Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions

A Study of Research Requirements

Peter O'Hara, John Freney and Marc Ulyatt

Report prepared for the Ministry of Agriculture and Forestry on behalf of the Convenor, Ministerial Group on Climate Change, the Minister of Agriculture and the Primary Industries Council

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Foreword
Ratification of the Kyoto Protocol will place legally-binding commitments on New Zealand, requiring it to meet 1990 greenhouse gas emission levels or take responsibility for any increase in those emissions.

The agricultural sector is the major contributor to New Zealand’s greenhouse gas inventory (approximately 55% of total emissions). Agricultural emissions are expected to increase above 1990 levels by 2010 by five million tonnes per annum (carbon dioxide equivalents) or more.

The agricultural sector has expressed concerns over the ratification of the Kyoto Protocol ahead of the majority of New Zealand’s major trade competitors and its impact on the future competitiveness of the industry. However, the sector recognises the need to work with Government on how best to meet these international commitments.

This report:
• reviews recent and current research;
• identifies potential research areas;
• proposes options for the development of a strategy; and
• estimates the funding required to carry out a credible research programme.

The report is comprehensive, balanced, robust and realistic in its conclusions. It does not pick winners or promote “silver bullets”, but seeks a pragmatic and economic outcome for farmers and New Zealand.

The subject area is complex and controversial at present. The report provides a solid foundation for future discussions involving the Government, the agricultural sector and the science community.

Hon Pete Hodgson
Convenor
Ministerial Group on Climate Change

Jeff Grant
Chair
Primary Industries Council
Foreword - Chair Review Team

The Ministry of Agriculture and Forestry (MAF), on behalf of the Convenor of the Ministerial Group on Climate Change, the Minister of Agriculture, and the Primary Industries Council have commissioned Dr John Freney (Honorary Research Fellow CSIRO and an expert on nitrogen in agriculture), Dr Marc Ulyatt (formerly Senior Research Scientist with AgResearch Ltd and an expert in ruminant metabolism and methane emission), and myself to undertake this study. We were asked to review the research that could create opportunities to abate the emissions of agricultural methane and nitrous oxide, and recommend a strategy for future research that could lead to a reduction in these emissions in the long-term.

We were required to comment specifically on:

- The prospects in each area of research for developing practical measures for reducing emissions.
- The identification of the best future opportunities and research priorities in terms of their abatement potential.
- A basis to enable future costing of the research and the institutional arrangements necessary to make progress.

We were required to produce the following outputs:

1. A critical analysis of past and current research with the emphasis on the last five years.
2. A framework for identifying and prioritising relevant research to maximise abatement opportunities.
3. A Workshop (jointly sponsored by MAF and the Australian Greenhouse Office) to consider abatement opportunities involving invited New Zealand, Australian and international scientists, farmers, policy advisers and agricultural industry representatives.
4. A report on a strategy and priorities for future research based on our review of the research and the conclusions of the Workshop.

The findings of our study are presented in three parts:


We hope that the results will be seen as a useful basis for moving forward. I thank my colleagues John Freney and Marc Ulyatt for their outstanding contributions, and their forbearance as this report was put to bed.

Peter O'Hara
Chair
Review Team
Part One:

A Strategy and Priorities for Future Research on the Abatement of Agricultural Methane and Nitrous Oxide Emissions: Conclusions and Recommendations
Introduction
This report presents the conclusions and recommendations of the authors on a strategy and priorities for future research on the abatement of methane and nitrous oxide emissions from New Zealand farms. It is based on a critical review of published and current research findings, and on the conclusions reached in a Workshop attended by New Zealand, Australian and international scientists, farmers, policy advisers and agricultural industry representatives.

For the purposes of this report the terms ‘abatement’ and ‘mitigation’ are treated as being synonymous. The words ‘abate’ and ‘mitigate are defined in the New Zealand Oxford Dictionary (1998) as “to make or become less strong or intense”. For the purpose of meeting Kyoto Protocol commitments, this will involve a human intervention that reduces emissions or creates sinks that lock up the greenhouse gases.

Throughout this report, references to our report An Assessment of the Needs for Research on the Abatement of Non-Carbon Dioxide Greenhouse Gases from Agriculture: A Review of Current and Published Research are provided in parentheses.

A Strategic Framework
In Chapter 9 of the above-mentioned report, the outline of a framework on which a research strategy might be based is provided. It is suggested that all future research on agricultural production that involves the performance of grazing ruminants, the improvement of forage systems, the management of animal wastes, or the management of carbon and nitrogen cycles in pastoral or cropping systems should have regard inter alia to greenhouse gas emissions. However, not all such research would be classified as research on greenhouse gas emission abatement for the purposes of funding.

A Definition of Greenhouse Gas Abatement Research
We recommend that research proposals be defined as research on the abatement of greenhouse gas emissions for the purposes of funding if the objectives relate specifically to abatement of emissions or the measurement of the impact of the adoption of abatement strategies.

This could include research on:

- Fundamental studies to provide an understanding of the processes by which methane and nitrous oxide are formed and emitted or processes or technologies that modify the production or emission of the gases.
- The abatement of methane or nitrous oxide emissions through new technologies or products.
- The abatement of methane or nitrous oxide emissions through farm management practices.
- Management at a farm-scale of soil carbon and nitrogen cycles that result in reduced GHG emissions.
- Whole farm management systems that incorporate abatement strategies in a manner that encourages uptake and adoption by farmers. This could include decision-support modeling and research into farmer attitudes to the management of greenhouse gas emissions and to the acceptability/adoptability of abatement strategies.
- Improvement of the National Inventory through the development of measurement techniques that can operate at national, regional, farm-scale or animal/paddock levels, emission estimation models and emission factors that reflect as closely as possible New...
Zealand agricultural practices and systems. An important feature of the future inventory will be the capacity to demonstrate, using the appropriate techniques, that any abatement strategies that are adopted are delivering the expected reduction in emissions.

**Desired Outcomes and Strategic Objectives**

At the present time, there is an inherent conflict within the government’s objective of reducing total agricultural methane and nitrous oxide emissions permanently, while maintaining an internationally competitive agricultural sector. Some of the technologies and management practices that could be introduced in the medium-term (up to and including the first commitment period) could reduce the rate of emissions per kilogram of digestible dry matter intake and per kilogram of product (meat, milk, fibre). However, they would not result in reduced total emissions unless animal numbers and/or production were limited. Nonetheless, improved productive efficiency as measured by reduced emissions per unit of production seems to be a worthwhile objective.

Technologies and systems that will achieve both productive efficiency and reduced total emissions require fundamental changes in biological processes or farming systems. Examples of such changed processes are:

- Reducing hydrogen produced in the rumen or diverting it from the methanogenic pathway to an alternative pathway that yields products useful to the animal.
- The development of diets for grazing animals that more closely matches the intake of energy and protein to the animal’s needs.
- Inhibitors of nitrous oxide synthetic pathways.
- Soil and water management practices that favour the conversion of soil nitrogenous compounds to nitrogen gas rather than nitrous oxide.

The fundamental studies that might yield these technologies will involve long-term discovery research or medium-term proof of concept research. Research findings are not likely to be adopted widely as practical systems in the period up to 2012.

In the interests of providing a sound basis for a research strategy, it is important that practical goals for the agricultural sector be developed. Until such time that the sort of technologies discussed above become available, we consider that technologies and farming systems that may yield greater efficiency of production should be pursued, even though total emissions may increase in the absence of limitations on animal numbers or their production.

We recommend that strategic goals on greenhouse gas emission management be developed for all sectors of agriculture. Such goals should recognise any conflicts between the national objective of reducing greenhouse gas emissions from agriculture and farm enterprise objectives that are dictated by market forces.

We consider that there are significant positive gains in farmer acceptance, understanding and willingness to adopt abatement measures to be obtained from establishing strategic objectives for each sector. The objectives should focus on areas where the greatest gains can be made, and should include a temporal component that takes account of the potential impact of future developments. Thus pig and poultry farmers may be concerned only with objectives related to manure management. Sheep and beef cattle farmers may focus on improving the efficiency of their farms through diet management pending the development of technologies that modify methane emissions. Cropping farmers could focus on the efficient use of nitrogen. In the short to medium-term, dairy farmers have the opportunity to enhance efficiency through diet manipulation, manure management and the efficient use of nitrogen fertiliser. In all cases,
there is a potential ‘win/win’ for farmers and the nation. Just as importantly, a culture of concern for emissions reductions can be fostered.

We recognise that the development of strategic objectives will be hampered initially by a lack of data on abatement potential, costs, practicability etc, but we see value in learning and sharing processes that will be involved.

Farmers are aware of their potential to create sinks such as forest blocks and biomass crops, as well as emissions, but there is scant data on the benefits and risks of doing these things, how they might be accounted for, or what incentives would lead farmers to adopt them. While it is recognised that there are significant impediments to creating a market approach to the management of greenhouse sources and sinks, a willingness to include them in discussion of objectives is likely to engender a more positive response from the industry than a focus only on sources of emissions that appears to emphasise the ‘bad’ things they are doing.

