) of DairyBase farms (year 2010/11).

**Table 14**. Total baseline annual GHG emissions (kg $CO_2$-eq) on a per-hectare (on-farm area only) basis, and the carbon footprint of milksolids (MS) and live-weight (LW) sold off farm for the 4 regions and 3 different intensity farms from the DairyBase farms for 2010/11. Results are compared with scenarios based on the substitution of all brought-in feed by maize silage, Brewers grain or PKE.

| | | Baseline | | | Maize silage | | | Brewers grain | | | PKE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | Intensity | kg $CO_2$-eq /ha (on-farm) | kg $CO_2$-eq /kg MS | kg $CO_2$-eq /kg LW | kg $CO_2$-eq /ha (on-farm) | kg $CO_2$-eq /kg MS | kg $CO_2$-eq /kg LW | kg $CO_2$-eq /ha (on-farm) | kg $CO_2$-eq /kg MS | GWP/kg LW | kg $CO_2$-eq /ha (on-farm) | kg $CO_2$-eq /kg MS | kg $CO_2$-eq /kg LW |
| Waikato | Low | 10,954 | 10.08 | 5.16 | 10,787 | 9.92 | 5.08 | 10,094 | 9.28 | 4.75 | 11,102 | 10.21 | 5.23 |
| | Med | 12,661 | 10.04 | 5.06 | 12,395 | 9.83 | 4.95 | 10,873 | 8.62 | 4.34 | 13,081 | 10.37 | 5.22 |
| | High | 14,570 | 10.32 | 5.46 | 13,988 | 9.91 | 5.24 | 11,115 | 7.87 | 4.16 | 15,272 | 10.82 | 5.72 |
| Bay of Plenty | Low | 11,613 | 10.29 | 5.42 | 11,473 | 10.17 | 5.36 | 10,840 | 9.61 | 5.06 | 11,756 | 10.42 | 5.49 |
| | Med | 13,464 | 10.62 | 5.79 | 13,266 | 10.63 | 5.70 | 11,952 | 9.58 | 5.14 | 13,643 | 10.93 | 5.86 |
| | High | 16,217 | 10.39 | 5.65 | 15,921 | 10.32 | 5.55 | 13,284 | 8.61 | 4.63 | 16,914 | 10.96 | 5.89 |
| Marlborough + Canterbury | Low | 13,680 | 9.82 | 4.62 | 13,666 | 9.78 | 4.62 | 12,959 | 9.28 | 4.38 | 14,027 | 10.04 | 4.74 |
| | Med | 16,299 | 9.78 | 4.79 | 16,254 | 9.75 | 4.78 | 14,861 | 8.92 | 4.37 | 16,895 | 10.14 | 4.96 |
| | High | 17,857 | 9.91 | 4.97 | 17,712 | 9.82 | 4.93 | 15,677 | 8.69 | 4.37 | 18,656 | 10.35 | 5.20 |
| Otago + Southland | Low | 11,366 | 10.05 | 5.02 | 11,339 | 10.03 | 5.01 | 10,590 | 9.37 | 4.68 | 11,680 | 10.33 | 5.16 |
| | Med | 12,850 | 9.32 | 4.83 | 12,810 | 9.29 | 4.81 | 11,500 | 8.34 | 4.32 | 13,402 | 9.72 | 5.04 |
| | High | 13,879 | 9.27 | 4.76 | 13,875 | 9.27 | 4.76 | 11,935 | 7.98 | 4.09 | 14,750 | 9.86 | 5.06 |

## 4.2 Modelled Dairy Farms

### 4.2.1 Base farms

The total annual GHG emissions per on-farm hectare for the modelled dairy farms were least from the low intensity farms and highest from the high intensity farms for both intensification approaches (i.e. increased productivity per cow or increased stocking rate), representing increases of 24-32% (Table 15). This coincided with increases in MS/ha of 25-40% (Table 6). The carbon footprint of MS ranged from 9.5 to 10.4 kg $CO_2$-eq/kg MS and decreased with intensification based on cow productivity (i.e. increased MS/cow), but increased with intensification based on increased stocking rate while keeping MS/cow constant. The carbon footprint of LW sold varied between 4.8 and 5.4 kg $CO_2$-eq/kg LW and followed the same pattern with intensification method as that for the carbon footprint of MS. The allocation value for the low intensity scenario based on cow productivity was 84% for MS relative to 16% for LW, while for all other scenarios it was 87-88% for MS and 12-13% for LW (data not presented).

**Table 15**. Summary of total annual GHG emissions on a per-hectare (on-farm area only) basis, and the carbon footprint of milksolids (MS) and live-weight (LW) sold off farm for the base modelled Waikato dairy farms.

| Intensification method | Intensity | kg $CO_2$-eq/ha (on-farm) | kg $CO_2$-eq/kg MS | kg $CO_2$-eq/kg LW |
|---|---|---|---|---|
| Cow Productivity | Low | 10,217 | 10.38 | 5.37 |
| | Medium | 11,644 | 9.70 | 4.85 |
| | High | 12,712 | 9.67 | 4.79 |
| Cow numbers | Low | 10,052 | 9.53 | 4.77 |
| | Medium | 11,644 | 9.70 | 4.85 |
| | High | 13,247 | 9.99 | 5.01 |

The relative contributions from various on-farm (dairy platform) and off-farm (replacement animals, brought-in feeds) sources to the total carbon footprint of MS are given in Table 16. The average on-farm emissions constituted 82% of the total carbon footprint of MS. Of the average off-farm emissions, the contribution to the total carbon footprint of MS from replacement animals ranged from 10.2-12.2% and from brought-in feeds (production, indirect land use change and transport) ranged from 2.1–11.1%.

**Table 16**. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the base modelled dairy farms.

| | Cow Productivity | | | Cow Numbers | | |
|---|---|---|---|---|---|---|
| | Low | Medium | High | Low | Medium | High |
| On-farm: | | | | | | |
| Cow $CH_4$ | 5.81 | 5.47 | 5.36 | 5.44 | 5.47 | 5.48 |
| Cow excreta + FDE $N_2O$ | 1.38 | 1.17 | 1.07 | 1.28 | 1.17 | 1.12 |
| N fertiliser ($N_2O$ + $CO_2$) | 1.15 | 0.94 | 0.86 | 1.07 | 0.94 | 0.85 |
| Others[a] | 0.51 | 0.44 | 0.40 | 0.48 | 0.44 | 0.41 |
| Off-farm: | | | | | | |
| Replacements $CH_4$ | 0.91 | 0.76 | 0.71 | 0.76 | 0.76 | 0.75 |
| Repl. excreta $N_2O$ | 0.28 | 0.23 | 0.21 | 0.23 | 0.23 | 0.21 |
| Repl. Others | 0.08 | 0.07 | 0.06 | 0.07 | 0.07 | 0.07 |
| Brought-in feed[b] | 0.26 | 0.63 | 1.00 | 0.20 | 0.63 | 1.11 |
| TOTAL | **10.38** | **9.70** | **9.67** | **9.53** | **9.70** | **9.99** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

A breakdown of the different feeds consumed by cows in the scenarios is given in Table 17. It shows that the proportion of total ME intake by cows from supplementary feeds (including a small constant component from pasture silage made on-farm) increased from 6-7% in the low intensity farms to 25-26% in the high intensity farms. The brought-in feed was assumed to be based on maize silage and PKE. The FARMAX modelling resulted in a very small decrease in the predicted amount of pasture DM consumed by grazing cows with increasing farm intensity. Thus, the grazed pasture component of the diet decreased from 94% on the low intensity modelled farm to 73% on the high intensity modelled farm.

