RUMINANT CONTRIBUTIONS TO METHANE AND GLOBAL WARMING – A NEW ZEALAND PERSPECTIVE

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1. Introduction

An overview of the implications, research and policies concerning greenhouse gas (GHG) emissions from New Zealand agriculture is presented. Most emphasis is given to methane from ruminants and to opportunities for mitigation in forage based feeding systems. The opportunities for practical reductions in both methane and nitrous oxide emissions are indicated.

The underlying principles affecting levels of methane emissions from ruminants are examined and compared with values obtained from sheep and cattle fed fresh forages. Opportunities for mitigation are presented as short, medium and long-term strategies. Topics include the bases for animal variance, effects of management and diet as well as potential mitigation through rumen additives.

The risks associated with mitigating a single GHG in isolation from others are demonstrated using a model of $C0_2$ and CH_4 emissions from contrasting dairy systems and the importance of maintaining economic viability in addition to environmental improvement is central to all considerations. The information presented here is based primarily on New Zealand experience. Our mixture of sheep, dairy and beef cattle and deer are farmed outdoors all year on pastures varying in topography, fertility and quality with diverse climatic conditions. New Zealand has a substantial challenge to determine agricultural GHG inventory and to mitigate emissions.

2. Relevance Of Greenhouse Gases For New Zealand Producers

Methane accounts for 38% of New Zealand greenhouse gas emissions (based on Tier II estimations), which is a higher percentage than emissions in Australia (24%), Canada (13%), USA (9%), and most industrialised countries which emit only 5-10% of GHG as methane [1]. Nitrous oxide (N_2O) accounts for 17% (largely Tier 1 estimates) and $C0_2$ 44% of our national GHG inventory (Table 1). Total annual emissions are 72.4 million tonnes of $C0_2$ equivalents, or about 18 tonnes per human [2]. Countries with higher emissions (tonnes head^{-1} of population) include Australia (25.1) USA (23.6) and Canada (22.6).

In New Zealand 88% of CH_4 emissions are associated with animal agriculture, of which 98% is from digestion, primarily in the rumen. A single source of CH_4 provides an excellent focus for both measurement and mitigation, especially as energy losses account for about 10% of metabolisable energy (ME) intake of ruminants grazing grass dominant pasture. Mitigation should be investigated on the basis of improved performance and efficiency of feed utilisation as well as GHG inventory. Examples include, halving CH_4 production to provide sufficient energy for an additional 400 kg milk cow^{-1} lactation^{-1} (average annual milk production from pasture fed cows is 3700 kg cow^{-1}). Alternatively, if total emissions could be collected from an adult cow over one year, the energy would fuel a mid-size car for 1000 km!

New Zealand government had intended to raise a ruminant tax (dubbed the “fart tax” by farmers and media) to generate research revenue. Planned taxation (per annum) was about NZ $0.70 per cow and NZ $0.11 per sheep but this was abandoned in the face of farmer protest and current annual investment (NZ$4.7m) supports about 32 full time equivalent researchers. Approximately 55% of funds are directed towards inventory, 20% to fundamental and 25% to abatement research. A comprehensive report on Abatement of Agricultural non-$C0_2$ GHG Emissions in New Zealand [3], summarises all current research and identifies research priorities.

There is good and increasing collaboration between Australian and New Zealand researchers with annual conferences and reports receiving direct government support. This collaboration is essential, given the relatively small investment in GHG research in both countries. Although Australia is not a signatory to the Kyoto protocol there is a strong commitment by Federal and State governments to GHG reduction.

Promotion of benefits from lower GHG emissions in terms of productivity and environmental sustainability are receiving guarded support from farmers and the public. The concept of energy wastage provides an appropriate avenue for lobbying farmers and agricultural professionals to secure their support for funding. New Zealand farmers are sensitive to their role as guardians of their land and the need to maintain or improve their environment. Successful mitigation (abatement) will require a mixture of consultation, education and awareness as well as research if it is to be successful in the longer term. Ironically, the threat of an emission ("fart") tax has contributed awareness, although it was of little benefit for research funding.

3. New Zealand GHG Inventory

3.1 Methane

New Zealand agricultural production is not subsidized and follows market demands, with significant reductions in sheep numbers over the past 20 years and concomitant increases in dairy cattle and deer. The census data (undertaken every five years) is crucial to the Tier 2 method for estimating CH_4 production, from livestock numbers, feed requirements and estimated feed intakes. This Tier 2 inventory calculation is based on monthly measurements of animal requirements and feed dry matter (DM) intakes [2, 4]. Briefly, the ruminant population is defined in terms of dairy cattle, beef cattle, sheep and deer (numbers of goats, horses and swine are very low (Table 2)). Each group is subdivided into categories based on farming systems, with monthly adjustment of numbers to account for births, deaths and transfer between age groups. Productivity and performance data required to estimate feed intakes, include average liveweights of all categories, milk yields and composition from dairy cows, growth rates of all categories and wool production from ewes and lambs. The ME content of diets consumed are measured and the DM intake determined from ME requirements for each population, using CSIRO algorithms [5].

These data form the basis of the Tier ll inventory, with current emissions (g CH_4 kg^{-1} DM intake) being 21.6 for adult dairy cattle, 20.9 for adult sheep and 16.8 for sheep aged less than one year grazing pasture (6.5, 6.3 and 5.1% of the gross energy (GE) intakes). The accuracy of methane emissions is given as $\underline{+}$ 50%, with a coefficient of variation of 23% [2]. The census data are accurate but concerns remain over the accuracy of predicted DM intakes and CH_4 emission $unit^{-1}$ DM intake (DMI).

Manure CH_4 emissions are low and are based on calculation of total animal manure production. Annual emissions from manure are calculated to be about 0.9 kg for cattle, 0.18 kg for sheep and 0.37 kg for deer [2].

3.2 Nitrous Oxides

Pastoral agriculture is the source of most N_2O in New Zealand. Emission estimates have been revised [6] on the basis of the Inter Governmental Panel on Climate Change [7] and use default values of 0.0125 kg N_2O-N kg^{-1} N for N_2O from all origins (Tier I). Emissions are derived primarily from N in animal excreta (about 53% of total) and nitrogenous fertilizers (10%) as well as other direct and indirect (leaching, run-off, volatilisation) emissions. Current research suggests N_2O-N losses kg^{-1} N of 0.007 and 0.003 are appropriate for dung and urine respectively [8], which is substantially lower than values used in calculations of inventory. All sheep, deer, beef and most dairy cattle waste is deposited on pasture.

4. Defining Mitigation

Methane emissions can be expressed in several ways:

- Gross emissions, which have significant meaning for inventory but little indication of the animals' performance or physiological status. Low emissions may be due to low performance and *vice versa*.