One important conclusion of the Workshop was the desirability of integrating the objectives of greenhouse gas emission abatement with other environmental management objectives. This is particularly relevant to the management of the nitrogen cycle in agriculture. For example, the use of properly managed drainage ditches and riparian strips may not only prevent nitrates reaching waterways, but also favour the conversion of nitrates to nitrogen gas rather than nitrous oxide.

We recommend that strategic objectives for the management of greenhouse gas emissions be developed for each sector of agriculture. In doing so, we recommend that consideration of both sources and sinks of all greenhouse gases be included and that, where appropriate, the objectives be integrated with objectives for environmental management.

A Research Strategy

The potential abatement technologies and management systems that are discussed below cover the spectrum of research methodology:

- ‘Discovery’ (fundamental studies intended to understand processes that may identify future abatement measures).
- ‘Proof-of-concept’ or ‘proof-of-function’ studies (research that demonstrates the feasibility of a hypothesis and defines the parameters of a technology in a research context).
- ‘Development’ (research to develop the technology to an appropriate form).

We consider that any future research portfolio will need to be designed to accommodate the full spectrum of research methodology, and recognise that the discovery research such as that which is needed to identify ways to fundamentally alter biological processes of the rumen may be long-term (10+ years).

We favour a research portfolio designed to enable the progressive development and adoption of abatement measures. The development phase of the research should include an educational process that requires the active involvement of farmers who can offer feedback on the practicality of the technologies being developed.

Selection of research programmes to be included in the portfolio is likely to be based on the type of criteria that are currently employed by research funders. Relevance to sectoral strategic goals and objectives will be a key criterion. The distribution of funds between programmes in the three phases described above will change over time as results are assessed and the research strategy is revised.
We recommend that the research portfolio for agricultural greenhouse gas abatement research be a balanced one that includes research programmes in the discovery, proof-of-concept and developmental phases of research and is designed to foster a progressive implementation of abatement technologies.

**Nitrous Oxide: Abatement Technologies and Recommended Research**

Addition of nitrogen to soil in any form (animal excreta, synthetic fertiliser, crop residues or biological fixation), results in increased nitrous oxide emissions. The bulk of the nitrogen added to New Zealand soils comes from the excreta of animals (1282 Gg N/y) and the addition of fertiliser (213 Gg N/y) (Section 6.4). On average only 10.5% of the nitrogen in grass, silage or other feedstuff is converted by grazing animals into milk, meat, eggs or wool, and the remainder is excreted in dung and urine (Section 6.6.2.2).

Nitrous oxide is emitted directly from soil as a result of these inputs. It is also generated indirectly when nitrate lost by leaching or run-off is converted to nitrous oxide in water bodies, and when nitrogen from excreta and fertiliser is lost as ammonia to the atmosphere and subsequently deposited on land. During 2000, nitrous oxide emission from these sources amounted to 25.2 Gg N (Section 6.5), compared with the 1990 base value of 24.4 Gg N.

- Of the direct emissions, 53% came from excreta and 10% resulted from the application of fertiliser.

- Indirectly leaching and run-off of nitrogen from animal excreta or fertiliser application contributed 23%, and deposition of ammonia which had been volatilised contributed a further 11%.

Because of their larger numbers, sheep were responsible for the bulk of the direct nitrous oxide emissions from animal excreta (5.5 Gg N/y; 45.5% of the total), and dairy cattle (3.3 Gg N/y; 27.3%) generated more nitrous oxide than non-dairy cattle (3.0 Gg N/y; 24.8%) (Section 6.6.2.2).

Mitigation options need to focus on limiting the direct loss of nitrogen from animal excreta and synthetic fertilisers, and the indirect loss caused by leaching, run-off and ammonia volatilisation. Options are available that could result in considerable reductions in nitrous oxide emission from grazing animals and fertiliser application. These include:

1. **For ruminants:**
   - Manipulating the diet of animals to influence the amount of nitrogen excreted, particularly urea nitrogen. For example, feeding dairy cattle protein that resists degradation in the rumen and high starch diets can result in less nitrogen being excreted in the urine, reduced ammonia volatilisation, and less nitrous oxide emission. In one experiment the reduction in urinary nitrogen was 24% (Section 6.6.2.2.2b).
   - Breeding forage cultivars that provide an energy-to-protein ratio more in keeping with the animal’s needs could improve nitrogen efficiency. Dairy cows fed grasses high in water soluble carbohydrate excreted 24% less nitrogen than those fed normal diets (Section 6.6.2.2.1d).
   - Keeping cattle on feed-pads during the wet autumn/winter period, so that excreta can be collected and utilised as fertiliser later in the year. Nitrous oxide emission from dairy excreta could be reduced by 25% and nitrate leaching by 40% (Section 6.6.2.2.2c).
   - Improving drainage and preventing soil compaction can reduce nitrous oxide emission by 3% each (Sections 6.6.1.1.4 and 6.6.2.2.1c).
If it is assumed that the effects are additive, and that the reductions achieved experimentally could be realised in a practical farming situation, there is the potential for nitrous oxide emission to be reduced from the sheep, dairy cattle, and beef cattle sectors by 16% (0.9 Gg N), 28% (0.9 Gg N) and 25% (0.8 Gg N) respectively (Section 6.7). It is accepted that these estimates of abatement potential will be subject to considerable variation, and that reductions of this order are unlikely to be achieved in a farm situation.

2 For cropping and forage production:

- Matching nitrogen supply with crop demand, tightening nitrogen flow cycles, and optimising tillage, irrigation and drainage could reduce nitrous oxide emissions from fertiliser use by 19% (0.6 Gg N) (Section 6.7).
- Nitrate leaching can be reduced by lowering fertiliser application rates, synchronising nitrogen supply to plant nitrogen demand, growing cover crops, and using buffer zones (Section 6.6.3.2).

If the total reduction of 3.2 Gg N was achieved, it would reduce the emissions calculated for the year 2000 to 22 Gg N (i.e. 2.43 Gg below the 1990 base value). However, even if nitrous oxide emissions were reduced below the 1990 level by implementing these options, it will only be maintained at that level if nitrogen inputs remain static. This means that fertiliser nitrogen use and animal numbers can not increase. Production could only increase by increasing the efficiency of nitrogen use by sheep and cattle, or by changing from animals with low nitrogen use efficiency (cattle 7.7%, sheep 6.2%) to those with high nitrogen use efficiency (swine 20.5%, poultry 33.8%) (Section 6.6.2.2). The options proposed for reducing nitrous oxide emission from animals could only be implemented by limiting a farmer’s options for increasing production. However, making more efficient use of animal manures and slurries will have numerous indirect benefits. If the options proposed for reducing emissions from fertiliser use were implemented, they would increase rather than decrease farmers’ incomes. If fertiliser nitrogen is used more efficiently, less money will be spent on fertiliser.

**Research Priorities**

A number of promising areas of research relating to nitrous oxide emission were revealed during the review and Workshop. These areas can be divided into three categories; mitigation, inventory and farming systems. Research needs related to the measurement and verification of the effect of abatement measures are dealt with below. As the emphasis in this project is mitigation, priority is given to this area of research, and the projects are listed in order of importance within each category.
**Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions**

**Methane: Abatement Technologies and Recommended Research**

Enteric emissions from the grazing ruminant are responsible for about 87% of New Zealand’s total methane emissions and for about 99% of the methane emissions from agriculture (Section 7.2.1). In 2000, sheep, dairy cows, beef cattle and deer were responsible for 46%, 29%, 21% and 3% of the ruminant emissions respectively. Since 1990, total ruminant emissions have risen by 7%, the percentage of this change being attributed to increases of 50%, 8% and 219% in dairy cows, beef cattle and deer and a decrease of 22% by sheep, mainly due to changes in livestock numbers. It is predicted that ruminant methane emissions will be 16% over 1990 levels by 2010 if the present trend continues.
Methane is produced in the rumen and caecum by the anaerobic microbial fermentation of pasture plant organic matter. Methane is synthesised from hydrogen and carbon dioxide at the end of the microbial digestion chain by the methanogenic archaea, a group of microorganisms that is widely distributed in nature and is also responsible for methane synthesis in manure, effluent ponds and the soil. If hydrogen is allowed to accumulate in the rumen it depresses digestion, so the archaea remove it as methane. Management of hydrogen in the rumen is the key to controlling ruminant methane emissions (Section 7.1.1.2).

It is important, for both inventory and mitigation purposes, that methane emission from grazing animals is measured as accurately as possible. To date only one technique, the sulphur hexafluoride (SF₆) tracer technique, is satisfactory for free ranging animals (Section 5.1.2). Further work is also needed before the SF₆ technique can be accepted as reliable: rigorous evaluation against the respiration calorimeter; confirmation of the proportion of methane that is excreted in the flatus; and evaluation of the high variability of the technique compared to chamber measurements.