**Table 17**. Breakdown of the Dry Matter Intake (DMI) from various feed sources from the base modelled dairy farms, all expressed in kg per on-farm (i.e. milking platform) hectare.

| | Cow Productivity | | | Cow Numbers | | |
|---|---|---|---|---|---|---|
| | Low | Medium | High | Low | Medium | High |
| Total MJ ME supplied | 119283 | 136068 | 145422 | 119740 | 136068 | 150089 |
| Supplementary feed MJ ME | 8400 | 24355 | 37068 | 7129 | 24355 | 38513 |
| % of ME requirement from supplements | 7% | 18% | 25% | 6% | 18% | 26% |
| Kg DMI pasture silage (on farm) | 121 | 122 | 122 | 123 | 122 | 121 |
| Kg DMI maize silage (brought-in) | 398 | 1440 | 1871 | 309 | 1440 | 1667 |
| Kg DMI PKE (brought-in) | 274 | 729 | 1473 | 241 | 729 | 1800 |
| Total kg DMI from supplements | 793 | 2291 | 3466 | 673 | 2291 | 3588 |
| Kg DMI pasture (grazed) | 9698 | 9733 | 9436 | 9844 | 9733 | 9715 |
| Total kg DMI | 10490 | 12023 | 12902 | 10517 | 12023 | 13303 |
| Pasture silage % of total DMI | 1.2% | 1.0% | 0.9% | 1.2% | 1.0% | 0.9% |
| Maize silage % of total DMI | 3.8% | 12.0% | 14.5% | 2.9% | 12.0% | 12.5% |
| PKE % of total DMI | 2.6% | 6.1% | 11.4% | 2.3% | 6.1% | 13.5% |
| Pasture (grazed) % of total DMI | 92.4% | 80.9% | 73.1% | 93.6% | 80.9% | 73.0% |

### 4.2.2 Supplementation with different feeds

Two scenarios were investigated whereby all the brought-in feed was assumed to be from maize silage or Brewers grain. Changing all of the brought-in feed to maize silage in the modelled medium Waikato farm resulted in a 2.7% decrease in total GHG emissions, while replacing all brought-in feed with Brewers grain, resulted in an 8.8% decrease in total GHG emissions (Table 18). In the low or high intensity farms, the effect of a change to all Brewers grain decreased the carbon footprint of MS by 3 or 14%, respectively (Appendix A5-A8).

**Table 18**. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) using different brought-in supplementary feeds for the modelled medium Waikato farm.

| | Base | All maize silage | All Brewers grain |
|---|---|---|---|
| On-farm: | | | |
| Cow $CH_4$ | 5.47 | 5.48 | 5.26 |
| Cow excreta + FDE $N_2O$ | 1.17 | 1.14 | 1.15 |
| N fertiliser ($N_2O$ + $CO_2$) | 0.94 | 0.94 | 0.94 |
| Others[a] | 0.44 | 0.44 | 0.44 |
| Off-farm: | | | |
| Replacements $CH_4$ | 0.76 | 0.76 | 0.76 |
| Repl. excreta $N_2O$ | 0.23 | 0.23 | 0.23 |
| Repl. Others | 0.07 | 0.07 | 0.07 |
| Brought-in feeds[b] | 0.63 | 0.40 | 0.02 |
| **TOTAL** | **9.70** | **9.44** | **8.85** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

All maize silage supplementation resulted in a decrease in animal $N_2O$ and brought-in feed emissions, but resulted in a slight increase in the enteric $CH_4$ levels associated with on-farm cows (Table 18). All supplementation with Brewers grain resulted in a decrease in on-farm $CH_4$, $N_2O$ and a 97% reduction in emissions associated with the production of brought in feeds (Table 18). This is because Brewers grain is considered to be a by-product of the brewing process and has a very low allocation factor.

### 4.2.3 Effects of mitigation practices

A range of different mitigation practices were examined for their potential to decrease GHG emissions. Results are shown for the medium farm in Tables 19 and 20, while all other farm results are in Appendix A.

#### 4.2.3.1 Fixed 15% change

When a fixed 15% change option was used for the mitigations, it showed the largest reductions in the carbon footprint of MS of 12 and 5% for the increased FCE and increased MS/cow scenarios, respectively (Table 19). The percentage reductions were similar across the different modelled farm intensities (Appendix A1-A4). A 15% decrease in N fertiliser use decreased the carbon footprint of MS by 1.2%, while the effects of a 15% reduction in electricity use or cow replacement rate were negligible.

#### 4.2.3.2 Realistic level of change

When realistic levels of change in GHG mitigation practices were modelled, the largest reduction of 8% was associated with cessation of use of N fertiliser and replacing the reduced pasture growth with brought-in maize silage (Table 20). The next highest levels of carbon footprint reduction were 4, 3 and 2% for +DCD, brought-in feed all as maize silage, and 3% increase in FCE, respectively. A 28% reduction in electricity use decreased the carbon footprint of MS by only 0.3%.

There was no effect of an 18% decrease in cow replacement rate on the carbon footprint of milk. However, it did decrease total GHG emissions per hectare (unallocated) by 2%, but because less LW was sold for meat due to the lower replacement rate there is a decrease in the percentage allocation of total GHG emissions to LW and a higher proportion allocated to milk.

A combination of all mitigations, including DCD, resulted in an 18-19% decrease in the carbon footprint of MS (Table 20; Appendix A5-8). Excluding DCD from this combination reduced the change to a 15-17% decrease in the carbon footprint of MS.

**Table 19**. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the fixed 15% change in mitigation options on the modelled medium Waikato farm

| | Base | Decreasing replacement rate by 15% | Increasing FCE by 15% | Reduced electricity by 15% | Increase MS/cow by 15% | 15% reduction in N fertiliser |
|---|---|---|---|---|---|---|
| On-farm: | | | | | | |
| Cow $CH_4$ | 5.47 | 5.55 | 4.65 | 5.47 | 5.30 | 5.47 |
| Cow excreta+FDE $N_2O$ | 1.17 | 1.19 | 0.95 | 1.17 | 1.03 | 1.15 |
| N fertiliser ($N_2O$ + $CO_2$) | 0.94 | 0.95 | 0.94 | 0.94 | 0.83 | 0.80 |
| Others[a] | 0.44 | 0.44 | 0.44 | 0.42 | 0.40 | 0.44 |
| Off-farm: | | | | | | |
| Replacements $CH_4$ | 0.76 | 0.66 | 0.76 | 0.76 | 0.67 | 0.76 |
| Repl. excreta $N_2O$ | 0.23 | 0.20 | 0.23 | 0.23 | 0.20 | 0.23 |
| Repl. Others | 0.07 | 0.06 | 0.07 | 0.07 | 0.06 | 0.07 |
| Brought-in feeds[b] | 0.63 | 0.64 | 0.54 | 0.63 | 0.74 | 0.67 |
| **TOTAL** | **9.70** | **9.70** | **8.56** | **9.68** | **9.24** | **9.58** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

**Table 20**. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the realistic mitigations for the modelled medium Waikato farm.

| | Base | Decreasing replacement rate to18% | Increasing FCE by 3% | Reduced electricity by 28% | All maize silage | no N fertiliser | +DCD | All combinations (+DCD) | All combinations (-DCD) |
|---|---|---|---|---|---|---|---|---|---|
| On-farm: | | | | | | | | | |
| Cow $CH_4$ | 5.47 | 5.59 | 5.30 | 5.47 | 5.48 | 5.51 | 5.47 | 5.43 | 5.43 |
| Cow excreta+FDE $N_2O$ | 1.17 | 1.20 | 1.12 | 1.17 | 1.14 | 1.04 | 0.87 | 0.84 | 1.13 |
| N fertiliser ($N_2O$ + $CO_2$) | 0.94 | 0.96 | 0.94 | 0.94 | 0.94 | 0.00 | 0.88 | 0.00 | 0.00 |
| Others[a] | 0.44 | 0.45 | 0.44 | 0.40 | 0.44 | 0.44 | 0.44 | 0.40 | 0.40 |
| Off-farm: | | | | | | | | | |
| Replacements $CH_4$ | 0.76 | 0.62 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.62 | 0.62 |
| Repl. excreta $N_2O$ | 0.23 | 0.19 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.19 | 0.19 |
| Repl. Others | 0.07 | 0.05 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.05 | 0.05 |
| Brought-in feeds[b] | 0.63 | 0.65 | 0.62 | 0.63 | 0.40 | 0.87 | 0.63 | 0.40 | 0.40 |
| **TOTAL** | **9.70** | **9.70** | **9.47** | **9.67** | **9.44** | **8.92** | **9.34** | **7.93** | **8.21** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

### 4.2.4 Scenario analysis: Effects of measured emission factors for maize silage

The effect of using measured $N_2O$ or enteric $CH_4$ emissions were assessed relative to the standard NZ GHG Inventory emission factors for a maize silage crop using the modelled dairy farms.