- Expressions as a function of feed intake, for example, DMI or digestible DMI. This expression enables comparisons between feeds, but high intakes by animals consuming good quality diets (with low CH_4 kg^{-1} DMI) may result in high gross emissions.

- Methane per unit of production. This appears to be a useful expression of “GHG efficiency”, especially from a systems perspective because total emissions can be judged on the basis of performance. This is a good procedure providing emissions are totalled over a cycle of events, e.g. growth of a lamb from conception to slaughter, or annual milk production from dairy cows. This procedure is easily abused, for example when expressing CH_4 $unit^{-1}$ milk production, because values will be low in early lactation when maintenance is a small proportion of energy intake (and the cow has lost weight) but high in late lactation as milk yield declines and the cow (and fetus) is gaining weight.

- Methane mitigation should be expressed in association with other GHG and economical scenarios. For example, feeding grains with forages will lower CH_4 yields kg^{-1} DMI and CH_4 kg^{-1} milk production but large $C0_2$ emissions are associated with soil organic matter losses (from cultivation), use of fuel, fertilisers, harvesting, drying and transport of grain. Furthermore, costly mitigation must not disadvantage producers in a competitive world economy.

Table 3 lists options for methane mitigation, with an indication of applicability, risk and a time-scale for commercial availability. Most consideration will be given to forages and feeding, constituent nutrients, animal management, variations among individuals and the importance of a whole system analysis. These options can be applied in the short term with a high level of acceptability.

5. Methane Mitigation

Opportunities for methane mitigation [3, 9-16] include short, medium and long-term strategies (Table 3). Mitigation must also be economical, sustainable, relatively inexpensive, persistent and high levels of methane production should not be viewed as an inevitable consequence of ruminant digestion. It can be reduced by 90% through daily administration of halogenated methane analogues [13] with minor effects on performance [17]. However total elimination of methane production during digestion is unlikely to be sustainable, acceptable or economical. Although halogenated methane compounds are potentially carcinogenic, less toxic alternatives for methanogen inhibition may become available and achieve consumer acceptance for registration and industry use.

Successful mitigation strategies can either lower production of the hydrogen substrate used for methane synthesis and/or increase available sinks for hydrogen disposal. Rumen bacterial degradation of fibre to acetate will inevitably release hydrogen ions and sinks must be available to prevent microbial inhibition.

Dairy cattle and feedlot animals provide excellent opportunities for mitigation because of daily administration of methane suppressors, mitigators or hydrogen “sinks/users” (acetogens) are practical and potentially cost-effective in animals producing high value commodities. However the majority of ruminants are raised under extensive grazing and mitigation can only involve occasional intervention hence the attraction of vaccination against methanogens [18] or protozoa.

Animal management techniques to improve productivity may offer benefits to producers as well as lower methane emissions per unit of product (e.g. milk or liveweight gain) but options will depend on government policies. For example one solution is inclusion of grains and concentrates in ruminant diets to boost production, however a full system appraisal of grain production, considering fertilizer, cultivation, fuel and other energy inputs and consequent emissions of CH_4, N_20 and especially $C0_2$ shows very high net GHG emissions per unit of ruminant production, compared to production from ruminants grazing pasture [19]. Any consideration of methane abatement should consider other GHG costs, economics and environmental consequences of change.

6. Relationship Between Diet Composition And Methanogenesis

The analysis of methane data by Blaxter and Clapperton [9] has served as reference for effects of intake, digestibility, feed-type and animal species on CH_4 emissions unit^{-1} feed intake. These data appear to be based on dried feeds but relationships between methane (as a percentage of GE) and digestible energy (DE) content or level of intake, were not consistent across dietary types. For example, there was no relationship between feed quality (DE content) and energy loss to methane for concentrate-roughage mixtures fed at maintenance, despite a significant correlation for dried roughages. These details appear to have been overlooked by some researchers.

A more recent analysis [20] failed to demonstrate any relationship ($r^2 = 0.052$) between observed GE loss to CH_4 (range 2.5 – 11.5%) and DE of the diet (range 50 – 87% of GE). These authors also showed a very poor relationship ($r^2 = 0.23$) between the

Blaxter & Clapperton [9] predictions of CH_4 losses from beef cattle fed a diverse range of diets and actual values.

An alternative equation derived from trials with dairy cows fed mixed rations [21], based on intakes of hemicellulose, cellulose and non-fibre carbohydrate (NFC) enabled 67% of the variance in predicted methane production to be explained:

$$CH_4 \text{ (MJ day}^{-1}\text{)} = 3.406 + 0.510 \text{ (NFC)} + 1.736 \text{ (hemicellulose)} + 2.648 \text{ (cellulose)}$$

where, NFC (DM less fibre, crude protein (CP), ash and lipid), hemicellulose and cellulose are daily intakes (kg).

The prediction was improved by using digestible NFC, hemicellulose and cellulose intakes, explaining 74% of the variance, but measurements of digestibility are not always available.

These authors [21] concluded that methane production by adult cattle at maintenance could be predicted from dry matter or total digestible carbohydrate intake, but accurate prediction at higher intakes, typical of lactating cows requires the type of dietary carbohydrate to be determined. The intercept of equations based on fibre and digestible fibre did not pass through zero, which emphasises the empirical nature of the relationship and precludes expression on the basis of GE intake.

Complex equations developed for lactating dairy cows [22] did not improve predictions over those based on carbohydrate fractions [21] and Wilkerson et al. [23] concluded that estimates based on cellulose, hemicellulose and NFC provided the highest correlation with actual methane emissions, and had the lowest errors. Use of either intakes or digestible intakes of carbohydrate fractions provided similar levels of accuracy for predicting energy loss to CH_4.

Prediction of emissions from animals fed contrasting diets are complicated by differences among individuals (e.g. 24-26; Figure 1). There is also some evidence that increasing the proportion of concentrates in a diet will increase the variation between individuals [9,14, 27].