Many possibilities for mitigating methane emissions have been proposed in the literature, and many of them have been evaluated experimentally. They include:

- Reducing livestock numbers. This is not an acceptable solution as a stand-alone option. However, it may be possible to reduce methane by combining improvements in animal efficiency with lower livestock numbers (Section 7.4.1).
- All animals have an obligatory maintenance requirement that results in no production, yet has an associated methane emission. The strategy must be to dilute the effects of this maintenance methane by various measures such as increasing feed intake, increasing metabolic efficiency and genetic improvement (Section 7.4.2.1).
- Manipulation of dietary composition by increasing digestibility, reducing cell wall carbohydrates, increasing starch, addition of certain lipids and increased protein can reduce methane.
- A wide range of feed additives has been proposed to reduce methane. These include alternative hydrogen acceptors (e.g. malate, fumarate), halogenated methane analogues (e.g. chloroform, bromoethanesulphonic acid), antibiotics (e.g. monensin, mevastatin), defaunating agents (e.g. manoxol, teric), probiotics, bacteriocins and naturally occurring plant compounds (e.g. condensed tannins). Problems with these compounds, such as toxicity to the microbes and the animal, short-lived effects due to microbial adaptation, volatility, expense, and failure to meet consumer acceptance have ensured that none have yet been used successfully in agriculture for reducing methane emissions. With grazing animals, other than dairy cows, a delivery system would be required to ensure regular delivery into the rumen. Delivery by breeding into pasture plants is possible, but the time needed to get viable pasture swards established under the range of New Zealand pastoral conditions should not be underestimated (Section 7.4.4).
- Immunisation of animals against methanogens has been attempted by Australian scientists. This is a good concept, but the experimental results to date have not been made public or available for scientific peer review (Section 7.4.5).
- Many suggestions have been made for manipulating the rumen microbial ecosystem to achieve methane reduction. These include targeting methanogens with microbial antibiotics, bacteriocins or phage, removing protozoa and developing alternative sinks for hydrogen such as acetogenic bacteria. Development of mitigation technologies from this type of research is well in the future because of the need to first understand the complexities of the rumen microbial ecosystem (Section 7.4.6).
• There are several nutritional and farm management strategies currently available that, if applied in a systematic manner, would be expected to reduce methane emissions (Section 8.1).

Research Priorities
In the area of methane mitigation, a review of the literature, visits to current research programmes in New Zealand, and Workshop deliberations identified a number of areas where further research could be warranted. In order of priority these are:

• A basic research programme studying the ecology of the rumen archaea should be supported. The aim should be two-fold: to identify opportunities for reducing methane synthesis; and to divert accumulated hydrogen into products that can be utilised by the animal. Core skills to do this exist (Section 7.4.6).

• The development of farm-scale modeling, resource accounting techniques and complementary on-farm testing protocols to implement both existing knowledge and technology-based developments of abatement strategies is seen as a high priority. Core skills and expertise to do this already exist: they need to be brought together and focused on this problem (Section 8.1).

• The large differences that seem to exist between animals in methane emission should be evaluated and, if proven, genetic markers should be sought to underpin a selection programme (Section 7.4.3).

• The CSIRO antimethanogenic vaccine is an interesting concept. There are plans to test the vaccine in New Zealand. Research into elucidating the mode of action of the vaccine and ensure that its efficacy is consistently greater than 20% is needed (Section 7.4.5).

• From time-to-time new feed additives/naturally occurring methane inhibitors will be identified within or external to the New Zealand programme (monensin, malate, condensed tannins). Before any research commences, the feasibility of each candidate should be evaluated with a desk study that considers criteria such as specific activity of the compound, proposed delivery vehicle, time frame and cost of development of a viable product, cost of product to the farmer, and acceptability to consumers (Section 7.4.4).

Opportunities for Synergy in the Research Strategy
Manipulation of the diet of ruminants offers the prospect of both reduced methane production in the rumen and reduced excretion of nitrogen, particularly excretion in urine. However, as discussed above, while some of these approaches are likely to improve the efficiency of the ruminant and achieve an emission reduction per unit of intake or unit of production, they will not achieve a reduction in total emissions unless total animal numbers and/or production are also limited.

Given what is already known about diet manipulation, we recommend that research on the development of farming systems that exploit this knowledge in a practical and economic way is deserving of a high priority.

Another area of potential synergy is the dual benefits of reduced nitrous oxide emissions and reduced flow of nitrates into water bodies that could be obtained from better management of the soil nitrogen cycle, in particular the leaching of nitrate. The technology for managing the application of nitrogen fertiliser to achieve efficient use and minimal losses already exists to a large degree. What may be lacking is an adequate match between the deployment of these technologies and farmers’ objectives.

We recommend that research aimed at optimising the application of nitrogen fertiliser in a variety of environments, and research directed at the efficient management of nitrogen
outflows from soils, the trapping of nitrates before they reach waterways and their conversion to nitrogen gas rather than nitrous oxide is high priority.

Other Research Needs
We have identified the ongoing development of measurement technology and modeling capability as two research areas that are critical to a research programme on emission abatement technology: the demonstration of the impact of the future adoption of abatement technologies; and systems and the use of decision-support systems by farmers.

Measurement of Methane and Nitrous Oxide Emissions
Research on measurement technology has been driven, and will continue to be driven, by the need to report on New Zealand’s emissions (Chapter 5). There is an ongoing need to refine emission factors appropriate to New Zealand conditions through models that are used to estimate emissions at an animal or farm-scale. However, the inherent variation in the biological processes that produce methane and nitrous oxide will dictate the level of accuracy of measurement that should be sought and the level of uncertainty around any measurements made. Thus the level of investment in measurement technology should be dictated by a pragmatic assessment of the minimum level of uncertainty that can be obtained.

Verification of the expected impacts of the adoption of abatement measures is likely to depend on modeling estimates at a farm-scale. We question whether direct measurement with micrometeorological techniques at this scale will ever yield the technical simplicity or level of accuracy that might have practical value. We consider that such techniques are likely to be more useful for measurements at a district or regional scale. However, we note that meteorological measurements at a regional or national scale can not distinguish between gases emitted by anthropogenic and natural sources or between indigenous and imported gases at present. They may therefore have limited utility as a verification tool.

Modeling Capability
We have noted that there are a range of models that are being adapted for greenhouse gas work, most being adaptations of models that have been developed for other purposes. We foresee that need for models and modeling capability for the following purposes:

- Inventory models that include Tier 2 emission factors as appropriate.
- Models to be used in scenario analysis to identify and assess research opportunities and evaluate research data. This implies an ongoing cycle of “model-analyse-design-input-empirical data”.
- Decision-support models to be used by farmers and planners for evaluation and implementation of abatement technologies.
- These are not necessarily different models because there will be a continuity of logic and data used. We consider the key issues to be:
- Selection of the models to be used with effort concentrated on the selected few.
- Alignment of modeling capability, with the empirical research being done in a manner to facilitate close and frequent communication between modelers and researchers.

We recommend, in the interests of getting people with modeling skills in universities, research institutes and the private sector working to a common purpose, that a Workshop be held for the purpose of defining what is needed and who is going to do it.
Funding

It has been difficult to get an accurate picture of the total investment in research on agricultural greenhouse gases over the last five years. This is due in part to the way the research has been classified and funded and to the timing of funding. The National Science Strategy Committee on Climate Change calculated that the total investment in climate change research in the period 1999 to 2001 was $23,500,000 per year, 90% of which came from government. Of this, $9,000,000 (39%) was spent on inventory and abatement research, and a further $4,000,000 (18%) was spent looking at the potential impacts of climate change, including impacts on agriculture.

In 2002/03, FRST and MAF will spend $3,263,000 on agricultural greenhouse gas emissions research, with $2,000,000 on inventory research, $700,000 on fundamental research and $435,000 on abatement research. In 2003/04, total FRST and MAF investment will rise to $4,715,000, of which $2,480,000 (53%) will fund inventory research, $700,000 will fund basic studies, and $1,532,000 will fund abatement research. There has been an approximately 5.5-fold increase in government funding of agricultural greenhouse gases research since 1999.

The present emphasis on developing Tier 2 emission factors and models to estimate emissions is appropriate. As abatement technology is adopted in the future, the ability to revise emission estimates and to verify through direct measurement that the technologies do result in reduced emissions, will be critically important. The ability to make estimates and measurements at a farm level will emerge as a priority if a market based approach to emission accounting is contemplated in the future.

We recommend that the government continue its current (2003/04) investment in research. We consider that the reporting of the National Inventory is the government’s role, and that the supporting research should continue to be government’s responsibility. We draw attention to the future need to be able to verify the impact of the adoption of abatement technologies.

The level of expenditure on research on abatement of agricultural emissions has risen sharply since 1999. FRST will spend $1,500,000 in 2003/04. The level of investment in abatement research by other public and private sources has been low.