#### 4.2.4.1 Effect of measured $N_2O$ emissions from a maize silage crop

Use of the measured $N_2O$ emissions from the maize silage crop (from the Milestone 5 study; Wyatt et al., 2014) resulted in an 18% lower carbon footprint for maize silage brought-in from a contract grower relative to that using NZ GHG Inventory emission factors (see Table 10), i.e. from 0.188 to 0.154 kg $CO_2$-eq /kg DM.

Table 21 shows the difference between the NZ inventory and the measured $N_2O$ emissions from a maize silage crop using an N fertiliser rate of 252 kg N/ha and assuming the crop yield was 20 t DM /ha. While the measured $N_2O$ emissions accounted for any effects of cultivation practices which are not in the NZ inventory, the reason for the difference was mainly due to the direct $N_2O$ emissions from N fertiliser use. Wyatt et al. (2014) estimated the direct $N_2O$-N emission from N fertiliser at 0.1% of the fertiliser-N compared to the Inventory value of 1%. When the post maize harvest contribution (from crop residues and pasture re-establishment) was included, the total measured $N_2O$ emissions were 51% of that calculated using the NZ GHG Inventory.

**Table 21**. Differences in $N_2O$ emissions calculated using the NZ GHG Inventory or measured in the field study (Wyatt et al., 2014) for a 20 t DM/ha maize silage crop. All results are kg $N_2O$-N/ha.

| | NZ Inventory | Measured |
|---|---|---|
| Cultivated control | | 1.44 |
| $N_2O$-N from N fertiliser | 2.904 | 0.252 |
| Post maize harvest period | 0.366 | 0.137 |
| Total kg $N_2O$-N/ha | 3.270 | 1.694 |

If these measured emissions were applied to all the brought-in feed maize silage scenarios, then the carbon footprint of MS would decrease by an average of 0.3%, 0.1% and 1.2% for the low, medium and high intensity farms, respectively (Table 22). However, it should be noted that maize silage grown in the South Island (particularly Southland) would yield less than 20 t DM/ha. This would increase the kg $CO_2$-eq/kg DM. We have not attempted to account for this regional variation in our modelling.

**Table 22**. Comparison of using the measured or NZ GHG Inventory $N_2O$ emissions for maize silage on the carbon footprint of MS for the modelled dairy farm scenarios based on all brought-in feed being maize silage. Measured $N_2O$ emission data were from Wyatt et al. (2014)

| Farm system change | Intensity | Measured kg $CO_2$-eq/kg MS | Inventory kg $CO_2$-eq/kg MS |
|---|---|---|---|
| Cow Productivity | Low | 10.24 | 10.27 |
| | Medium | 9.37 | 9.45 |
| | High | 9.11 | 9.22 |
| Cow Numbers | Low | 9.42 | 9.44 |
| | Medium | 9.37 | 9.45 |
| | High | 9.33 | 9.44 |

#### 4.2.4.2 Effect of measured enteric methane emission factors for different levels of maize silage supplementation

The percentage of maize silage in the diet for the six modelled farms varied between 5 and 27% (Table 23). Measured $CH_4$ emission factors were calculated based on extrapolation from the equation in Jonker et al. (2015), $Y=18.2+0.975X-0.001X^2$. Using the % of maize silage in the diet (X), the measured enteric $CH_4$ emission factor was calculated for the level of maize silage in the diet and compared to the low intensity farm, which was assumed to be at the NZ GHG Inventory value. For example, applying this equation to the cow productivity farm system, the low $CH_4$ emission factor was calculated at 19.13 g $CH_4$/kg DMI and for the medium intensity farm, the $CH_4$ emission factor was calculated at 20.61 g $CH_4$/kg DMI (i.e. 1.08% increase in the emission factor). However, these emission factors from Jonker et al. (2015) were based on a sheep study and not using dairy cows. Therefore, it was assumed that the low intensity farm had the NZ inventory $CH_4$ emission factor for cows of 21.6 g $CH_4$/kg DMI and the % increase in emission factor for the medium intensity farm (1.08%) was added to give the $CH_4$ emission factor for the medium farm of 23.3 g $CH_4$/kg DMI (Table 23). Application of these measured $CH_4$ emission factors resulted in an increase in the carbon footprint of MS by 0.75% for the medium intensity farms and 2% for the high intensity farms compared to using the NZ inventory results.

**Table 23**. Measured enteric methane ($CH_4$) emission factors based on different levels of maize silage supplementation for sheep from the study of Jonker et al. (2015), applied to dairy cows in the modelled farm systems where the sole supplementary feed was maize silage. Results are given for the carbon footprint of milksolids in kg $CO_2$-eq/kg MS.

| Farm system | Intensity | Maize silage (as % of diet) | Measured Emission Factor[a] (g $CH_4$/kg DMI) | Measured kg $CO_2$-eq/kg MS | NZ inventory kg $CO_2$-eq /kg MS |
|---|---|---|---|---|---|
| Cow Productivity | Low | 6.5 | 21.6 | 10.27 | 10.27 |
| | Medium | 18.3 | 23.3 | 9.52 | 9.45 |
| | High | 26.3 | 24.2 | 9.39 | 9.22 |
| Cow Numbers | Low | 5.3 | 21.6 | 9.44 | 9.44 |
| | Medium | 18.3 | 23.5 | 9.53 | 9.45 |
| | High | 26.5 | 24. 5 | 9.63 | 9.44 |

[a]Adjusted for dairy cows by setting the Emission Factor for the Low intensity system as the standard value from the NZ GHG Inventory

#### 4.2.4.3 Combination of measured $N_2O$ and enteric methane emissions for different levels of maize silage supplementation

Table 24 shows the results when the combination of the measured $N_2O$ and the measured enteric $CH_4$ emission factors was applied to the six modelled dairy farms. The only change to the low intensity farms was the decrease in brought-in feed emissions due to the decreased $N_2O$ emissions associated with the production of the maize silage crop. The medium intensity farms stay relatively constant, with the decrease in brought-in feed emissions being balanced by the increase in enteric $CH_4$ emissions. The high intensity farms show an increase in total emissions compared to the NZ inventory method due to the extra high emissions generated from the measured enteric $CH_4$ factors being more than the decrease in $N_2O$ emissions from the brought-in feeds (Table 24).

**Table 24**. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for modelled dairy farms comparing the measured $N_2O$ emissions and enteric $CH_4$ emission factors from a maize silage crop to the NZ GHG inventory calculations (where NZI=New Zealand GHG Inventory and M=Measured).

| | Cow Productivity | | | | | | Cow Numbers | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low (M) | Low (NZI) | Med (M) | Med (NZI) | High (M) | High (NZI) | Low (M) | Low (NZI) | Med (M) | Med (NZI) | High (M) | High (NZI) |
| On-farm: | | | | | | | | | | | | |
| Cow $CH_4$ | 5.82 | 5.82 | 5.55 | 5.48 | 5.55 | 5.38 | 5.45 | 5.45 | 5.56 | 5.48 | 5.70 | 5.51 |
| Cow excreta + FDE $N_2O$ | 1.37 | 1.37 | 1.14 | 1.14 | 1.02 | 1.02 | 1.27 | 1.27 | 1.14 | 1.14 | 1.05 | 1.05 |
| N fertiliser ($N_2O$ + $CO_2$) | 1.15 | 1.15 | 0.94 | 0.94 | 0.86 | 0.86 | 1.07 | 1.07 | 0.94 | 0.94 | 0.85 | 0.85 |
| Others[a] | 0.51 | 0.51 | 0.44 | 0.44 | 0.40 | 0.40 | 0.48 | 0.48 | 0.44 | 0.44 | 0.41 | 0.41 |
| Off-farm: | | | | | | | | | | | | |
| Replacements $CH_4$ | 0.91 | 0.91 | 0.76 | 0.76 | 0.71 | 0.71 | 0.76 | 0.76 | 0.76 | 0.76 | 0.75 | 0.75 |
| Repl. excreta $N_2O$ | 0.28 | 0.28 | 0.23 | 0.23 | 0.21 | 0.21 | 0.23 | 0.23 | 0.23 | 0.23 | 0.21 | 0.21 |
| Repl. Others | 0.08 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Brought-in feeds[b] | 0.12 | 0.15 | 0.33 | 0.40 | 0.46 | 0.57 | 0.10 | 0.12 | 0.33 | 0.40 | 0.48 | 0.59 |
| TOTAL | 10.24 | 10.27 | 9.45 | 9.44 | 9.28 | 9.22 | 9.42 | 9.44 | 9.46 | 9.44 | 9.52 | 9.43 |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b] Includes all GHG emissions associated with the production and transportation of brought-in feeds

## 4.3 Sheep and Beef Farms

### 4.3.1 Baseline farms

The total GHG emissions per effective hectare for the Class 4 farm were 16% higher than that for the Class 6 farm. However, there was little difference between these farms in the carbon footprint per kg of product sold, i.e. cattle LW, lamb LW, mutton LW or greasy wool (Table 25).