7. Methane Emissions From Ruminants Fed Fresh Forages

7.1 New Zealand measurements

New Zealand research has focussed on measurement of methane emissions from sheep and cattle fed fresh forage diets (usually perennial ryegrass dominant pasture) throughout the season and with animals differing in age and physiological status. Four data sets have been analysed using multiple regression to define relationships among treatment means (CH_4 kg^{-1} DMI) and linear combinations of dietary components (soluble sugars, NFC, CP, ash, lipid, condensed tannin (CT), neutral detergent fibre (NDF), acid detergent fibre (ADF), hemicellulose (H) and cellulose (C)). Analyses have been undertaken for sheep fed ryegrass based pasture (15 data sets), sheep fed legumes and herbs alone or in mixtures (12 data sets), lactating Friesian cows fed pasture (12 data sets) and lactating Friesian cows fed a range of diets including pasture (n=22). Perennial ryegrass feeding with sheep included *ad libitum* grazing [24, 25, 28, 29] and indoor feeding [30, 31] with forage quality ranging from immature to mature (CP 29 – 11%, NDF 36 – 51%). Methane emissions ranged from 13 – 26 g kg^{-1} DMI (Table 4; 3.8

– 7.6% of GE). Correlation coefficients (r^2) between CH_4 kg^{-1} DMI and NFC, NDF and ADF concentrations were 0.47, 0.28 and 0.58 respectively. Multiple regression using the criteria developed by Moe & Tyrrell [21] for cattle showed only 51% of the variance in methane yield was explained by NFC, hemicellulose (H) and cellulose (C) concentrations in the DM:

$$CH_4 \text{ (g kg}^{-1}\text{ DMI)} = 0.468 \text{ NFC} - 0.075 \text{ H} + 0.737 \text{ C} \quad r^2 = 0.51$$

A similar analysis was undertaken for legumes and herbs fed to sheep held indoors as single components or mixtures (Table 4). These forages usually yielded lower CH_4 emissions than ryegrass dominant pastures ranging from 12.0 g kg^{-1} DMI for white clover to 20.6 g kg^{-1} DMI for alfalfa. There were no significant correlations between methane production and feed components and the equation incorporating NFC, NDF and ADF accounted for 18% of the variance between diets (NS).

Analyses of methane production from cows were also compared with diet composition. Twelve data set were based on perennial ryegrass given as a sole diet, either grazing or cut and fed indoors and a further six data sets included mixtures of perennial ryegrass pasture fed with maize or pasture silage or fresh white clover. Two trials involved *Lotus corniculatus* and sulla (*Hedysarum coronarium*) fed as sole diets. Analyses of either the 12 ryegrass data sets or the 22 data sets including pasture, pasture with legumes or silage did not demonstrate any significant relationships between CH_4 emission kg^{-1} DMI for any component or combination of components in the diets.

In summary, legumes and herbs usually resulted in lower CH_4 emissions from rumen fermentation than ryegrass pastures, but the chemical composition of the feed eaten, including the concentration of condensed tannin, did not explain variations in CH_4 production. Chemical composition explained about 50% of the variance in emissions from sheep fed perennial ryegrass dominant pasture but did not explain the variance in methane production from cow trials, even though indoor measurements enable an accurate determination of feed eaten. These data suggest a poor understanding of methanogenesis in sheep and cattle fed fresh forages, exacerbated in some (but not all) situations by difficulty in determining intakes. Research needs to revisit the physiology of digestion to better explain the formation of methane during digestion.

7.2 Pasture Methane Measurements Outside New Zealand

Although the focus on fresh forages has been with New Zealand measurements, data are available from Australia, United Kingdom, Canada, the United States and elsewhere. Data from cattle research do little to clarify the confusion associated with our analyses. For example [32] reported CH_4 yields of 15.5 and 27.3 g CH_4 kg^{-1} DMI (4.7 and 8.4% of GE) from steers grazing alfalfa/brome grass pastures containing 50 and 54% NDF and 19.2 and 17.9% of CP the DM, respectively. Boadi & Wittenberg [33] reported CH_4 emissions of 6.0, 7.1 and 6.9% of gross energy intake (GEI) from beef and dairy heifers fed *ad libitum* legume and grass hays containing 41.8, 58.1 and 68.8% NDF in the DM, respectively. Methanogenesis was not related to feed quality. These values are higher than those reported by [34] for steers grazing alfalfa/meadow-brome grass pastures (4.1 – 5.2% of GEI) with widely differing composition (31 – 64%

NDF) but similar to a later trial with grazing cattle [35]. This range of values and apparently minimal relationship to fibre and other components of forage highlights the need to better understand processes affecting methanogenesis in ruminants grazing pasture.

8. Condensed Tannins And Methanogenesis

Waghorn et al. [30] reported a 16% depression in CH_4 emissions kg^{-1} DMI (from 13.8 to 11.5 g kg^{-1} DMI) due to the presence of CT in a diet of *Lotus pedunculatus* fed to sheep housed indoors. The sheep were fed at about 1.4 x maintenance to ensure minimum selection of plant components (leaf vs. stem) and given a twice-daily oral administration of polyethylene glycol (PEG) which preferentially binds to and inactivates CT. The PEG does not affect other aspects of digestion, so daily dosing effectively creates a CT-free lotus, and enables evaluation of CT *per se*. More recently [36] carried out a similar trial with cows fed *Lotus corniculatus*, containing a lower concentration of CT in the DM (2.62 g $100g^{-1}$) compared to 5.3% in the *L. pedunculatus* fed to sheep. This trial comprised four treatments, ryegrass/white clover without and with PEG, and *L. corniculatus* without and with PEG. Methane was 24.2, 24.7, 19.9 and 22.9 g kg^{-1} DMI for the respective treatments (Table 5). The CT in lotus reduced methane kg^{-1} DMI by 13% ($p<0.05$) and the cows fed lotus produced 32% less methane kg^{-1} milk solids (fat + protein) compared to those fed good quality ryegrass.

The difference in GE loss to CH_4 for lotus vs. ryegrass (Table 4) enables a calculation of energy potentially available for milk production. For cows consuming 15kg pasture DM day^{-1}, there would be 64g less CH_4 day^{-1} from the lotus diet, which if absorbed as VFA, could contribute 0.6 kg milk or 48 g milk solids day^{-1}.

The lower CH_4 losses attributed to CT are supported by lower CH_4 production unit^{-1} feed intake from cows fed sulla containing 2.7% CT in the DM vs. ryegrass pasture [37]. Emissions were 19.5 vs. 24.6 g CH_4 kg^{-1} DMI for the respective feeds (6.1 vs. 7.2% of GEI). Puchala et al. [38] have also reported low CH_4 emissions from goats fed Serecia lespedeza *(Lespedeza cuneata*) containing 6% CT in the DM, compared to grass dominant forage (6 vs. 14.1 g kg^{-1} DMI for the respective diets).

Mechanisms for CT inhibition of methanogenesis are largely hypothetical. Animal trials have shown that the CT in temperate legumes containing CT protect dietary protein from rumen degradation and can increase absorption of essential amino acids from the intestine, to give very good animal performance [39, 40]. CT inhibit microbial activity *in vitro* [41] and *in vivo* [42, 43] but proportions of VFA are unchanged, so there will be a similar yield of hydrogen with or without CT. Mechanisms by which polyphenolics affect a reduction in methanogenesis are speculative.