However the establishment of the Pastoral Greenhouse Gas Research Consortium (PGGRC) will significantly alter the level of private sector investment in abatement research. The partners in the Consortium are Fonterra Cooperative Group Ltd, Meat NZ, AgResearch Ltd, Wrightson Ltd and DEEResearch. Industry funds have been matched by FRST funding to create an initial funding level of approximately $1,500,000. We assume that the FRST funds are part of its total investment referred to above. Funding from both sources is expected to grow over the initial five-year term of the Consortium.

PGGRC’s initial science strategy is based on a balanced portfolio of short, medium and long-term research on methane production in ruminants that can lead to practical on-farm methods of reducing emissions. Such methods need to be shown to be safe, leave no residues in meat or milk, be cost-effective and be applicable to grazing animals. The focus in the first three to four years will be on discovery and proof-of-concept research that is intended to uncover a range of abatement processes and products that can be further developed as practical abatement measures. The research portfolio includes studies of potential animal, plant and rumen microbial targets.
The six key science areas of investigation and a brief description are:

1. **Rumen microbial strategies to lower methane emissions**
   Exploit rumen processes which influence methanogenesis and the survival of methanogens to provide novel on-farm strategies.

2. **Forage and plant inhibitors to lower methane emissions**
   Identify and quantify inhibitory properties of forage inhibitors.

3. **Genomics for identifying methanogen inhibition targets**
   Compare and contrast rumen and non-rumen methanogens in order to pin-point areas of archael/bacterial ‘weakness’.

4. **Animal factors affecting methane emissions**
   Quantify the genetic and environmental components of between-animal variations.

5. **Proof-of-function of possible methane-reducing technologies**
   Animal assessments to establish potential of possible on-farm technologies, safety, and acceptance to consumer.

6. **On-farm testing**
   Acceptability at a farm systems level (to follow successful leads from above).

These areas of science investigation form interlinked strands that will inform, negate and encourage certain lines of ongoing research (the ‘go/no go’ questions for the Science Advisory Group).

In recommending a level of future investment in a balanced programme of research, we believe that the principal determinant of the size and scope of a future programme will be the availability of appropriately trained scientists. Scientists with these skills are likely to be in demand around the world. For this reason, we have based our estimate of the costs of a research portfolio on the number of full-time scientist equivalents we believe to be needed to put in place the programme we have outlined above and in the following table.

**Table 1: Estimated Number of Additional Scientists and their Associated Costs Needed to Mount the Recommended Research Programme**

<table>
<thead>
<tr>
<th>Research Area</th>
<th>Scientists (full-time equivalents)</th>
<th>Investment per year ($000)$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Optimum</td>
</tr>
<tr>
<td>Fundamental studies on rumen microbiology and physiology$^2$</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Studies on diet manipulation that includes animal and forage factors</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Farming management/systems</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Soil/water/manure management</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Modeling Resource accounting</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Inventory/verification</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>15</strong></td>
<td><strong>28</strong></td>
</tr>
</tbody>
</table>

$^1$ We have assumed that each scientist requires a dedicated technician and that the cost is $150,000 per full-time equivalent scientist or technician.

$^2$ Some or all of this additional investment may be made by PGGRC.
If this additional investment were obtained, the total research programme would be of the order of $9,900,000 to $14,000,000 per year, with approximately one-third being invested in inventory and verification research and the balance on abatement studies.

| **We recommend that in addition to the current government investment (approximately $4,700,000 in 2003/04) and the investment by the Pastoral Greenhouse Gas Research Corporation ($800,000), an additional minimum 12 and optimum 23 full-time scientists will be needed to mount a comprehensive research programme. This is estimated to cost between $4,500,000 and $8,400,000 per year.** |

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**Management of the Research Programme**

We feel that we are not able to comment substantively on the most appropriate institutional arrangements for the conduct of the management of a future research programme, because so much depends on what is agreed between the government and the agricultural sector representatives. The form of management structure that would be appropriate for a partnership between government and the agricultural sector would not be appropriate if the research programme were imposed on an unwilling sector. However, we make the following observations:

1. The scientific skill base is limited and dispersed among several research organisations. The future management structure will need to be able to draw effectively on all available skills, and we believe that all research providers should feel confident that they will receive even-handed treatment by the funding/management organisation.

2. The current informal network (NzONET) encourages close and effective collaboration among scientists working on various aspects of nitrous oxide emissions and government policy advisers, and has been an effective tool in determining research priorities for inventory-related research. However, it may need a more formal approach if it is to serve a wider role.

3. METHNET is a useful communication network, but does not yet have a central role in setting research priorities and may never have given the establishment of the PGGRC.

4. The Research Consortium model offers a satisfactory management and accountability mechanism should a partnership between government and the sector emerge. We are firmly of the view that a partnership is the only viable relationship that will offer the long-term continuity that the research programme demands.

5. The PGGRC has set itself a specific role of basic research on methane emission abatement, at least at its initial development. The Consortium includes AgResearch Ltd, both as a partner and as a major research provider. This arrangement may be appropriate, given that AgResearch’s predominant expertise is in the fields of research that PGGRC has adopted in its initial portfolio. Nevertheless, the dual role that AgResearch plays raises a question of how the conflict of interest is managed. We question whether such an arrangement is appropriate for a more comprehensive research programme to be delivered by a range of research providers.
Collaboration with Other Countries

The Workshop demonstrated that there is considerable potential to enhance existing collaborative research and to develop new relationships with research organisations in other countries. We note that there is already a significant level of collaborative research, such as the cooperation with the US and Canada on methane emission measurements, and the arrangement between PGGRC and CSIRO on the testing of methanogen vaccines. We also note that at a scientist-to-scientist level there is a high level of communication and cooperation.

We consider that New Zealand is well placed to attract cooperative and collaborative interest through its leadership in the relevant research fields. For this reason, it is important that the funding and the management of the research programme creates the opportunity for collaborative effort to occur.
Part Two:

An Assessment of the Needs for Research on the Abatement of Non-Carbon Dioxide Greenhouse Gas Emissions from Agriculture

A Review of Current and Published Research
Executive Summary

This report is a review of current and published research on agricultural methane and nitrous oxide emissions, with particular emphasis on research into the abatement of these emissions.

The New Zealand government’s policy is to exempt the agricultural sector from any emission charges related to methane and nitrous oxide emissions, at least in the first commitment period (2008 to 2012), in exchange for a commitment from the sector to fund research that will lead to a permanent reduction in emissions.

In the period 1999 to 2002, approximately $23,500,000 per year was invested in all aspects of climate change research. Ninety percent of this came from government sources. Indicative figures of current investment in agricultural greenhouse gas emissions, based on a survey of the principal research providers, shows the following levels:

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999/00</td>
<td>$582,000</td>
</tr>
<tr>
<td>2000/01</td>
<td>$510,000</td>
</tr>
<tr>
<td>2001/02</td>
<td>$2,649,000</td>
</tr>
</tbody>
</table>

Expenditure by the Foundation for Research, Science and Technology (FRST) and the Ministry of Agriculture and Forestry (MAF) in 2002/03 is $3,263,000 and will be $4,715,000 in 2003/04.

Improving the National Inventory, and the re-ordering of production systems research to examine abatement options, were the main areas of investment over the period 1999 to 2002. A strong emphasis on measurement and inventory related research is maintained in the period 2002/2004, and research on abatement technologies has been boosted 3.5 to 5 times over the 1999/00 level.

The establishment of the Pastoral Greenhouse Gas Research Consortium represents a significant new area of investment in methane research, and is an important step in the establishment of a partnership between government and the agricultural industry in finding ways to manage agricultural greenhouse gas emissions.

National Inventory

In 2000, the official estimates of New Zealand’s greenhouse gas emissions showed that methane and nitrous oxide represented 59.6% of total emissions in CO2 equivalent terms, and emissions from agriculture were 55% of total emissions. Compared to 1990, methane emissions were 6.17% less, a fall largely attributable to the fall in sheep numbers, and nitrous oxide was 6.35% more.

The most important source of agricultural methane is ruminant enteric fermentation (98.7%). The most important sources of nitrous oxide are faeces and urine deposited by grazing animals on pasture, animal waste and fertiliser nitrogen in soils, and indirect emissions from these sources through atmospheric deposition and leaching.

Revised models for estimating methane and nitrous oxide emissions that take into account animal numbers, animal productivity and New Zealand specific emission rates that are based on empirical data show that the official estimates understate the trends in emission rates and that there is a rising linear trend. Extrapolation of the curves to 2010 indicates that methane emissions will exceed 1990 levels by 15.7% in gross terms, and nitrous oxide emissions will exceed 1990 levels by 20-30%. In the decade 1990 to 2000, productivity gains have been significant, particularly in the dairy and sheep industries. For example, the production of sheep meat in 2000 exceeds that of 1990, in spite of a one
third decline in sheep numbers. The use of nitrogen fertiliser is increasing at an exponential rate.

Emission rates are most sensitive to changes in total animal numbers and to productivity. An emerging policy question is how the trade-off will be made between that national objective of maintaining emissions at 1990 levels and individual farmer’s objectives for the performance of their livestock. A number of abatement strategy options may confer productivity advantages as well as reduced emissions.