**Table 25**. Summary of total annual GHG emissions on a per-hectare basis, carbon footprint of live-weight (LW) sold off farm for lamb and mutton, and carbon footprint of wool for the Class 4 and Class 6 Sheep and Beef farms (with no forage cropping). A protein mass allocation method was used to allocate emissions between sheep LW and wool.

| Farm Class | kg $CO_2$-eq/ha | kg $CO_2$-eq/kg $LW_{cattle}$ | kg $CO_2$-eq/kg $LW_{lamb}$ | kg $CO_2$-eq/kg $LW_{mutton}$ | kg $CO_2$-eq/kg wool |
|---|---|---|---|---|---|
| Class 4 | 3,739 | 13.32 | 6.63 | 6.62 | 24.51 |
| Class 6 | 3,229 | 13.37 | 6.78 | 6.78 | 25.09 |

### 4.3.2 Addition of summer and winter brassica crops

The inclusion of summer and/or winter brassica feed crops resulted in sheep feed intake remaining relatively constant for both Class 4 and Class 6 farms (Table 9). Beef feed intake was 6-11% higher for the winter and both crop scenarios for both Class 4 and Class 6 farms (Table 9). For lambs fed the summer rape crop, the feed intakes actually decreased in both farm classes due to the MJME of the rape crop being higher than pasture so that less dry matter intake was needed to get the same amount of energy intake (Table 9).

The addition of brassica crops in summer, winter or both seasons increased the total GHG emissions per effective hectare by 1%, 3% and 3% for Class 4 farms and by 2%, 2% and 4% for Class 6 farms, respectively (Table 26).

Integration of the summer crop decreased all product carbon footprints for Class 4 farms by 0.7-2.4%. However, the summer crop had a more varied effect on the Class 6 farm product carbon footprints, decreasing those for beef and mutton whilst increasing those for lamb and wool (Table 26).

Inclusion of the winter crop increased the carbon footprint of beef for both farm classes, whilst it had no effect on the Class 4 lamb, mutton and wool carbon footprints and decreased (marginally) the Class 6 lamb, mutton and wool carbon footprints (Table 26).

**Table 26**. Summary of total annual GHG emissions on a per-hectare basis, and the carbon footprint of live-weight (LW) sold off farm for lamb, beef and mutton and carbon footprint of wool for the Class 4 and Class 6 Sheep and Beef farms. A protein mass allocation method was used to allocate emissions between sheep LW and wool.

| Farm Class | On-farm crop | kg $CO_2$-eq/ha | kg $CO_2$-eq/kg $LW_{beef}$ | kg $CO_2$-eq/kg $LW_{lamb}$ | kg $CO_2$-eq/kg $LW_{mutton}$ | kg $CO_2$-eq/kg wool |
|---|---|---|---|---|---|---|
| Class 4 | none | 3,739 | 13.32 | 6.63 | 6.62 | 24.51 |
| | Summer[a] | 3,762 (0.6%) | 13.20 (-0.9%) | 6.58 (-0.7%) | 6.46 (-2.4%) | 24.34 (-0.7%) |
| | Winter[b] | 3,838 (2.7%) | 13.44 (0.9%) | 6.62 (0.0%) | 6.62 (0.0%) | 24.50 (0.0%) |
| | both | 3,860 (3.3%) | 13.33 (0.1%) | 6.53 (-1.4%) | 6.43 (-2.9%) | 24.17 (-1.4%) |
| Class 6 | none | 3,229 | 13.37 | 6.78 | 6.78 | 25.09 |
| | Summer[a] | 3,303 (2.3%) | 13.27 (-0.8%) | 6.84 (0.8%) | 6.60 (-2.6%) | 25.30 (0.8%) |
| | Winter[b] | 3,293 (2.0%) | 13.55 (1.3%) | 6.76 (-0.4%) | 6.76 (-0.4%) | 25.00 (-0.4%) |
| | both | 3,366 (4.2%) | 13.45 (0.6%) | 6.81 (0.5%) | 6.58 (-3.0%) | 25.21 (0.5%) |

[a] Fed to lambs only

[b] Fed to cattle only

The effect of inclusion of both crops in the farm systems on the carbon footprint per kg of product sold (for Class 4 and Class 6, respectively) was largest for mutton (down by 2.9% and 3.0%), followed by lamb (down by 1.4%, up by 0.1%), wool (down by 1.4%, up by 0.5%) and lastly beef (up by 0.1% and 0.6%) (Table 26).

Tables 27 and 28 show the contribution of gases to the carbon footprint of lamb LW sold for both the Class 4 and Class 6 farms. Inclusion of a summer brassica crop increased the $N_2O$ and $CO_2$ emissions due to the crop inputs but decreased the $CH_4$ emissions.

**Table 27**. Contribution of various on-farm sources to the total carbon footprint of lamb LW sold (kg $CO_2$-eq/kg LW sold) for a Class 4 Sheep and Beef farm with the addition of a summer and/or winter brassica crop.

| Farm system | No crops | Summer crop | Winter crop[a] | Both crops |
|---|---|---|---|---|
| Methane | 79% | 77% | 79% | 77% |
| Nitrous oxide | 16% | 17% | 16% | 17% |
| Carbon dioxide | 5% | 6% | 5% | 6% |
| Sources of methane: | | | | |
| Enteric rumen | 99% | 99% | 99% | 99% |
| Dung and FDE | 1% | 1% | 1% | 1% |
| Sources of nitrous oxide: | | | | |
| Excreta | 96% | 90% | 97% | 90% |
| N fertiliser | 4% | 4% | 3% | 4% |
| Crop residues | 0% | 6% | 0% | 6% |
| Sources of carbon dioxide: | | | | |
| Pasture fertiliser | 35% | 32% | 35% | 32% |
| Crop fertilisers | 0% | 4% | 0% | 4% |
| Lime | 25% | 23% | 25% | 22% |
| Electricity | 2% | 2% | 2% | 2% |
| Fuel | 38% | 39% | 38% | 40% |

[a] Note that the winter crop was fed to cattle only and therefore no winter crop related emissions were allocated to sheep

**Table 28**. Contribution of various on-farm sources to the total carbon footprint of lamb LW sold (kg $CO_2$-eq/kg LW sold) for a Class 6 Sheep and Beef farm with the addition of a summer and/or winter brassica crop.

| Farm system | No crops | Summer crop | Winter crop[a] | Both crops |
|---|---|---|---|---|
| Methane | 76% | 73% | 76% | 73% |
| Nitrous oxide | 16% | 17% | 16% | 17% |
| Carbon dioxide | 8% | 10% | 8% | 10% |
| Sources of methane: | | | | |
| Enteric rumen | 99% | 99% | 99% | 99% |
| Dung and FDE | 1% | 1% | 1% | 1% |
| Sources of nitrous oxide: | | | | |
| Excreta | 94% | 84% | 94% | 84% |
| N fertiliser | 6% | 12% | 6% | 12% |
| Crop residues | 0% | 4% | 0% | 4% |
| Sources of carbon dioxide: | | | | |
| Pasture fertiliser | 19% | 16% | 19% | 16% |
| Crop fertilisers | 0% | 16% | 0% | 16% |
| Lime | 38% | 31% | 38% | 31% |
| Electricity | 2% | 2% | 2% | 2% |
| Fuel | 41% | 35% | 41% | 35% |

[a] Note that the winter crop was fed to cattle only and therefore no winter crop related emissions were allocated to sheep

### 4.3.3 Scenario Analysis: Measured versus Inventory emission factors for use of a forage rape crop

#### 4.3.3.1 Effect of measured $N_2O$ emissions from a forage rape crop

The measured $N_2O$ emissions from a forage rape crop (Milestones 5 and 9; Luo et al. 2015a) were 78% higher than the calculated emissions using the NZ GHG Inventory methodology (Table 29). It should be noted that the measured $N_2O$ emissions were from a winter rape crop, when emissions are likely to be higher than during the production of a summer crop, due to drier soil conditions. Additionally, the field study was grazed by cattle which are likely to have higher excreta-N emissions than if grazed by lambs, and therefore the calculations in Table 29 did not include the emissions from cattle grazing (i.e. was based on cut forage), but used the calculated emissions for lambs grazing the crop in both scenarios.