9. Animal Variation In Methanogenesis

Within groups of sheep or cattle fed fresh forages, about 10% have very high and 10% low methane emissions (per kg DMI) and the difference between the two groups is about 40%. For example Pinares-Patino et al., [25] showed mean methane production from four highest and four lowest producing sheep (selected from a random group of 20 animals) over a four month period was 3.75 vs. 5.15% of GEI. Earlier reports [24] found

86% of variation in methane production by sheep consuming 900-1700 g DM day^{-1} was due to animal variation and only 14% was attributable to diet. Ulyatt et al. [44] summarized data from six trials involving either sheep or cattle fed forages and showed that 71 – 95% of variation between days was attributable to animals even though intakes and composition of each diet were relatively constant.

The impact of genotype was highlighted in a trial involving New Zealand Friesian (NZHF) and Overseas Holstein (OSHF) cows fed either pasture or total mixed rations (TMR; Table 6). The OSHF genotypes produced significantly less CH_4 kg^{-1} DMI when fed both TMR and pasture diets at both 60 and 150 days of lactation [26]. Genotype differences had disappeared by day 240. Individual cow data, summarised in Figure 1, demonstrate a persistent high or low methanogenesis for some, but not all cows fed pasture. A similar variation between individuals was evident for TMR diets fed to cows. Animal differences in methane yield kg^{-1} DMI provide an ideal opportunity for selection of low methane producers, providing the trait is heritable. Pinares-Patino et al. [25] showed sheep with high CH_4 yields had larger rumen volumes, a slower particulate outflow rate, higher fibre digestibility and longer retention times than sheep with low CH_4 kg^{-1} DMI. Methane yield was best predicted as a function of particulate fractional outflow rate, organic matter intake (g kg LW$^{-0.75}$) and molar proportion of butyrate ($r^2 = 0.88$). Smuts et al. [45] suggested that rumen retention time was a heritable characteristic in sheep.

Differences between animals may be affected by salivation, feed communition (or eating rate) as well as rumen pool size, turnover and outflow. Animal effects on rumen microflora have been demonstrated by widely differing *in sacco* degradation rates and contrasting populations of cellulolytic bacteria [46, 47]. Variation in susceptibility to bloat appears affected by salivary proteins and bloat prone cattle produce bloat prone offspring [48, 49]. This capacity to affect their microflora offers potential for development of anti-methanogen or anti-protozoal vaccines.

10. Management To Mitigate Methane In Grazing Animals

Effective management to mitigate methane could be viewed in terms of animal productivity vs. animal methane emissions. Expression could be on an annual basis to avoid short term bias, for example cows grazing ryegrass pastures produced 11.7, 19.4 and 24.3 g CH_4 kg^{-1} milk at day 60, 150 and 240 of lactation [26]. The difference in emissions was largely due to a liveweight loss contributing energy to milk synthesis in early lactation and use of dietary energy to restore liveweight in late lactation. A similar scenario applies to sheep, with very high CH_4 emissions associated with wool growth (typically 10-12 g day^{-1}) in adult animals, but a lesser emission cost associated with growing lambs and reproduction.

Mitigation can be achieved by minimizing maintenance costs as a proportion of feed intake and maximizing the productive worth of livestock. High intakes of high producing animals dilute their maintenance cost and lower the methane emissions per unit of production. This will be best achieved by offering high quality diets to animals of high genetic merit and imposing good livestock and pasture management practices.

These effects are illustrated [3] for 30 kg lambs growing at 100, 200 and 300 g day^{-1} with methane emissions of 166, 115 and 98 g kg^{-1} liveweight gain respectively.

Comparative values for 450 kg grazing dairy cows producing 12, 20 or 24 kg milk day^{-1} were 17.2, 13.6 and 12.7 g CH_4 kg^{-1} milk. The methane emissions associated with production increased from 49 to 61 and 66% for the respective treatments.

Animal performance can be improved by selection for a high metabolic efficiency or by using rumen modifiers to alter products of digestion. Any factor able to improve feed conversion efficiency will lower CH_4 emissions unit^{-1} production. However farmers need to achieve a balance between increasing efficiency of feed utilisation and the efficiency of pasture utilisation.

11. Feed Additives

There is extensive literature concerning the impact of feed additives on methanogenesis [e.g. 12, 15, 50-52], so a brief summary of viable options is presented here. Feed additives may be hydrogen sinks, influence the rumen microflora to lower hydrogen production or influence the methanogenic archaea directly. Antibiotics, bacteriocins and probiotics seem to have short-term effectiveness [15] and all need to be evaluated *in vivo*. Consistent responses are essential for commercial application. Products must be acceptable to consumers and increased use of antibiotics is likely to be restricted by legislation.

11.1 Oils

Oils offer a practical approach to reducing methane in situations where animals can be given daily feed supplements, but excess oil is detrimental to fibre digestion and production. Oils may act as hydrogen sinks but medium chain length oils appear to act directly on methanogens and reduce numbers of ciliate protozoa [53]. This group reported a methane suppression of 10-26% with a variety of oils given to sheep, although these values were about half of their effect *in vitro*.

A 27% reduction in methane emission kg^{-1} DM intake has been demonstrated at this laboratory from lactating cows fed pasture and receiving a daily dose of 500 ml of sunflower/fish oil mixture (Woodward et al., unpublished). In contrast Johnson et al. [54] found no response to diets containing 2.3, 4.0 and 5.6% fat (cottonseed and canola) fed over an entire lactation.

11.2 Ionophors

Ionophors (e.g. monensin) improve the net feed efficiency of cattle fed total mixed rations by increasing the proportion of propionate: acetate from rumen fermentation so that daily gain is maintained but with 5-6% lower feed consumption [55]. However responses to monensin by cows fed forage diets are usually low, often variable and sometimes there are no performance gains in either feed utilization or milk production [56].

Monensin is available in a slow release (100 day) formulation and is used to reduce the risk of bloat in cattle and can lower methane emissions. Clark et al. [57] reported emissions of 158 and 179 g CH_4 day^{-1} from cows fed ryegrass based pasture with and without monensin treatment. Intakes were not affected by monensin and there was a significant reduction in methane kg^{-1} milksolids (milk fat + protein) for monensin (375 g

kg^{-1}) vs. control (420 g kg^{-1}; p= 0.05) cows. In that study the monensin treatment continued to lower methane emission after 60 days but persistence of methane suppression by ionophors is variable [14, 58, 59] and often not sustained [13].