Current and planned research is directed at:

- Extending the range of methane emission measurements from animals
- Improving the measurements of nitrous oxide release from excreta under a variety of soil and seasonal conditions
- Improving the assessment of indirect emissions
- Improving (or selecting) the models that can be used to estimate emissions in the future leading to robust estimates that conform with IPCC good practice
- Developing methodologies that allow broad scale assessments of herbage quality and paddock/farm/locality emissions.

Measurement and estimation that can verify that any abatement strategies adopted in the future are delivering the expected effects will be crucial. Methods of measuring and estimating methane and nitrous oxide emissions are discussed in Chapter 6.

**Nitrous Oxide**

Addition of nitrogen to soil in any form (animal excreta, synthetic fertiliser, crop residues or biological fixation) results in increased nitrous oxide emissions. In New Zealand, agriculture is based largely on animals grazing grass-legume pastures, but the animals do not utilise the nitrogen they ingest efficiently. On average only 10.5% of the nitrogen in grass, silage or other feedstuff is converted into milk, meat, eggs or wool (Table 7.5) and the remainder is excreted in dung and urine. Thus the bulk of the nitrogen added to New Zealand soils comes from the excreta of animals (1 282 Gg N/y) and addition of fertiliser (213 Gg N/y) (Table 7.1).

Additional nitrous oxide is emitted directly from soil as a result of these inputs. It is also generated indirectly when nitrate lost by leaching or run-off is converted to nitrous oxide in water bodies, and when nitrogen from excreta and fertiliser is lost as ammonia to the atmosphere and subsequently deposited on land. During 2000, nitrous oxide emissions from these sources amounted to 25.2 Gg N, compared with the 1990 base value of 24.4 Gg N.

- Of the direct emissions, 53% came from excreta and 10% resulted from the application of fertiliser.
- Indirectly leaching and run-off of nitrogen from animal excreta or fertiliser application contributed 23%, and deposition of ammonia which had been volatilised contributed a further 11%.
- Because of their larger numbers, sheep were responsible for the bulk of the direct nitrous oxide emissions from animal excreta (5.5 Gg N/y or 45.5% of the total), and dairy cattle (3.3 Gg N/y or 27.3%) generated more nitrous oxide than non-dairy cattle (3.0 Gg N/y or 24.8%).

It is apparent from this discussion of sources that mitigation options need to focus on limiting the direct loss of nitrogen from animal excreta and synthetic fertilisers and the indirect loss caused by leaching, run-off and ammonia volatilisation. Options are
available that could result in considerable reductions in nitrous oxide emission from grazing animals and fertiliser application. These include:

- Manipulating the diet of animals. Feeding dairy cattle low degradable protein and high starch diets should result in 24% less nitrogen being excreted in the urine, reduced ammonia volatilisation and less nitrous oxide emission.

- Breeding cultivars that improve nitrogen efficiency. Dairy cows fed grasses high in water soluble carbohydrate excreted 24% less nitrogen than those fed normal diets.

- Keeping cattle on feed-pads during the wet autumn/winter period, so that excreta can be collected and utilised as fertiliser later in the year. Nitrous oxide emission from dairy excreta could be reduced by 25% and nitrate leaching by 40%.

- Improving drainage and preventing soil compaction can reduce nitrous oxide emission by 3% each.

- If these options were adopted by farmers, and the effects were additive, there is the potential for nitrous oxide emission to be reduced from the sheep, dairy cattle, and beef cattle sectors by 16% (0.9 Gg N), 28% (0.9 Gg N) and 25% (0.8 Gg N) respectively (Table 7.8).

- Matching nitrogen supply with crop demand, tightening nitrogen flow cycles, and optimising tillage, irrigation and drainage could reduce nitrous oxide emissions from fertiliser use by 19% (0.6 Gg N).

- Nitrate leaching can be reduced by lowering fertiliser application rates, synchronising nitrogen supply to plant nitrogen demand, growing cover crops and using buffer zones.

- If the total reduction of 3.2 Gg N was achieved, it would reduce the emissions calculated for the year 2000 to 22 Gg N (i.e. 2.43 Gg below the 1990 base value).

However, even if nitrous oxide emissions were reduced below the 1990 level by implementing these options, it will only be maintained at that level if nitrogen inputs remain static. This means that fertiliser nitrogen use and animal numbers can not increase. Production could only increase by increasing the efficiency of nitrogen use by sheep and cattle.

- If the options proposed for reducing emissions from fertiliser use were implemented they would increase rather than decrease farmer’s income. If fertiliser nitrogen is used more efficiently less money will be spent on fertiliser.

- The options proposed for reducing nitrous oxide emission from animals could only be implemented at a cost to the farmer, and thus may not be accepted.

However, making more efficient use of animal manures and slurries will have numerous indirect benefits.

**Methane**

The predominant source of methane in New Zealand is the fermentation of pasture plants in the rumen of farm animals. Methane is synthesised from H₂ and CO₂ at the end of the microbial digestion chain by the methanogenic archaea, a group of microorganisms that are widely distributed in nature and are also responsible for methane synthesis in manure, effluent ponds and the soil. If H₂ is allowed to accumulate in the rumen it depresses digestion, so the archaea remove it as methane. Management of H₂ in the rumen is the key to controlling ruminant methane emissions.

There is limited data available in the world literature on methane emission from animals grazing pasture. The best set is from New Zealand, where measurements have been made
over a range of pasture types and management scenarios using the SF$_6$ tracer technique. There is good agreement that mature dairy cows and sheep grazing high quality pastures (>75% DM digestibility) produce about 26 g methane per kg DM digested (DDMI). On poorer quality diets, dairy cows and sheep produce about 35 g methane per kg DDMI. Other sources of methane such as manure, dairy effluent ponds and the soil appear to be trivial compared to enteric digestion. The soil in fact is a major sink for methane through oxidation by methanotrophic bacteria.

Several major nutritional factors are known to have an influence on methane emission which increases with feed intake, although the relationship is not strong because of the high degree of variation between individual animals. However, there is a stronger negative relationship between methane emitted per unit of feed intake and feed intake. So there is an advantage, in terms of methane emission, to feed animals on as high an intake as possible. It is generally accepted that digestion of cell wall carbohydrates produces more methane than the digestion of soluble carbohydrates. Protein and lipids appear to have a negative effect on methane production, but the effects are variable, and in the case of lipids toxicity to the rumen microbes can be a problem.

Many technologies have been proposed for mitigating ruminant methane emission. Livestock numbers are the major determinant of emission at the national scale. While it might be considered politically naive to advocate reducing livestock numbers, sheep farmers over the last 15 years have reduced numbers by 33% without compromising total production. This shows that farming has the inherent flexibility to respond to a meaningful economic incentive.

There are possibilities for reducing methane via improvements in animal efficiency. All animals have an obligatory maintenance requirement that results in no production, yet has an associated methane emission. The strategy must be to dilute the effects of maintenance by various measures such as increasing feed intake, manipulation of dietary composition to increase feed quality (e.g. decrease cell wall carbohydrate), increasing metabolic efficiency and genetic improvement. Dairy cows that have been selected for feed conversion efficiency produce less methane on the same diet. These efficiency improvements should form the basis for on-farm strategies to reduce methane in the short-term.

A wide range of feed additives have been proposed to reduce methane. These include alternative hydrogen acceptors (e.g. malate, fumarate), halogenated methane analogues (e.g. chloroform, bromoethanesulphonic acid), antibiotics (e.g. monensin, mevastatin), defaunating agents (e.g. manoxol, teric), probiotics, bacteriocins and naturally occurring plant compounds (e.g. condensed tannins). There are problems with these compounds such as toxicity to the microbes and the animal, short-lived effects due to microbial adaptation, volatility, expense and failure to meet consumer acceptance. With grazing animals, other than dairy cows, a delivery system would be required to ensure regular delivery into the rumen. Delivery by breeding into pasture plants is possible, but the time needed to get a viable plant established in the national pasture should not be underestimated.

Immunisation of animals against methanogens has been suggested by Australian scientists. This is a good concept, but we are still a long way from the delivery of an efficacious vaccine.

There are many possibilities available for manipulating the rumen microbial ecosystem to achieve methane reduction. These include targeting methanogens with microbial antibiotics, bacteriocins or phage, removing protozoa, and developing alternative sinks for H$_2$ such as acetogenic bacteria. The development of mitigation technologies from this
type of research are well in the future because of the need to first understand the complexities of the rumen microbial ecosystem.

Investment on research into methane mitigation should cover a suite of technologies that range in their potential delivery time from short-term (on-farm systems research) to long-term (rumen microbial manipulation). A successful technology will deliver a win/win result with respect to methane reduction and increased animal production.