When the measured $N_2O$ emissions were used in the Class 4 and 6 sheep and beef farm systems with a summer rape crop instead of the NZ GHG Inventory emissions for the crop, there was a 0.9-1.3% increase in total GHG emission per hectare (Table 30). The carbon footprint of lamb and wool increased by 1.8 and 1.2% for Class 4 and 6 farms, respectively. In contrast the mutton carbon footprint decreased by 1.6 and 0.9%, respectively.

**Table 29**. Comparison of $N_2O$ emissions based on the NZ GHG Inventory methodology and the measured $N_2O$ emissions (Luo et al., 2015a) for the establishment of a winter forage rape crop, grazing and subsequent pasture renewal.

| | NZ GHG Inventory kg $N_2O$-N/ha | Measured kg $N_2O$-N/ha |
|---|---|---|
| Forage rape establishment (cultivation, no fertiliser) | 0.51[a] | 0.45[b] |
| Nitrogen fertiliser | 0.11 | 0.13 |
| Forage rape harvest & new pasture establishment (no grazing) | 0.16[c] | 1.44 |
| Excreta return on grazing[d] | 0.81 | 0.81 |
| **Total kg $N_2O$-N/ha** | **1.59** | **2.83** |

[a] From residues (stubble plus roots) from pasture prior to crop establishment

[b] This would include emissions from previous pasture residues released during establishment and production of the crop

[c] From residues from the rape crop

[d] Calculated from expected excreta returns from sheep grazing based on assumed intake of the crop and using NZ GHG Inventory methodology

#### 4.3.3.2 Effect of changes in lamb enteric methane emission factor when fed forage rape

Two scenarios with reduced $CH_4$ emission factors from sheep grazing rape were used based on respiration chamber studies with sheep (from SLMACC-AGR30737) equating to reductions of 13% from two summer rape studies or 28% from the meta-analysis of all rape studies. When these factors were included in the Class 4 and 6 sheep and beef farm systems with a summer rape crop and applied only to the lambs that grazed the rape crop, they resulted in a decrease in total GHG emission per hectare of 0.4-0.6 and 0.8-1.3% compared to that where the NZ GHG Inventory emission factor was used (Table 30). The carbon footprint of lamb and wool decreased by 0.8 and 1.8% for the 13 and 28% $CH_4$ reduction factors for the Class 4 farm and by 0.5 and 1.0% for the Class 6 farm, respectively. Similarly, the mutton carbon footprint decreased by 0.7 and 1.7% for the Class 4 farm and by 0.5 and 1.0% for the Class 6 farm, respectively.

**Table 30**. Summary of total annual GHG emissions on a per-hectare basis, and the carbon footprint of live-weight (LW) sold off farm for lamb, beef and mutton and wool for the Class 4 and Class 6 Sheep and Beef farms with inclusion of a summer rape crop for feeding lambs, using a protein mass allocation method. NZ inventory calculations are compared to the measured $N_2O$ emissions for a forage brassica crop from Luo et al. (2015a) and the decreased methane emission factor ($CH_4$ EF) from consumption of rape by lambs of 13% or 28% from research in the SLMACC-AGR30737 project (Sun and Pacheco, *pers. comm.*).

| Farm Class | GHG methodology | kg $CO_2$-eq/ha | kg $CO_2$-eq/kg $LW_{beef}$ | kg $CO_2$-eq/kg $LW_{lamb}$ | kg $CO_2$-eq/kg $LW_{mutton}$ | kg $CO_2$-eq/kg wool |
|---|---|---|---|---|---|---|
| Class 4 | NZ Inventory | 3,762 | 13.20 | 6.58 | 6.46 | 24.34 |
| | Measured crop $N_2O$ emissions | 3,811 (1.3%) | 13.20 (0%) | 6.69 (1.8%) | 6.36 (-1.6%) | 24.76 (1.8%) |
| | Decreased $CH_4$ EF (by 13%) | 3,740 (-0.6%) | 13.20 (0%) | 6.53 (-0.8%) | 6.41 (-0.7%) | 24.14 (-0.8%) |
| | Decreased $CH_4$ EF (by 28%) | 3,714 (-1.3%) | 13.20 (0%) | 6.46 (-1.8%) | 6.35 (-1.7%) | 23.91 (-1.8%) |
| Class 6 | NZ Inventory | 3,303 | 13.27 | 6.84 | 6.60 | 25.30 |
| | Measured crop $N_2O$ emissions | 3,333 (0.9%) | 13.27 (0%) | 6.92 (1.2%) | 6.54 (-0.9%) | 25.60 (1.2%) |
| | Decreased $CH_4$ EF (by 13%) | 3,291 (-0.4%) | 13.27 (0%) | 6.81 (-0.5%) | 6.57 (-0.5%) | 25.18 (-0.5%) |
| | Decreased $CH_4$ EF (by 28%) | 3,277 (-0.8%) | 13.27 (0%) | 6.77 (-1.0%) | 6.53 (-1.0%) | 25.04 (-1.0%) |

# 5. Discussion

## 5.1 DairyBase Farms

Increased dairy intensification associated with moving from low to high intensity dairy farm systems, including through the use of increased brought-in supplementary feed, was associated with an increase in GHG emissions per hectare. However, when GHG emissions were expressed per kg milksolids (MS) there was no clear effect of farm intensity, except in Otago + Southland which had higher emissions/kg MS on low intensity farms. In practice, there were a range of management practices and farm inputs other than brought-in feed that varied with farm system intensity, such as increased MS/cow and increased N fertiliser rate with increased intensity (Table 4). Thus, it was not possible to relate GHG emissions/kg MS directly to level of brought-in feed across the surveyed farms in each farm intensity category. Therefore, in order to evaluate the specific effects of increased supplementation with brought-in feed, a modelling approach (using FARMAX) was used for Waikato farms.

## 5.2 Modelled FARMAX Dairy Farms

Increasing the intensity of a Waikato dairy farm system solely by changing the use of brought-in feed on-farm (i.e. from 650 kg DM/ha up to 4090 kg DM/ha) resulted in an increase in the carbon footprint of MS by up to 5% when the stocking rate was increased to utilise the extra feed (i.e. while keeping MS/cow constant). If the increase is too great then MS/cow will fall) However, when the increased brought-in feed was utilised through an increase in MS/cow, while keeping stocking rate constant, there was a decrease in carbon footprint of MS of up to 7%. In this study, the change was from 318 to 446 kg MS/cow, which is well within the feasible range within NZ, but there will be a limit in the extent to which MS/cow can be increased. In practice, intensification is generally associated with a combination of increased stocking rate and MS/cow (e.g. see Table 4). The corresponding effects on the carbon footprint of LW for meat were a 5% increase with increased stocking rate and an 11% decrease with decreased stocking rate. The larger relative reduction in carbon footprint of LW corresponded to a decrease in the % allocation of total GHG emissions to LW from 16% to 12% was because of the amount of LW sold remaining constant while the amount of milk sold increased.

This modelled dairy farm system analysis was based on using the medium intensity Waikato farm from the DairyBase farms and a simplification based on using only maize silage and PKE as the brought-in feeds (which in practice were the dominant feeds) and these were scaled up or down to achieve the high and low intensity categories respectively. In practice the final results for GHG emissions will be dependent on the particular type(s) of brought-in feed used.