11.3 Removing The Protozoa (Defaunation)

Hegarty [60] reviewed the impact of total or partial defaunation to improve ruminant performance and lower methane emissions. Improved performance has been associated with increased microbial flow to the intestine (protozoa consume bacteria) and increased proportions of propionate (protozoa produce acetate, butyrate as well as hydrogen gas). There is also a close (symbiotic) association between protozoa and methanogens, and defaunation is likely to lower methane emissions by 20 – 50%. Defaunation is somewhat risky, and is frequently incomplete, with a return of protozoa within weeks or months even if defaunated animals are kept separate from faunated livestock. However even partial defaunation is likely to achieve substantial benefits for CH_4 reduction and animal performance, especially when grazing diets with a medium-low protein content. Australian research is investigating an anti-protozoal vaccine [61] that would have wide applicability and minimal toxicity for ruminants.

12. Targeting Methanogens

Halogenated methane analogues can be very potent methane inhibitors, including chloralhydrate, chloroform, bromochloromethane and bromoethanesulphonic acid. CSIRO (Australia) have patented an anti-methanogen comprising bromochloromethane in a cyclodextrin matrix. In a trial with steers, Tomkins & Hunter [17] showed dose rates of 0, 0.15, 0.3 and 0.6 g 100 kg^{-1} liveweight reduced methane from 3.9 to 1.0, 0.6 and 0.3% GEI. Dry matter intakes for the respective treatments were 6.2, 7.4, 5.6 and 5.5 kg. In a separate trial average daily gain (1.5 kg day^{-1}) was unaffected by a twice daily dose of 0.3 g kg^{-1} DMI for 85 days of treatment.

In a review of data from sheep and cattle trials involving administration of halogenated methane compounds [62], intake reduction (0 -13%) was minor and did not always occur. In most *in vivo* studies feed conversion efficiency was increased by 0-11% and liveweight gain tended to be 5% lower, due to reduced intakes. They concluded that a partial inhibition of methanogenesis could have beneficial effects on animal production, especially if acetogens could utilise the hydrogen arising from fermentation.

The unique membrane lipids of methanogens and other *Archaea* contain glycerol linked to long chain isoprenoid alcohols. A key precursor of isoprenoid synthesis is mevalonate formed by reduction of hydroxymethyl glutaryl – S-CoA (HMG-CoA). The HMG-CoA reductase enzyme (which enables the formation of mevalonate) is a target of drugs used to lower cholesterol in humans and these compounds (lovastatin; mevinolin) are potentially able to inhibit growth of methenogenic archaea in the rumen [63]. Other bacteria do not contain HMG-CoA and should be unaffected by these inhibitors. These authors demonstrated an *in vitro* inhibition of *Methanobrevibacter* strains using HMG-CoA inhibitors without effecting a range of rumen cellulolytic and other bacteria. The concentration of inhibitor is equivalent to about 400 mg 100 kg^{-1} rumen content, but unlike halogenated methane analogues, lovastatin is prescribed to humans (i.e. safe) and it is relatively inexpensive.

Other specific targets for methanogens include phage and vaccines.

12.1 Vaccine

A vaccine developed from a three-methanogen mixture produced a 7.7% reduction (kg^{-1} DM) in methane emissions from sheep ($P = 0.051$) despite only one antigen being effective against the methanogenic species in the sheep. The vaccine [18] was much more effective than the seven methanogen mix tested previously and was able to increase saliva and plasma antibody titres by 4 – 9 fold over the seven methanogen mixture. Successful elevation of antibody titres in saliva, and a significant reduction in methane emissions offers real potential for a widespread application to ruminants in all environments. At present vaccines do not have sufficient efficacy for commercial use and funding has recently been curtailed.

Opportunities through rumen additives, defaunation and specific compounds targeting methanogens provide several routes for reducing methane production. However these agents have not addressed the inevitable production of hydrogen from fermentation of fibre. Ruminants are able to utilise fibre because of their microflora and hydrogen production is an unavoidable consequence. Excess hydrogen accumulation will inhibit microbial growth, but acetogens offer an opportunity for production of acetate as well as removing accumulated hydrogen. Acetogens are present in moderate concentrations in the digestive tract of horses, llamas and buffalo (10^4 – 10^5 ml^{-1}) but values for sheep and cattle have been very low [64]. Acetogens require a higher partial pressure of hydrogen to become active [11, 60] and could become important hydrogen users in the event of methanogen suppression.

13. Agronomy And Complementary Feeds

The commonly held view is that fibrous, low quality pastures yield a higher proportion of CH_4 GEI^{-1} than good quality, low fibre forages. This is probably true but other factors have contributed a great deal of variability, so that Johnson & Johnson [20] found no relationship between CH_4 and digestible energy (both % of GEI) for cattle ($r^2 = 0.05$) and results presented in this manuscript were unable to account for between trial variations in CH_4 production on the basis of diet composition.

These findings present a serious challenge to researchers attempting to create an inventory or account for effects of diet upon energy losses to methane. Good relationships between methane production and animal or forage factors (for example rumen and out flow rates) have been obtained within trials, [25]. Pinares-Patino et al., [65] also demonstrated consistent methane emissions $unit^{-1}$ digestible NDF intake (53 g kg^{-1}) from Charolais cattle grazing timothy (*Phleum pratense*) grass of widely different quality (4 – 31% CP in the DM).

At this laboratory we have investigated the effect of substituting ryegrass with increasing amounts (0 – 60%) of white clover, for dairy cows. White clover diets resulted in very low CH_4 emissions when fed to sheep (12.5 g kg^{-1} DMI; Table 4) but in this trial a 60% substitution reduced emissions by only 16% (21.7 to 18.1 g kg^{-1} DMI ($P = 0.004$)). In contrast, substitution of pasture with maize silage (to 38% of DMI) increased methane emissions by 16% (16.3 to 19.0 g kg^{-1} DMI ($P=0.14$)). Significant reductions in NDF content and increases in starch for the respective diets had minor effects on net methane production. Diet is able to effect methane production but greatest benefits may be from lowering CH_4 unit^{-1} product when high quality diets are fed.

14. Nitrous Oxide Emissions And Abatement

Nearly all N_20 emissions arise from agricultural soils in New Zealand [66] and 85% of these are grazed by livestock. Emissions of N_20 arise from both reduction of soil nitrates (denitrification) and also from oxidation of ammonium to nitrite and nitrate. The extent and type of processes are determined mainly by mineral N availability and aeration (or water logging) of soils [8].

The processes are:

Denitrification:

$$\underset{\text{nitrate}}{N0_3^-} \rightarrow \underset{\text{nitrite}}{N0_2^-} \rightarrow \underset{\text{nitric oxide}}{N0} \rightarrow \underset{\text{nitrous oxide}}{N_20} \rightarrow \underset{\text{nitrogen}}{N_2}$$

Nitrification:

$$\begin{tikzcd} NH_4^+ \arrow[r] & NH_20H \arrow[r] & [HN0] \arrow[r] & N0_2^- \arrow[r] \arrow[d] & N0_3^- \\ & & & N_20 & \end{tikzcd}$$

In general, the proportion of soil N released as N_20 vs. N_2 increases as nitrate concentration increases especially in saturated, anaerobic soil conditions. Mitigation is achieved by either reducing soil N availability (less inputs as fertiliser, urine, dung), limiting water saturation by provision of drainage and especially by minimizing treading damage (pugging) in wet conditions. Application of lime to raise soil pH can also lessen N_20 emissions. A brief overview of emissions, mitigation options and the extent to which emissions may be reduced [67] is presented with emphasis for grazing animals (Table 7).