**Whole Farm Systems**

There have been only a limited number of studies of whole farm management systems and strategies that aim to reduce greenhouse gas emissions. However, the available evidence points to this approach in providing medium-term gains in emission management, and in the more efficient use of the energy intake (carbon) converted to methane by rumen microbes (6% of gross energy intake) or nitrogen that is cycled in the farm production system. More efficient capture of methane-carbon or nitrogen as animal tissue or product offers a win/win situation in terms of reduced emissions and increased productivity. Further, it appears that measures to reduce losses of methane-carbon and nitrogen may be complementary or even synergistic.

The continuing development of farm-scale modeling, resource accounting techniques and complementary on-farm testing protocols to support technology-based developments of abatement strategies is seen as a high priority. Core skills and expertise to do this already exist.

**A Framework for Developing a Research Strategy**

It is suggested that all future research that is related to agricultural production should have specific regard to greenhouse gas emissions.

However, to be considered as research on abatement, the research objectives should have some aspect of greenhouse gas abatement as its primary purpose. This research could include basic studies to understand the processes by which the gases are produced or abated, measurement and inventory development (particularly that which enables the impact of any abatement strategies to be measured), and research to develop specific abatement strategies based on technologies, products or farm practices. Research to integrate such strategies into whole farm management systems would also qualify.

A framework that is based on deriving a national research strategy from an identification of national objectives for agricultural greenhouse gas emissions is set out in Chapter 9.
Chapter 1
Introduction

Methane and nitrous oxide play an important role in the radiative balance of the atmosphere, and are particularly significant because their global warming potentials (GWP) are greater than that of carbon dioxide: methane GWP=21, nitrous oxide GWP=310 (FCCC, 1999). The Intergovernmental Panel on Climate Change (IPCC) has revised the GWP values slightly (methane GWP=23 and nitrous oxide=296), but these figures do not have to be used until the second commitment period.

While natural sources of methane and nitrous oxide are important contributors to the total emission load, the anthropogenic sources have increased sharply over the last two centuries and these are the concern of the United Nations Framework Convention on Climate Change (UNFCCC). IPCC estimates of sources are summarised in Table 1.1.

Table 1.1: Sources of Natural and Anthropogenic Methane and Nitrous oxide

<table>
<thead>
<tr>
<th>Source</th>
<th>Methane (million tonnes per year)</th>
<th>Nitrous oxide (million tonnes N per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural (oceans, wetlands, soils etc)</td>
<td>110-210</td>
<td>9.0 (4.3-14.7)</td>
</tr>
<tr>
<td>Anthropogenic:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil fuel related</td>
<td>70-120</td>
<td>7.2 (2.1-19.7)</td>
</tr>
<tr>
<td>Biosphere related</td>
<td>200-350</td>
<td>1.3 (0.7-1.8)</td>
</tr>
</tbody>
</table>

Source: IPCC, 1996

New Zealand is not a major contributor of greenhouse gas emissions in the world, but its emissions are significant for the following reasons.

1. Methane and nitrous oxide are dominant in the national emissions profile, i.e. 59.5% of total emissions on a carbon dioxide equivalent basis (National Inventory).
2. The principal sources of methane and nitrous oxide are from pastoral agricultural lands and the animals that graze on them (55% of total emissions in 2000).
3. The gross levels of New Zealand’s emissions (ignoring sinks) are steadily increasing and will exceed the 1990 levels by 50-75 000 000 tonnes carbon dioxide equivalent in the first commitment period on a ‘business-as-usual’ basis (Ministry for the Environment).
4. The New Zealand government has decided to ratify the Kyoto Protocol. The government is determined to show leadership and control emissions consistent with its obligations under the Protocol.
5. Responsible management of its environment is part of the protection of New Zealand’s ‘clean green’ image on which the marketing of many of our exports depends.

The way to implementation of the decision to ratify the Protocol has been paved by the passage of the Climate Change Response Bill and decisions on policies related to meeting the nation’s obligations under the Protocol. A statement of the government’s policy and a National Interest Analysis can be found on the New Zealand Climate Change Project’s website (www.climatechange.govt.nz).

In its development of policies, the government has adopted four guiding principles to meet the national goal of a significant reduction in greenhouse gas emissions by 2012 and a permanent downward track in the amounts produced.

1. They must result in permanent reductions in worldwide emissions over the long-term.
2. They need to be responsive to a changing international context.

3. They need to be consistent with a growing and sustainable economy.

4. They need to be designed so as not to disadvantage the vulnerable in our society.

Of particular significance are the decisions that relate to agriculture, and to the management of emissions from the agricultural sector, since these emissions represent about 55% of New Zealand’s total greenhouse gas emissions.

Government’s policy for agriculture is to exempt the sector from any charge for methane and nitrous oxide emissions arising from enteric fermentation or agricultural soils for at least the first commitment period (2008-2012). However, it expects that the agricultural industries will make a contribution to research during the period (and beyond) leading to developing technologies and systems that result in a permanent reduction in such emissions from the sector. This policy recognises that not only do commercial farms fall into the ‘competitiveness-at-risk’ group of enterprises, but at present farmers have no effective means of reducing methane and nitrous oxide emissions in a meaningful way except by reducing numbers. Measurement of emissions from agricultural land and farm animals is also technically difficult and subject to uncertainty.

The Convenor of the Ministerial Group on Climate Change, the Minister of Agriculture, and the Primary Industries Council commissioned this review of recent and current research on abatement of agricultural non-carbon dioxide greenhouse gas emissions with a view to identifying the most pressing information needs and the most promising emission abatement options that warrant further research. It is anticipated that the review will be a platform for a research strategy to be pursued through a joint government/industry funded programme.

References


Chapter 2
Terms of Reference and Review Methods

2.1 Terms of Reference

The terms of reference require a critical review of recent and current New Zealand and international research on abatement of ruminant methane emissions and the emission of nitrous oxide from agricultural production systems. The purpose of the review is to identify the best future practical opportunities for abatement of these emissions and the research needed to achieve this objective. A research strategy with prioritisation of research effort is a prerequisite for costing the research to be funded by government and the agricultural sector and developing appropriate institutional arrangements for its management. An extract from the reviewers’ terms of reference can be found in Appendix 1.

2.2 The Reviewers

The scientists appointed to undertake the review were:

Dr John Freney, Honorary Research Fellow, CSIRO Division of Plant Industry. Dr Freney has had a long career in research into the cycling of nitrogen, including the production and emission of nitrous oxide from agricultural systems in Australia, New Zealand and other countries. He has served on a number of international expert panels concerned with the interaction of soil chemicals and the atmosphere.

Dr Marc Ulyatt, recently retired Senior Scientist with AgResearch Ltd and formerly with DSIR. Dr Ulyatt has a distinguished research career in ruminant digestion and rumen physiology. The first estimate of methane emissions from New Zealand ruminants was based on a model of ruminant digestion and ruminant production developed by Dr Ulyatt and co-workers. He continues to be engaged in refining the parameters of the model.

Dr Peter O’Hara, formerly Deputy Director-General of the Ministry of Agriculture and Forestry (MAF) and Group director of MAF Technology, chairs the Review Team. He is currently Chairman of the National Science Strategy Committee for Possum and Bovine Tuberculosis Control.

2.3 Scope

The scope of the review is limited to the emission of methane from animals as the result of: enteric fermentation; animal manure management; emissions from soils and the burning of crop residues and the release of nitrous oxide from nitrogenous sources in agricultural production systems including soils; animal excreta in animal waste management systems; excreta spread on soils and deposited by grazing animals; nitrogen-fixing plants; and crop residues and indirect emissions from volatilisation and leaching. The review does not include the emission of carbon dioxide from farms, the emission of greenhouse gases from the use of farm machinery, or emissions from downstream agricultural enterprises such as processing plants.

2.4 Review Process

The review has proceeded in three stages.
**Stage 1**

An initial report prepared by the Review Team sets out a critical review of research, mainly recent and current research based on:

- Published refereed papers
- Conference proceedings and other published material (including technical and policy papers)
- Discussion with scientists
- Information on current research projects
- Relevant published research from Australia and other countries.

The report encompasses:

- Sources and processes for the synthesis and emission of methane, nitrous oxide and linkages between the two.
- Emission levels, including commentary on measurement and models to estimate emission levels.
- Abatement technologies and management systems.
- Potential levels of abatement achievable by these technologies and management methods individually and collectively.
- The integration of abatement technologies and management systems into whole farm management systems or systems that operate on a broader scale.
- The costs of current research, the institutions and people involved and any instutional arrangements.

The report recommends: a framework for a research strategy that includes a definition of the type of research that can be considered as abatement research; and criteria for identifying, considering and prioritising research on emission abatement opportunities.

**Stage 2**

A Workshop jointly sponsored by Australia (Australian Greenhouse Office) and New Zealand (MAF) provided an opportunity for invited New Zealand, Australian and overseas scientists, policy analysts and industry representatives to discuss and debate the opportunities for achieving reductions in the emissions of methane and nitrous oxide.