In other NZ modelling studies, Beukes et al. (2010) used a Whole Farm Model and OVERSEER in a partial LCA to assess GHG emissions from an average dairy farm system and estimated that allocating 6% of the dairy farm to maize silage production increased GHG emissions/ha and per kg MS by 7%. However, they did not account for GHG emissions associated with the production and use of the maize silage. In a dairy farm system research study examining the effects of increasing production using maize silage, Luo et al. (2008) measured whole-farm $N_2O$ emissions and found that use of maize silage decreased $N_2O$ emissions per kg MS by 22%. The study by Luo et al. (2008) included measurements in an N-fertilised maize crop that produced emissions of 2.1 kg $N_2O$-N/ha compared to the 1.7 kg $N_2O$-N/ha measured in the field study (Milestone 5) reported in Table 21. Using LCA, Basset-Mens et al. (2009) evaluated dairy farmlet systems in Waikato with intensification using N fertiliser and maize silage, and estimated an increase in the carbon footprint/kg MS from N fertiliser use by 18%, and by 17% when maize silage was used with N fertiliser. Similarly, LCA studies in Denmark showed increased GHG emissions per hectare and per kg MS with dairy system intensification, and they attributed this largely to increased emissions from use of increased N fertiliser and brought-in feed.

## 5.3 Effects of feed type on total GHG emissions

Determination of the total GHG emissions (i.e. carbon footprint) for the production of a range of feeds showed variation between 0 kg $CO_2$-eq/kg DM for some fruit and vegetable wastes (since they are waste by-products), to 0.004 kg $CO_2$-eq/kg DM for Brewers grain (since most emissions are associated with the main product of beer and little to this feed co-product) and up to 0.506 kg $CO_2$-eq/kg DM for PKE (which includes emissions associated with land use change; Table 10). Sensitivity analysis using the DairyBase dairy farms from across the four main NZ regions (Table 14) revealed that changing the current mix of brought-in feeds to only Brewers grain would decrease the total GHG emissions/ha (and the carbon footprint of MS and LW) by an average of 12%, while use of only PKE would increase them by an average of 4% (bearing in mind that PKE is already a dominant feed type on current farms, particularly in the North Island, Table 5). A more realistic option of switching to all maize silage decreased the total GHG emissions/ha by an average of 1%, but again maize silage is already a major feed source in the North Island. When only the high intensity farms across regions were used in the sensitivity analysis, it changed the effects on the total GHG emissions/ha to -17%, +5% or -2% for all Brewers grain, PKE or maize silage, respectively.

## 5.4 Effects of use of GHG mitigation practices on dairy farms

The modelled dairy farm systems were used to evaluate the effects of a range of GHG mitigation practices. This analysis initially examined the effects of a 15% change in mitigation to understand the relative reduction potentials of different practices and revealed that the most sensitive mitigation option was increasing FCE (giving 11-12% decrease in total GHG emissions and carbon footprint of MS; Table 19, Appendix A1-A4). This is due to the dominant effects of FCE on feed intake, which determines animal $CH_4$ and excreta $N_2O$ emissions, and together these emissions make up 79-83% of the on-farm GHG emissions (Table 13) or 62-71% of the total GHG emissions (i.e. including all off-farm components; Table 12). The second most sensitive mitigation (giving a 4-5% decrease in carbon footprint of MS) was increasing milksolids production per cow and this also acts via increasing the proportion of feed eaten that is converted into milk (with relatively lower proportion to animal maintenance requirements).

Interestingly, there was no effect of reducing the cow replacement rate on the carbon footprint of MS. However, there was a 2% decrease in total GHG emissions and this was allocated to a 2% decrease in carbon footprint/kg LW. Mitigation practices such as decreasing the replacement rate or increasing the MS/cow have the effect of producing less meat from LW sold relative to the amount of milk sold. If such practices were to occur in a world with a fixed milk demand there would be less meat produced from the dairy sector and this deficit would then have to be met elsewhere, such as from increased meat from traditional beef farm systems. Potentially, that can have the perverse effect of increasing overall GHG emissions for the same total amount of milk and beef production, since traditional beef cattle systems have higher GHG emissions per kg meat than beef from cull dairy cows (Flysjö et al., 2012).

When the realistic mitigation options were evaluated, the largest decrease in total GHG emissions of 7-9% was due to nil use of N fertiliser and replacing the reduced pasture growth with brought-in maize silage (Table 20, Appendix A5-A8). The second largest reduction of 3-5% from a single mitigation was from the use of the nitrification inhibitor DCD. Use of the realistic level of increase in FCE of 3% based on NZ research (Macdonald et al., 2014) resulted in a 2% decrease in total GHG emissions. However, a combination of all of the mitigations examined corresponded to a decrease in carbon footprint of MS of 15-19% (or 15-17% when DCD is excluded, which is not currently used in NZ). Thus, there is significant potential to reduce total GHG emissions per kg milk and meat from the use of feeds with a low carbon footprint in combination with the use of other mitigation practices on farm.

Beukes et al. (2010) used a partial LCA modelling of a Waikato dairy farm system and calculated reduced GHG emissions per hectare and per kg MS of up to 30% from ceasing use of N fertiliser and major changes in herd efficiency (very low replacement rate and very high genetic merit cows with high MS/cow and lower cows/ha). Similarly, dairy LCA studies in Denmark identified reduced stocking rate and high herd efficiency as the most promising methods to reduce the carbon footprint of milk (Kristensen et al., 2011).

## 5.5 Effects of using measured GHG emissions relative to NZ Inventory emissions for dairy farms

This project included several experimental studies where $N_2O$ emissions were measured from a maize field crop and where enteric $CH_4$ emissions were measured from diets with different levels of maize silage or grain inclusion. The total measured $N_2O$ emissions from a maize crop were 51% of that calculated using the NZ GHG Inventory, with the main difference associated with the N fertiliser emission factor (0.1% compared to the Inventory value of 1%). It should be noted that the $N_2O$ emission factor for N fertiliser (EF1) has been reviewed downwards in some countries from the IPCC default of 1% (which is used in NZ) and is being currently reviewed in NZ. The effect of using these measured $N_2O$ emissions across the modelled dairy farm systems was a 0.3-1.2% decrease in the carbon footprint of MS. Conversely, the $CH_4$ study indicated a higher enteric $CH_4$ emission factor with maize silage inclusion that represented a 0.5-2% increase in carbon footprint of MS. The latter study was based on using sheep and not cattle, although broadly similar trends have been observed in cattle studies (Jonker and Pacheco, 2014) using mixed diets. However, there is a need to evaluate it(? The carbon footprint?) under practical conditions where silage is often used as a supplement (e.g. fed on a feed-pad) separate to the time grazing pasture, rather than as a mixed diet. In practice, these are single studies and more research is required before such changes should be considered and reviewed for updating the NZ GHG Inventory.

## 5.6 Sheep and Beef Farms

On the sheep and beef farms, a summer brassica crop was used to meet most of the feed requirements of lambs, while a winter crop was used to meet cattle winter requirements. This corresponded to relative farm areas under crops of 5-9% for the summer crop, and 1-2% for the winter crop (Table 9). The summer brassica crop increased FCE of lambs by 8-11% and LW sold by 4-6%. Similarly, the winter crop increased cattle LW sold by 8-11%. The associated effects on the total GHG emissions were small with increased per-hectare emissions of <4% for sheep or cattle. The summer crop had little effect on the carbon footprint of lamb at -1% to +1%, and of mutton at -2% to -3% (Table 26). Similarly, the winter crop had only a minor effect with the carbon footprint of beef increasing by about 1%.

In all cases, the brassica crops were estimated to increase animal productivity (e.g. heavier lambs sold or more cattle carried) and provide some reduction in enteric $CH_4$ and excreta $N_2O$ per kg LW sold (which dominated total GHG emissions, Tables 27 and 28). However, this was largely countered by the increased GHG emissions associated with planting of the crop and the associated emissions from the crop inputs (particularly fertiliser for the Class 6 farm).

Overall, the carbon footprint per kg LW sold for sheep meat was about one-half of that for beef, which was due in part to allocating some emissions to the wool co-product for sheep.

## 5.7 Effects of using measured GHG emissions relative to NZ Inventory emissions for sheep and beef farms

Field $N_2O$ emissions were measured in a rape crop in winter in Waikato and showed 78% higher emissions than estimated from the NZ GHG Inventory. This contrasts with results from the maize crop on a nearby site where measured emissions were half that of Inventory-based estimates (discussed in section 5.5). Use of these measured emissions from the rape crop in the sheep and beef farm system with a summer rape crop resulted in 1% higher GHG emissions/ha and a 1-2% higher carbon footprint of lamb compared to that using the Inventory methodology.