14.1 Mitigation Options

Improved N fertilizer management can be achieved by application on the basis of requirement. Soil testing and skilled management will enable the correct amount of N fertiliser to be applied to best meet plant requirements and minimise wastage. Controlled release fertilizers and those containing nitrification inhibitors (e.g. dicyandiamide; [68]) can lessen losses and improve plant N utilization, especially with strategic placement beneath the surface, or on the basis of need using global positioning systems technology. These technologies will lower fertilizer use and improve profitability as well as reduce environmental pollution from N runoff to streams and waterways, volatilisation and N_20 emissions.

In confined animal systems, manure (feces and urine) management has important consequences for GHG emissions, but New Zealand management is through fertilizer and dietary manipulation because animals graze out doors year round. Apart from reducing stock numbers, viable options for limiting N_20 emissions include increasing productivity per animals, management to lessen pasture and soil damage and lowering dietary (and therefore waste) nitrogen concentrations. Plants containing condensed tannins alter digestion and repartition N from urine (with high N_20 emissions) toward feces.

Nutritional management offers good opportunities to mitigate N_20 especially in dairy farming where pasture supplementation (e.g. with maize silage) is becoming standard practice. Animal management to minimize pasture damage is also becoming an attractive option for farmers and this impacts upon N_20 emissions. All of these changes to traditional farming practice are driven by acceptable prices for farm commodities and a general desire for both cost effective agriculture and environmental sustainability by most farmers.

Cropping and irrigation play a small but increasingly significant role in New Zealand agriculture and good water management to avoid deficits and excess will minimize N_20 losses as well as make best use of irrigation water. Cultivars either requiring less N or making better use of applied N will minimize losses to N_20. However many forage species are dependent upon high levels of fertility (N, P, S, K) to achieve the performance claimed by breeders and marketers.

Nitrogen fixing forages (such as white clover) used to be the principal source of N for grasses in New Zealand pasture but the advent of relatively inexpensive urea has contributed to increased N_20 losses. Clovers remain an important component of pastures, but urea application in early spring provides a rapid and early grass growth to meet needs of dairy cows and of lambing ewes in some regions. The combination of N fixation and urea fertilizer has resulted in high concentrations of dietary N (often in excess of 4% of dietary DM) and a large amount is voided in urine and feces.

14.2 Animal Management And Feeding

A major aspect of N_20 research concerns measurement of N_20 emissions from a range of soil types, water contents and from dung and urine to better predict emission. Sagger et al. [69] emphasized the impact of uneven deposition of excreted N, with low emissions in dry periods and high values in winter. Dairy grazed pastures yielded about five times as much N_20 as those grazed by sheep. Sagger et al. [69] consider the IPCC [7] default methodology under-predict urinary losses from dairy pastures and over-predict losses from sheep urine. N_20 emissions have been defined for a range of soil types [8] and in association with drainage using sheep and cow urine [70]. They have demonstrated a range from 0.3 – 2.5% of N loss to N_2O for cow urine with lower values for sheep. Values for dung are half (or less) of those for urine.

These variations emphasise the difficulty in attaining an accurate, predictable and defensible inventory of N_20 from grazing animals. However, dietary manipulation does offer a viable option to lessen N_20. Typical spring diets for all ruminants contain 22-29% crude protein. This far exceeds optimal or desirable concentrations for ruminant nutrition, but extensive degradation of protein by rumen microflora causes a high loss of protein to ammonia, which is absorbed and excreted in the urine. Methods for lowering the protein (N) content of the diet, without inducing N limitations for performance, include use of forages containing lower N concentrations (e.g. maize silage) to be fed with pasture, selecting forage species with a slower rate of protein degradation (e.g. containing condensed tannins) or feeding forages with a higher proportion of non-structural carbohydrates (high sugar grasses). The caveat to all of these options is that the species must be competitive once sown, highly productive, disease resistant and persistent.

From a nitrogen viewpoint, maize grown for silage offers good advantages as a stock feed. Clark et al. [67] calculated that 1000 kg N fertilizer applied to a maize crop would produce about 100 tonne of DM. This represents a much more efficient N capture compared to the response from pasture to urea N application. When pasture is highly productive, the marginal response to N application is low and losses to leaching, volatilization and from animal waste is high. Maize silage can complement spring pasture for cows and reduce the amount of N deposited in urine by about 30% compared to a pasture diet. Use of N for maize silage production will reduce both fertilizer and urinary N inputs and outputs compared to an all-grass system. Cow performance will be maintained, but a whole systems analysis would indicate high $C0_2$ emissions associated with maize production.

Table 7 summarizes the impact of nutrition and other forms of intervention on N_20 emissions for dairy cattle. Impacts on sheep and beef industries are likely to be less, because farms are usually less fertile and have a hilly terrain, so fertilizer inputs will be lower and there is less likelihood of saturated soils having treading damage.

15. Whole Farm Systems

Concern about individual vs. all GHG emissions resulted in a partial life cycle analysis of emissions from a conventional New Zealand pasture based (with silage supplements) dairy farm and one in which total mixed rations were fed [19]. This analysis assumed typical dairy herd sizes (250 cows) but only estimated CH_4 and $C0_2$ emissions over an entire lactation. Inputs to the TMR [71] were based as far as possible on grains, silages and forages grown in New Zealand with appropriate use of herbicides, fuel, cultivation and fertiliser. Protein supplements (fishmeal, soy and cotton seed meals) were imported and calculations made for production costs with adjustments where crops yielded multiple products (e.g. cotton fibre as well as meal) to achieve a fair distribution of GHG costs across products [19]. Inputs to the pastoral system included costs of renovation (every 15 years) with a maize silage crop grown on cultivated pasture prior to re-establishment.

Milk production and cow data [71] were from the same animals used previously to measure methane emissions from both pasture (Table 6) and TMR [26]. Inputs and emissions for this model are summarised in Table 8.

Principal findings were a higher intake of cows fed TMR compared to pasture, a doubling of milk production and 58% increase in CH_4 emissions from cows fed the TMR ration. When expressed in terms of milk production, TMR yielded significantly less methane (19.5 g kg^{-1} milk) than pasture (24.6 g kg^{-1}) suggesting benefits for the grain based ration. However, this is a shortsighted appraisal because pastoral grazing is based on *in situ* harvesting by cows with minimal inputs to energy or carbon losses to cultivation.