The objective of the Workshop was to enable the participants to identify:

- The most promising technologies and management systems that will lead to abatement of methane and nitrous oxide from agriculture in the long-term.
- The research needed to enable these technologies/systems to be taken up by farmers and graziers.
- The research needed to integrate the abatement technologies/systems into farming practices, land use decisions and regional or national policy making.
- The means of demonstrating that any adopted strategies are producing the expected abatement outcome.
- The research investment priorities.
- The organisational and institutional arrangements that will facilitate the conduct of the research.
- The opportunities for collaborative research within each country, between Australia and New Zealand, and with other international organisations.

**Stage 3**

A final report prepared by the Review Team, based on the earlier analysis and the conclusions of the Workshop, develops the framework previously described and recommends a strategy
and priorities for future methane and nitrous oxide research. The strategy is intended to enable an assessment of future research costs, the potential to make progress, and the risks associated with the research and the implementation of any technology or system developed.

### 2.5 Approach

In assessing opportunities for abatement of emissions, the Review Team has taken as a starting point that any technology or system for abatement should allow the farmer or grazier to continue to make his or her management decisions as the market for the products of the farm dictates. Included in that market mix in the future may be a cost of emissions (not planned for the first commitment period).

Should an abatement technology or management system impose a cost of production in order to achieve a return to the nation in terms of reduced emissions, the decision as to where that cost should lie is a policy decision beyond the scope of this review. However, where such trade-off decisions might be taken is flagged in this review.
Chapter 3
A Summary of Current Research Investment in New Zealand

Summary

In the period 1999 to 2002, approximately $23.5 million per year was invested in all aspects of climate change research. Ninety percent of this came from government sources. Indicative figures of current investment in agricultural greenhouse gas emissions based on a survey of the principal research providers shows the following levels:

<table>
<thead>
<tr>
<th>Year</th>
<th>Expenditure ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999/00</td>
<td>582,000</td>
</tr>
<tr>
<td>2000/01</td>
<td>510,000</td>
</tr>
<tr>
<td>2001/02</td>
<td>2,649,000</td>
</tr>
</tbody>
</table>

Expenditure by FRST and MAF in 2002/03 is $3,263,000 and will be $4,715,000 in 2003/04.

Improving the National Inventory and the re-ordering of production systems research to examine abatement options were the main areas of investment over the period 1999 to 2002. A strong emphasis on measurement and inventory related research is maintained in the period 2002/2004, and research on abatement technologies has been boosted 3.5 to 5 times over the 1999/00 level.

The establishment of the Pastoral Greenhouse Gas Research Consortium represents a significant new area of investment in methane research, and is an important step in the establishment of a partnership between government and the agricultural industry in finding ways to manage agricultural greenhouse gas emissions.

Table 3.1: Summary of Research Expenditure in 2000/01 by Type

<table>
<thead>
<tr>
<th>Category</th>
<th>Content of Category</th>
<th>Expenditure ($ million)</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processes</td>
<td>Physical climate system including greenhouse gases</td>
<td>10 (43%)</td>
<td>Static</td>
</tr>
<tr>
<td>Responses</td>
<td>Inventories, mitigation and management of climate change, identification of environmental technologies</td>
<td>9 (39%)</td>
<td>Increasing as result of private sector investment and re-classification of FRST projects</td>
</tr>
<tr>
<td>Effects</td>
<td>Actual and potential impacts of climate change on land use and terrestrial and aquatic ecosystems and people</td>
<td>4 (18%)</td>
<td>Increased 1/3</td>
</tr>
</tbody>
</table>

Source: National Science Strategy Committee for Climate Change, 2000

In a report to the Minister for Research, Science & Technology, FRST (2000) advised that 6.7% of its available funds ($340,000,000) was invested in climate change research in 2000/01. While FRST considered that the level of investment was sufficient to support an
internationally credible research effort, it recommended that increased research effort was required in the areas of methane and nitrous oxide measurement and mitigation, transport emission reduction, and socio-economic analysis of climate change effects and responses. FRST also drew attention to the need for university climate change research to be strengthened to safeguard the supply of future scientists.

FRST’s Strategic Portfolio Outline, ‘Global Environmental Processes and Change’, sets out a broad ranging programme of research investment with a strong emphasis on global strategic issues. Its investment in research related to inventory, mitigation and change management matters was $5,500,000 in 2000/01 (29% of its total investment). This was 60% of the investment by all sectors (government, university, private and local government).

In the 2001 Budget, the government voted the Ministry of Agriculture and Forestry $2,750,000 over four years to improve inventory measurements for agricultural emissions. In addition, government provided FRST with $1,000,000 for ruminant methane research.

In the years 2002/03 and 2003/04, FRST has allocated $2,565,000 and $3,776,000 respectively to research on climate change matters that relate to agriculture. The Ministry of Agriculture and Forestry has allocated $500,000, $700,000 and $940,000 (approximately) to inventory research in the years 2001/02, 2002/03 and 2003/04 respectively. The allocations are summarised in Table 3.2.

**Table 3.2: Research Expenditure by the Foundation for Research, Science & Technology (FRST) and the Ministry of Agriculture and Forestry (MAF) on Greenhouse Gas Research**

<table>
<thead>
<tr>
<th></th>
<th>Expenditure ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2002/03</td>
</tr>
<tr>
<td><strong>FRST</strong></td>
<td></td>
</tr>
<tr>
<td>Fundamental processes</td>
<td>0.710</td>
</tr>
<tr>
<td>Inventory</td>
<td>1.418</td>
</tr>
<tr>
<td>Mitigation</td>
<td>0.435</td>
</tr>
<tr>
<td><strong>MAF</strong></td>
<td></td>
</tr>
<tr>
<td>Inventory – methane</td>
<td>0.340</td>
</tr>
<tr>
<td>Inventory – nitrous oxide</td>
<td>0.360</td>
</tr>
</tbody>
</table>

*Source: MAF; FRST; Survey of Research Providers (see Appendix 2)*

The information summarised in Table 3.3 on current New Zealand research on agricultural greenhouse gases and related areas of research was obtained from responses to a questionnaire completed by AgResearch Ltd, Landcare Research Ltd, Crop & Food Research Ltd, the National Institute of Water and Atmosphere and Lincoln University. Projects were allocated on the basis of their title and objectives to one category of research (see Table 3.3), but the allocation was in some cases somewhat arbitrary because the research spanned more than one category. Because the funding data included sources not cited in Tables 3.1 and 3.2, and there is a lack of some data, the figures obtained from the questionnaire could not be completely reconciled with the other data sources and therefore should be regarded as indicative.
Table 3.3: Expenditure on Nitrous Oxide, Methane and Related Research (1999-2002)

<table>
<thead>
<tr>
<th>Expenditure by category¹ ($000)</th>
<th>Year</th>
<th>1999/00</th>
<th>2000/01</th>
<th>2001/02</th>
<th>2002/03</th>
<th>2003/04³</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nitrous oxide</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic knowledge</td>
<td></td>
<td>58</td>
<td>58</td>
<td></td>
<td></td>
<td>220</td>
</tr>
<tr>
<td>National inventory</td>
<td></td>
<td>150</td>
<td>150</td>
<td>279</td>
<td>124</td>
<td>124</td>
</tr>
<tr>
<td>Abatement technologies, products and farm management systems</td>
<td></td>
<td>75</td>
<td>75</td>
<td>463</td>
<td>671</td>
<td>106</td>
</tr>
<tr>
<td><strong>Methane</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic knowledge</td>
<td></td>
<td>84</td>
<td>185</td>
<td>185</td>
<td></td>
<td></td>
</tr>
<tr>
<td>National inventory</td>
<td></td>
<td></td>
<td>694</td>
<td>694</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abatement technologies, products and farm management systems</td>
<td></td>
<td>215</td>
<td>215</td>
<td>517</td>
<td>587</td>
<td>361</td>
</tr>
<tr>
<td><strong>General Methane and Nitrous Oxide Research</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic knowledge</td>
<td></td>
<td>93</td>
<td>93</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>National inventory²</td>
<td></td>
<td>12</td>
<td>368</td>
<td>719</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Abatement technologies, products and farm management systems</td>
<td></td>
<td>50</td>
<td>236</td>
<td>283</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>582</td>
<td>510</td>
<td>2 649</td>
<td>3 309</td>
<td>1 144</td>
</tr>
</tbody>
</table>

¹ The categories were
- Basic knowledge on processes, technologies etc with no immediate practical outputs
- Primarily to improve the National Inventory
- Primarily to improve the abatement and mitigation of methane or nitrous oxide through new technologies, products or farm management systems

² This category excludes research on atmospheric processes that have an application beyond agricultural GHG

³ Data incomplete because some contracts were yet to be finalised.