An allied SLMACC project (SLMACC-AGR30737) included studies where enteric $CH_4$ emissions were measured in several studies comparing rape and ryegrass diets and showed a lower emission factor for rape (by 13 or 28% for summer rape or summer and winter rape studies, respectively). Extrapolation of this higher reduction factor to the sheep and beef farm system with a summer rape crop resulted in 1% lower GHG emissions/ha and a 1-2% lower carbon footprint of lamb compared to that using the Inventory methodology. While the measured crop $N_2O$ data was from a single field study and more data is required before any Inventory factors should be reviewed, the rape enteric emission factors were based on up to 7 studies and therefore much more confidence can be placed on a reduced enteric $CH_4$ emission factor for rape. This is important since enteric $CH_4$ is the single largest contributor to total GHG emissions, but the lamb-only related enteric emissions were much smaller than those for the breeding sheep component of the farm system.

# 6. Conclusions and Recommendations

This study has shown that significant intensification of dairy farming has occurred in NZ over the last 50 years and is ongoing, associated with increased farm inputs particularly brought-in feeds. Evaluation of survey dairy farms (from DairyBase) across farm system levels showed that total GHG emissions per on-farm ha increased with intensification by up to 40%, but there was no clear change in the total GHG emissions per kg MS (i.e. the carbon footprint). There was a wide variation in the total GHG emissions associated with production of different feeds and the use of low carbon footprint feeds has the potential to reduce the average carbon footprint of MS from NZ farms by up to 12%. However, one sheep study indicated that incorporation of feeds such as maize silage in an animal's diet may increase the enteric $CH_4$ emission factor, thereby countering some of the other benefits in reducing the carbon footprint of MS. Integration of a range of realistic multiple GHG mitigation practices (e.g. increased cow productivity, decreased N fertiliser use, low-GHG brought-n feeds and decreased electricity use) on farms were estimated to be able to decrease the average carbon footprint of MS by up to 16%.

On sheep and beef farms, the integration of forage crops for specialist roles such as lamb finishing had little effect on total GHG emissions per hectare or per kg product. The benefits of increased FCE and reduced GHG emissions per kg lamb from use of summer rape were relatively small compared to the associated feed intake and emissions from the breeding ewes and replacements, as well as the GHG emissions associated with production of the forage crop. However, a lower enteric $CH_4$ emission factor from feeding a crop such as rape can be sufficient to reduce overall farm system GHG emissions from the integration of such crops.

More research (involving field experimentation and LCA modelling) across farm systems is required to define optimal practices to reduce the carbon footprint of milk, meat and fibre products for farm systems involving intensification in combination with a wider range of mitigations. It is also recommended that more field data is collected on GHG emissions associated with production of key forage crops, and on enteric $CH_4$ emissions by cows fed on different levels of important supplementary feeds such as maize silage.

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## Appendix A

Table A1. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the fixed mitigation results on the modelled increased cow productivity - low Waikato farm

| | Base | Decreasing replacement rate by 15% | Increasing FCE by 15% | Reduced electricity by 15% | Increase MS/cow by 15% | 15% reduction in N fert |
|---|---|---|---|---|---|---|
| On-farm: | | | | | | |
| Cow $CH_4$ | 5.81 | 5.92 | 4.94 | 5.81 | 5.65 | 5.83 |
| Cow excreta+FDE $N_2O$ | 1.38 | 1.41 | 1.13 | 1.38 | 1.23 | 1.36 |
| N fertiliser ($N_2O$ + $CO_2$) | 1.15 | 1.17 | 1.15 | 1.15 | 1.02 | 0.98 |
| Others[a] | 0.51 | 0.52 | 0.51 | 0.50 | 0.47 | 0.51 |
| Off-farm: | | | | | | |
| Replacements $CH_4$ | 0.91 | 0.80 | 0.91 | 0.91 | 0.81 | 0.91 |
| Repl. excreta $N_2O$ | 0.28 | 0.24 | 0.28 | 0.28 | 0.25 | 0.28 |
| Repl. Others | 0.08 | 0.07 | 0.08 | 0.08 | 0.07 | 0.08 |
| Brought-in feeds[b] | 0.26 | 0.26 | 0.22 | 0.26 | 0.41 | 0.30 |
| **TOTAL** | **10.38** | **10.41** | **9.22** | **10.36** | **9.91** | **10.25** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

Table A2. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the fixed mitigation results on the modelled increased cow productivity - high Waikato farm

| | Base | Decreasing replacement rate by 15% | Increasing FCE by 15% | Reduced electricity by 15% | Increase MS/cow by 15% | 15% reduction in N fert |
|---|---|---|---|---|---|---|
| On-farm: | | | | | | |
| Cow $CH_4$ | 5.36 | 5.43 | 4.55 | 5.36 | 5.20 | 5.36 |
| Cow excreta+FDE $N_2O$ | 1.07 | 1.09 | 0.87 | 1.07 | 0.95 | 1.06 |
| N fertiliser ($N_2O$ + $CO_2$) | 0.86 | 0.87 | 0.86 | 0.86 | 0.76 | 0.73 |
| Others[a] | 0.40 | 0.40 | 0.40 | 0.38 | 0.37 | 0.40 |
| Off-farm: | | | | | | |
| Replacements $CH_4$ | 0.71 | 0.62 | 0.71 | 0.71 | 0.63 | 0.71 |
| Repl. excreta $N_2O$ | 0.21 | 0.19 | 0.21 | 0.21 | 0.19 | 0.21 |
| Repl. Others | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| Brought-in feeds[b] | 1.00 | 1.01 | 0.85 | 1.00 | 1.07 | 1.03 |
| **TOTAL** | **9.67** | **9.67** | **8.51** | **9.65** | **9.22** | **9.57** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

Table A3. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the fixed mitigation results on the modelled increased cow numbers - low Waikato farm

| | Base | Decreasing replacement rate by 15% | Increasing FCE by 15% | Reduced electricity by 15% | Increase MS/cow by 15% | 15% reduction in N fert |
|---|---|---|---|---|---|---|
| On-farm: | | | | | | |
| Cow $CH_4$ | 5.44 | 5.52 | 4.62 | 5.44 | 5.30 | 5.45 |
| Cow excreta+FDE $N_2O$ | 1.28 | 1.31 | 1.04 | 1.28 | 1.14 | 1.26 |
| N fertiliser ($N_2O$ + $CO_2$) | 1.07 | 1.09 | 1.07 | 1.07 | 0.95 | 0.91 |
| Others[a] | 0.48 | 0.48 | 0.48 | 0.46 | 0.44 | 0.48 |
| Off-farm: | | | | | | |
| Replacements $CH_4$ | 0.76 | 0.67 | 0.76 | 0.76 | 0.68 | 0.76 |
| Repl. excreta $N_2O$ | 0.23 | 0.20 | 0.23 | 0.23 | 0.20 | 0.23 |
| Repl. Others | 0.07 | 0.06 | 0.07 | 0.07 | 0.06 | 0.07 |
| Brought-in feeds[b] | 0.20 | 0.21 | 0.17 | 0.20 | 0.36 | 0.25 |
| **TOTAL** | **9.53** | **9.54** | **8.45** | **9.52** | **9.13** | **9.41** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

Table A4. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the fixed mitigation results on the modelled increased cow numbers - high Waikato farm

| | Base | Decreasing replacement rate by 15% | Increasing FCE by 15% | Reduced electricity by 15% | Increase MS/cow by 15% | 15% reduction in N fert |
|---|---|---|---|---|---|---|
| On-farm: | | | | | | |
| Cow $CH_4$ | 5.48 | 5.56 | 4.65 | 5.48 | 5.31 | 5.48 |
| Cow excreta+FDE $N_2O$ | 1.12 | 1.14 | 0.90 | 1.12 | 0.99 | 1.10 |
| N fertiliser ($N_2O$ + $CO_2$) | 0.85 | 0.86 | 0.85 | 0.85 | 0.76 | 0.72 |
| Others[a] | 0.41 | 0.41 | 0.41 | 0.39 | 0.38 | 0.41 |
| Off-farm: | | | | | | |
| Replacements $CH_4$ | 0.75 | 0.66 | 0.75 | 0.75 | 0.67 | 0.75 |
| Repl. excreta $N_2O$ | 0.21 | 0.19 | 0.21 | 0.21 | 0.19 | 0.21 |
| Repl. Others | 0.07 | 0.06 | 0.07 | 0.07 | 0.06 | 0.07 |
| Brought-in feeds[b] | 1.11 | 1.12 | 0.94 | 1.11 | 1.16 | 1.14 |
| **TOTAL** | **9.99** | **10.01** | **8.79** | **9.97** | **9.51** | **9.88** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