When $C0_2$ emissions from soils, machinery, fuel for cultivation, harvesting, transport, processing and drying are accounted (Table 8) relative emissions are altered considerably. Carbon loss from soils was 3-4 tonnes ha^{-1} per annum [72,73]. Summation of total carbon and methane emissions, as $C0_2$ equivalents suggested losses of 0.84 kg kg^{-1} milk from conventional pastoral dairying compared to 1.51 kg kg^{-1} milk for TMR systems.

These data illustrate the dangers of a narrow focus for GHG calculations. Whilst it could be argued that $C0_2$ emission do not apply to agricultural inventory, $C0_2$ is a significant greenhouse gas and any change of land use (e.g. from pastoral to cultivated systems) will incur emissions costs/taxes. The data of van der Nagel et al. [19] provide a basis for modeling whole farm systems to include nitrous oxide emissions in addition to carbon dioxide and methane. Recent experimental findings enabling more accurate accounting of N_20 emissions from dung and urine patches under a range of environmental conditions and soil types [6,8,70] will improve inventory. It is important to base modeling and systems predictions on actual data with minimal assumptions and speculation, because small changes in agricultural procedures can have major impacts on overall greenhouse gas emissions.

16. Summary and Conclusions

New Zealand greenhouse gas (GHG) emissions include a high proportion of methane (37%) mainly derived from ruminant animals. Methane inventory calculations are based on animal census, physiological status, feed intakes and methane production kg^{-1} dry matter intake. The New Zealand farming community supports environmental sustainability and recognises nitrogen and methane pollution, in part because of publicity surrounding an attempt to levy livestock farmers to fund GHG research. Mitigation can be expressed in terms of total emissions, a proportion of gross energy intake or on the basis of production. Principal opportunities for short term methane mitigation include improved feed quality, animal performance and pasture management. Long term strategies include selection of low methane producers, vaccination and use of slow release, non-toxic, methanogen inhibitors. Analysis of experimental data from sheep and cattle fed fresh forage diets showed a poor prediction of methane emissions on the basis of diet composition; an improved understanding of rumen digestive physiology should complement mitigation strategies. Nitrous oxide emissions are dependent on nitrogen inputs from urine, faeces and fertilizer and are exacerbated by soil moisture content. Strategic placement of appropriate fertilizers and matching ruminant requirements to feed composition will lessen nitrous oxide losses. Practical solutions for GHG mitigation require an integrated assessment of all GHG and costs of implementation must not penalise producers.

Mitigation can be measured in absolute terms or in terms of production, and one GHG should not be lowered at the expense of others. Mitigation must not add to costs of production. These constraints and those associated with food safety, limit opportunities for major reductions in methane emissions from ruminants in the short term, but there are good options for mitigation in the longer term.

Selection of highly productive animals will minimize the proportion of methane associated with maintenance and good quality balanced diets, including the use of legumes will lessen methane costs per unit production. Future options include selecting animals with low emissions, prudent fertilizer application and development of chemical inhibitors and vaccines in the longer term. Mitigation should apply to animals under both intensive and extensive farming.

Central to successful methane mitigation will be an improved understanding of digestive physiology, including contributions of animal, feed and microbial components to methanogenesis. Producers should apply multiple technologies to mitigate GHG emissions and these may compliment future developments to target rumen methanogenesis.

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Table 1. Annual (2001) New Zealand greenhouse gas emissions (as $C0_2$ equivalents) [2].

	Total CO_2 equivalents (tonnes x 10^6)	**% of total**
New Zealand		
Carbon dioxide	32.43	44.6
Methane	27.06	37.5
Nitrous oxides	12.58	17.4
PFC, HFC, SF_6	0.31	0.4
Agriculture	35.85	51.0
Energy	30.93	39.0
Industrial	3.18	5.0
Waste	2.31	5.0
Agricultural emissions		**% of CH_4 or N_2O**
Methane		
From digestion	23.12	84.5
From manure	0.55	2.0
Nitrous oxides[a]		
From animal production	7.12	56.6
Indirect from agricultural soils	3.13	24.9
Direct from agricultural soils	1.81	14.4

[a] Nitrous oxide emissions apply to all agriculture, with some direct and indirect emissions attributable to animal agriculture.

Abbreviations: PFC, perfluorocarbons; HFC, hydrofluorocarbons; SF_6, Sulphur hexafluoride.

Table 2. Animal numbers (3 year average), CH_4 emission rates and total annual emissions for New Zealand in 2001. Data are calculated from census data, monthly feed requirements, estimated intakes and methane emissions unit^{-1} intake [2].

Species	**Numbers (x10^6)**[a]	**Emission rate (kg CH_4 hd^{-1} yr^{-1})**	**Total CH_4 emissions**[b] **tonne x 10^3**	**(%)**
Sheep	41.36	10.6	438.7	40.0
Dairy	4.98	74.7	372.5	33.8
Beef	4.54	56.0	254.0	23.0
Deer	1.55	20.9	32.7	3.0
Goats	0.17	8.9	1.5	0.1
Swine	0.35	1.5	0.5	0.0
Horses	0.08	18.0	1.4	0.1

[a] Adult equivalents.

[b] Excludes contribution from manure.

Table 3. Options for reducing methane emissions, in total or per feed intake or per unit product from ruminants fed forages.

Technique	Application	Limitations	Consequences [a]	Potential uptake
Short term				
Maintain forage quality	Medium-high fertility grazing	No limitations; require skilled management	Improved animal performance, must limit excess fertiliser use	High
Feed legumes/herbs, high quality grasses	All situations depending on species	Costs of establishment and maintenance lower yields could lower profitability	Improved animal performance but more agronomic care needed	Moderate
Incorporate condensed tannin into diet	Widespread, especially with lotuses, sainfoin	Lower yield and persistence except lotus in low fertility	Very good animal performance, 13-17% reduction in methane and lower N_20 emissions	Moderate
Specific lipids	Currently limited to dairy unless expressed in forage plants	Cost effectiveness	May affect product flavour	High with incentive
Balancing rations to meet animal needs	Systems involving supplementary feeding	Requires nutritional knowledge and advice	Improved performance from high producers. Could lessen N_20 emissions by lowering N intake	Moderate
Select high producing animals	Normal practice	High producers require good feeding and management	Lower stock numbers, increased profitability	High