Table A5. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the realistic mitigations for the modelled increased cow productivity - low Waikato farm

| | Base | Decreasing replacement rate to18% | Increasing FCE by 3% | Reduced electricity by 28% | All BIF maize silage | no N fert | DCD | All combinations (+DCD) | All combinations (-DCD) | All BIF Brewers grain |
|---|---|---|---|---|---|---|---|---|---|---|
| On-farm: | | | | | | | | | | |
| Cow $CH_4$ | 5.81 | 5.98 | 5.64 | 5.81 | 5.82 | 5.92 | 5.81 | 5.81 | 5.81 | 5.70 |
| Cow excreta+FDE $N_2O$ | 1.38 | 1.43 | 1.33 | 1.38 | 1.37 | 1.24 | 0.98 | 0.97 | 1.36 | 1.36 |
| N fertiliser ($N_2O$ + $CO_2$) | 1.15 | 1.18 | 1.15 | 1.15 | 1.15 | 0.00 | 1.08 | 0.00 | 0.00 | 1.15 |
| Others[a] | 0.51 | 0.53 | 0.51 | 0.48 | 0.51 | 0.51 | 0.51 | 0.47 | 0.47 | 0.51 |
| Off-farm: | | | | | | | | | | |
| Replacements $CH_4$ | 0.91 | 0.75 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.75 | 0.75 | 0.91 |
| Repl. excreta $N_2O$ | 0.28 | 0.23 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.23 | 0.23 | 0.28 |
| Repl. Others | 0.08 | 0.07 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.07 | 0.07 | 0.08 |
| Brought-in feeds (BIF)[b] | 0.26 | 0.27 | 0.25 | 0.26 | 0.15 | 0.55 | 0.26 | 0.15 | 0.15 | 0.01 |
| **TOTAL** | **10.38** | **10.42** | **10.15** | **10.35** | **10.27** | **9.48** | **9.91** | **8.44** | **8.84** | **10.00** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

Table A6. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the realistic mitigations for the modelled increased cow productivity - high Waikato farm

| | Base | Decreasing replacement rate to18% | Increasing FCE by 3% | Reduced electricity by 28% | All BIF maize silage | no N fert | DCD | All combinations (+DCD) | All combinations (-DCD) | All BIF Brewers grain |
|---|---|---|---|---|---|---|---|---|---|---|
| On-farm: | | | | | | | | | | |
| Cow $CH_4$ | 5.36 | 5.47 | 5.20 | 5.36 | 5.38 | 5.40 | 5.36 | 5.33 | 5.33 | 5.10 |
| Cow excreta+FDE $N_2O$ | 1.07 | 1.10 | 1.03 | 1.07 | 1.02 | 0.96 | 0.82 | 0.77 | 1.01 | 1.04 |
| N fertiliser ($N_2O$ + $CO_2$) | 0.86 | 0.88 | 0.86 | 0.86 | 0.86 | 0.00 | 0.81 | 0.00 | 0.00 | 0.86 |
| Others[a] | 0.40 | 0.41 | 0.40 | 0.37 | 0.40 | 0.40 | 0.40 | 0.36 | 0.36 | 0.40 |
| Off-farm: | | | | | | | | | | |
| Replacements $CH_4$ | 0.71 | 0.58 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.58 | 0.58 | 0.71 |
| Repl. excreta $N_2O$ | 0.21 | 0.17 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.17 | 0.17 | 0.21 |
| Repl. Others | 0.06 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.05 | 0.06 |
| Brought-in feeds (BIF)[b] | 1.00 | 1.02 | 0.97 | 1.00 | 0.57 | 1.22 | 1.00 | 0.56 | 0.56 | 0.02 |
| **TOTAL** | **9.67** | **9.67** | **9.44** | **9.64** | **9.22** | **8.97** | **9.36** | **7.83** | **8.06** | **8.40** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

Table A7. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the realistic mitigations for the modelled increased cow numbers - low Waikato farm

| | Base | Decreasing replacement rate to18% | Increasing FCE by 3% | Reduced electricity by 28% | All BIF maize silage | no N fert | DCD | All combinations (+DCD) | All combinations (-DCD) | All BIF Brewers grain |
|---|---|---|---|---|---|---|---|---|---|---|
| On-farm: | | | | | | | | | | |
| Cow $CH_4$ | 5.44 | 5.57 | 5.28 | 5.44 | 5.45 | 5.54 | 5.44 | 5.40 | 5.40 | 5.34 |
| Cow excreta+FDE $N_2O$ | 1.28 | 1.32 | 1.23 | 1.28 | 1.27 | 1.15 | 0.91 | 0.89 | 1.26 | 1.26 |
| N fertiliser ($N_2O$ + $CO_2$) | 1.07 | 1.10 | 1.07 | 1.07 | 1.07 | 0.00 | 1.00 | 0.00 | 0.00 | 1.07 |
| Others[a] | 0.48 | 0.49 | 0.48 | 0.45 | 0.48 | 0.48 | 0.48 | 0.44 | 0.44 | 0.48 |
| Off-farm: | | | | | | | | | | |
| Replacements $CH_4$ | 0.76 | 0.62 | 0.76 | 0.76 | 0.76 | 0.76 | 0.76 | 0.62 | 0.62 | 0.76 |
| Repl. excreta $N_2O$ | 0.23 | 0.19 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.19 | 0.19 | 0.23 |
| Repl. Others | 0.07 | 0.05 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.05 | 0.05 | 0.07 |
| Brought-in feeds (BIF)[b] | 0.20 | 0.21 | 0.20 | 0.20 | 0.12 | 0.48 | 0.20 | 0.12 | 0.12 | 0.00 |
| **TOTAL** | **9.53** | **9.54** | **9.32** | **9.50** | **9.44** | **8.70** | **9.10** | **7.71** | **8.08** | **9.22** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds

Table A8. Contribution of various on-farm and off-farm sources to the total carbon footprint of milksolids (kg $CO_2$-eq/kg MS) for the realistic mitigations for the modelled increased cow numbers - high Waikato farm

| | Base | Decreasing replacement rate to18% | Increasing FCE by 3% | Reduced electricity by 28% | All BIF maize silage | no N fert | DCD | All combinations (+DCD) | All combinations (-DCD) | All BIF Brewers grain |
|---|---|---|---|---|---|---|---|---|---|---|
| On-farm: | | | | | | | | | | |
| Cow $CH_4$ | 5.48 | 5.60 | 5.31 | 5.48 | 5.51 | 5.52 | 5.48 | 5.47 | 5.47 | 5.21 |
| Cow excreta+FDE $N_2O$ | 1.12 | 1.15 | 1.07 | 1.12 | 1.05 | 1.01 | 0.85 | 0.80 | 1.04 | 1.07 |
| N fertiliser ($N_2O$ + $CO_2$) | 0.85 | 0.87 | 0.85 | 0.85 | 0.85 | 0.00 | 0.80 | 0.00 | 0.00 | 0.85 |
| Others[a] | 0.41 | 0.42 | 0.41 | 0.37 | 0.41 | 0.41 | 0.41 | 0.37 | 0.37 | 0.41 |
| Off-farm: | | | | | | | | | | |
| Replacements $CH_4$ | 0.75 | 0.61 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.61 | 0.61 | 0.75 |
| Repl. excreta $N_2O$ | 0.21 | 0.17 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.17 | 0.17 | 0.21 |
| Repl. Others | 0.07 | 0.05 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.05 | 0.05 | 0.07 |
| Brought-in feeds (BIF)[b] | 1.11 | 1.13 | 1.07 | 1.11 | 0.59 | 1.32 | 1.11 | 0.58 | 0.58 | 0.02 |
| **TOTAL** | **9.99** | **10.01** | **9.75** | **9.96** | **9.43** | **9.29** | **9.67** | **8.05** | **8.30** | **8.60** |

[a]Others includes: non N fertilisers, electricity, pesticide, fuel on farm, refrigerant, pasture renewal, feeding calves
[b]Includes all GHG emissions associated with the production and transportation of brought-in feeds