Optimal farm management	Widespread but requires good skills	Depends on commodity prices; need consultant advice	Potential for high profitability	Moderate
Medium term				
Selection of low methane producing animals	Widespread if trait is heritable	None known but low CH_4 producers may only apply to some diets	Unlikely to have detrimental consequences	High with incentive [b]
Use of ionophores	Widespread if viable	Current data show inconsistent responses, variable persistence with forage diets	If viable an added benefit is protection from bloat and possible improved feed conversion	Low – medium
Probiotics	Dairy, unless available as slow release	Minimal evidence of efficacy *in vivo*	Unknown	Unknown
Halogenated compounds	Could be widespread if in slow release form	Need approval and verification of persistence	Consumer avoidance of products	High with incentive
Acetogens	Dairy cows	Require daily administration	Responses not defined. Excess acetate will not benefit high producing ruminants fed forage.	Low unless incentive
Defaunation	Moderate, depending on diet	Current technology risky. A vaccine would help.	Beneficial for animals fed poor forage	Moderate if safe

High efficiency animals	Widespread	Require selection of animals with efficient nutrient utilisation	Selections may be feed specific	Moderate
Long-term				
Vaccines – methanogens	Widespread	Good opportunities hampered by lack of funding	Potential for improved animal performance	High
Vaccines – protozoal	Moderate	Probably minimal	OK when poor feed is available	Moderate
Specific methanogen inhibitors (HMG-S-CoA and Phage)	Widespread	Depends on specific inhibition of methanogens	Improved performance if intakes maintained	High with incentive

[a] Consequences refer to the animal or environment; a net reduction in CH_4 kg^{-1} feed or product is implied.

[b] If performance is not enhanced an incentive may be required to use these materials.

[C] HMG-CoA , hydroxymethyl glutaryl - S-CoA

Table 4. Composition, digestibility and methane production from sheep fed a range of legumes and herbs [30].

Forage	**DM Composition (%)**				**DM digestibility** (%)	**Methane g kg^{-1} DMI**
	CP	Soluble CH0	Hemi-cellulose	Cellulose		
Lucerne	24.0	30.4	2.9	18.1	71.3	20.6
Sulla	17.5	41.5	0.0	10.3	72.8	17.5
Sulla/lucerne [a]	25.9	36.3	0.6	12.5	71.1	19.0
Chicory	12.3	58.8	0.0	4.0	79.3	16.2
Red clover	24.4	28.6	10.0	15.4	75.6	17.7
Sulla [b]	19.7	37.9	2.8	11.0	63.2	17.5
Chicory/sulla [a]	15.5	46.8	12.0	0	71.1	16.9
Chicory/Red clover [a]	19.5	42.7	2.1	8.1	76.5	19.7
White clover	26.9	31.2	6.3	11.5	78.8	12.9
Lotus	26.4	23.6	8.4	12.4	70.0	11.5
Lotus + PEG [c]	26.4	23.6	8.4	12.4	76.9	13.8

[a] mixtures are 50:50, DM basis.
[b] two trials each including sulla, one year apart.
[c] PEG, polyethylene glycol preferentially binds to and inactivates tannin.

Table 5. Effect of diets containing condensed tannins on milk and methane production by Holstein-Friesian cows in late lactation [36, 37].

	Ryegrass		**Lotus corniculatus**		**SED**
		+ PEG[a]		+ PEG[a]	
Trial 1					
DM intake (kg cow^{-1} day^{-1})	14.9	14.9	17.4	17.1	0.46
Milk (kg cow^{-1}day^{-1})	18.5	19.0	24.4	22.1	0.70
Milk protein (%)	3.59	3.56	3.63	3.61	0.05
Methane					
Total (g cow^{-1} day^{-1})	360	368	343	392	12.40
g kg^{-1} DM I	24.2	24.7	19.9	22.9	0.78
g kg^{-1} Milksolids [b]	250	244	171	216	10.6
% of GEI	7.50	7.66	5.98	6.89	
Trial 2		-	Sulla	-	
DM intake (kg cow^{-1} day^{-1})	10.7	-	13.1	-	0.6
Milk (kg cow^{-1} day^{-1})	8.4	-	11.2	-	0.35
Milk protein (%)	3.76	-	4.05	-	0.06
Methane		-		-	
Total	260	-	254	-	24.7
g kg^{-1} DM I	24.6	-	19.5	-	1.6
g kg^{-1} milksolids	327		243		24.7
% of GEI	7.2		6.1		0.4

[a] PEG, polyethylene glycol to remove effects of condensed tannins

[b] milksolids is fat + protein.

Table 6. Effect of cow genotype (overseas Holstein, OSHF vs. New Zealand Friesian, NZHF) on methane production when grazing pasture. (5 cows treatment^{-1}) [26].

	Days of lactation					
	60		**150**		**240**	
	Mean	sd	Mean	sd	Mean	sd
DM intake (kg day^{-1})						
NZHF	17.2	1.70	17.0	0.80	15.0	2.44
OSHF	17.7	1.58	17.6	3.15	16.3	1.75
Milk production (kg day^{-1})						
NZHF	26.5	1.69	19.5	1.78	14.7	1.74
OSHF	27.9	3.72	20.0	3.69	16.1	4.46
CH_4 production (g day^{-1})						
NZHF	308	19.7	376	20.4	353	33.5
OSHF	267	33.2	345	59.8	379	33.5
CH_4 g kg^{-1} DMI						
NZHF	18.0	1.41	22.2	1.32	23.8	2.15
OSHF	15.1	1.76	19.9	3.48	23.4	1.30
CH_4 g kg^{-1} milk						
NZHF	11.7	1.01	19.4	1.88	24.3	3.62
OSHF	9.7	1.38	17.4	1.36	24.9	6.44

Table 7. Nitrous oxide mitigation options and potential reductions for dairy farms in New Zealand [67, 70].

Mitigating option	**Approximate decrease in N_20 (%)**
Improve performance, lower numbers	4 – 5
Alter diet to reduce N contents or enable better N capture by rumen bacteria and production	7 – 14
Improve cow winter management to protect pastures	6 – 7
Improve spread of excreta from sheds and feed pads	4 – 5
Liming to raise soil pH	4 – 5
Improve fertiliser management	6 – 8
Improved drainage and lessen compaction	5 – 10

Table 8. A comparison of pastoral based dairying and total mixed ration (TMR) systems for feed dry matter (DM) intake, milk production and methane and carbon dioxide emissions [19].

	Pasture	**TMR**
Feed DM intake (kg cow^{-1} p.a.)	4560	6050
Milk yield (kg cow^{-1} p.a.)	3650	7300
Methane (kg cow^{-1} p.a.)	90	142
Methane/milk (g kg^{-1})	24.6	19.5
C0$_2$ equivalent emissions from herds (tonnes p.a.)		
From soils	186	1784
Machinery, fuel, fertiliser etc	91	198
Methane	495	783
Total	772	2765
C0$_2$ equivalent milk^{-1} (kg kg^{-1})	0.84	1.51