Source: Questionnaire completed by AgResearch Ltd, Landcare Research Ltd, Crop & Food Research Ltd, the National Institute of Water and Atmosphere and Lincoln University

Table 3.2 demonstrates a substantial increase in funding and effort in 2001/02 and 2002/03 that is expected to continue in 2003/04. The development of a joint government/industry research programme may lead to a further increase in investment. The notable increases have been in research related to improving the national inventory and in research on the management of emissions through farm management practices. It is likely that at least some of the research in the latter category is a re-direction of effort from other aspects of research on production improvement to a more specific investigation of the mitigation of greenhouse gas emissions. The ‘general’ category is not a new category, but represents a focussing of effort on improving the national inventory and farm management systems. A more complete summary of current research programmes is provided in Appendix 2.
A significant new development is the establishment of the Pastoral Greenhouse Gas Research Consortium (PGGRC) involving Fonterra Cooperative Group Ltd, Meat New Zealand, AgResearch Ltd, Wrightson Ltd and DEEResearch. Industry funds have been matched by FRST funding to create an initial funding level of approximately $1,500,000. Funding from both sources is expected to grow over the initial five year term of the Consortium. PGGRC’s initial science strategy is based on a balanced portfolio of short, medium and long-term research on methane production in ruminants that can lead to practical on-farm methods of reducing emissions. Such methods need to be shown to be safe, leave no residues in meat or milk, be cost-effective, and be applicable to grazing animals. The focus in the first three to four years will be on discovery and proof-of-concept research that is intended to uncover a range of abatement processes and products that can be further developed as practical abatement measures. The research portfolio includes studies of potential animal, plant and rumen microbial targets.

The six key science areas of investigation and a brief description are:

1. Rumen microbial strategies to lower methane emissions
   - Exploit rumen processes which influence methanogenesis and the survival of methanogens to provide novel on-farm strategies.

2. Forage and plant inhibitors to lower methane emissions
   - Identify and quantify inhibitory properties of forage inhibitors.

3. Genomics for identifying methanogen inhibition targets
   - Compare and contrast rumen and non-rumen methanogens in order to pin-point areas of archael/bacterial ‘weakness’.

4. Animal factors affecting methane emissions
   - Quantify the genetic and environmental components of between-animal variation.

5. Proof-of-function of possible methane-reducing technologies
   - Animal assessments to establish potential of possible on-farm technologies, safety, and acceptance to consumer.

6. On-farm testing
   - Acceptability at a farm systems level (to follow successful leads from above).

These areas of science investigation form interlinked strands that will inform, negate and encourage certain lines of ongoing research (the go/no-go questions for the Science Advisory Group).

Although PGGRC’s initial research portfolio concentrates on methane, work on nitrous oxide is planned.

**Conclusions**

The research emphasis on agricultural greenhouse gases, their sources and abatement technologies has been a recent phenomenon. Funding of studies on abatement has risen 3.5 to 5 times the 1999/00 levels, but more time will be needed for these studies to bear fruit. The increased investment in measurement and inventory work will also need to be sustained in the long-term, not only to improve the National Inventory, but also to ensure that any abatement measures that may be adopted in the future can be measured or estimated.

The emergence of the PGGRC represents an important step towards a partnership between government and the agricultural industry in dealing with their respective interests in controlling agricultural emissions.
Comments on the content of current research can be found in the chapters which follow.

**References**


Chapter 4
New Zealand’s Greenhouse Gas Emissions and the Contribution from Agriculture

Summary

In 2000, the official estimates of New Zealand’s greenhouse gas emissions showed that methane and nitrous oxide represented 59.6% of total emissions in CO₂ equivalent terms, and emissions from agriculture were 55% of total emissions. Compared to 1990, methane emissions were 6.17% less, a fall largely attributable to the fall in sheep numbers, and nitrous oxide was 6.35% more.

The most important source of agricultural methane is ruminant enteric fermentation (98.7%), and the most important sources of nitrous oxide are faeces and urine deposited by grazing animals on pasture, animal waste and fertiliser nitrogen in soils, and indirect emissions from atmospheric deposition and leaching.

Research is leading to the adoption of revised models for estimating methane and nitrous oxide emissions that take into account animal numbers, animal productivity and New Zealand specific emission rates that are based on empirical data. In the decade 1990 to 2000, productivity gains have been significant, particularly in the dairy and sheep industries. The effect of the revised methodology is to show that the official estimates understate emission rates and that there is a rising linear trend in emission rates. Extrapolation of the curves to 2010 indicates that methane emissions will exceed 1990 levels by 15.7% in gross terms, and nitrous oxide emissions will exceed 1990 levels by 20-30%.

The use of nitrogen fertiliser is increasing at an exponential rate. Emission rates are most sensitive to changes in total animal numbers and to productivity. An emerging policy question is how the trade-off will be made between that national objective of maintaining emissions at 1990 levels and individual farmer’s objectives for the performance of their livestock. A number of abatement strategy options may confer productivity advantages as well as reduced emissions.

Current and planned research is directed at:
- Extending the range of methane emission measurements from animals.
- Improving the measurements of nitrous oxide release from excreta under a variety of soil and seasonal conditions.
- Improving the assessment of indirect emissions.
- Improving (or selecting) the models that can be used to estimate emissions in the future leading to robust estimates that conform with IPCC good practice.
- Developing methodologies that allow broad scale assessments of herbage quality and paddock/farm/locality emissions.

It is particularly important that methods can verify that any abatement strategies adopted in the future are delivering the expected effects.

The New Zealand greenhouse gas emissions that have relevance to this report are summarised in Table 4.1.
### Table 4.1: Summary of New Zealand’s Greenhouse Gas Emissions

<table>
<thead>
<tr>
<th>Gas</th>
<th>1990 CO₂ Equiv (Gg)</th>
<th>2000 CO₂ Equiv (Gg)</th>
<th>% Change 1990 to 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>25 266.88</td>
<td>30 851.78</td>
<td>22.10</td>
</tr>
<tr>
<td>CH₄</td>
<td>35 390.17</td>
<td>33 204.84</td>
<td>-6.17</td>
</tr>
<tr>
<td>N₂O</td>
<td>11 898.73</td>
<td>12 654.41</td>
<td>6.35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>73 161.17</strong></td>
<td><strong>76 955.61</strong></td>
<td><strong>5.19</strong></td>
</tr>
</tbody>
</table>


Total emissions from agriculture were 43 311 Gg CO₂ equivalents in 1990 (59.2% of total) and 41 940 Gg CO2 equivalents in 2000 (54.5% of total). The 2000 figures represent an increase of 0.5% over 1999, but are 3.17% less than in 1990, due in large part to the reduction in sheep numbers.

The revised 1996 IPCC methodology was used in the preparation of the report. IPCC Good Practice Guidance was followed by subjecting the agricultural sector inventory to quality control and quality assurance procedures with scientific peer review. Changes from the previous National Report included adoption of a June figure for animal population statistics, and the emission factor for field burning of agricultural residues was increased from 0.05 to 0.5.

The report identifies the following planned work that will be incorporated in the next national report:

- Improvement in the methodology for calculating ruminant methane emissions
- A review of soil derived N₂O emissions factors.

The report notes that the level of uncertainty in the inventory is very high, but no numerical estimates of the level are possible owing to a lack of the means to quantify uncertainty levels for the non-CO₂ sources, particularly N₂O.

### 4.1 Estimation of Agricultural Methane Emissions

Agricultural methane emissions arise from three principal sources (5th National Inventory Report). The relative importance of each source is reflected by the percent of total CH₄ emissions from each source:

- Enteric fermentation by ruminants that results in methane release by eructation and flatus (98.7%)
- Manure management (1.2%) (the estimate excludes emissions from pig and poultry manure – see below)
- Field burning of agricultural residues (0.07%).

#### 4.1.1 Estimation of methane from enteric fermentation

Methods of measurement of methane are discussed in Chapter 6.
Estimation of enteric methane emissions from ruminants in the National Inventory Report 1999/2000 is based on a Tier 1/Tier 2 hybrid method using the livestock numbers for the June year averaged over three years, multiplied by emission factors derived from a model of ruminant digestion developed by Ulyatt et al (1991). The model utilises climatic regions, land areas and grassland types to estimate the number of animals grazing particular types of forage, animal types (breeding and other) to estimate liveweight gain curves and the intake of digestible dry matter, and a mathematical model of methane production developed by Baldwin et al (1987) to estimate CH₄ synthesis. The elements of the model are illustrated in Figure 4.1.

Figure 4.1 Elements of the Model Used to Estimate Enteric Methane Emissions from Ruminants

Source: Ulyatt et al, 1991

Clark and Ulyatt (2002) have reviewed the 1991 model with the following conclusions:
1. The climatic zones, North, Central, East and South with their temperature and rainfall descriptors were retained.
2. The three grassland types (improved, unimproved and tussock) used in the 1991 model were replaced by a single type since studies by Clark (2001) showed that doing so altered emissions by <1%. A weighted average energy concentration for pastures in each climatic zone and for each animal class was calculated and used for all years.
3. The animal numbers by species were those for the June year, and were based on census data or MAF estimates in those years where census data did not exist. Rolling three year averages were used as required by IPCC 1996 methodology.
4. Actual production data for each year was derived from three sources (MAF, Livestock Improvement Corporation, The Economic Service). Milk yield data was available on a regional basis, but national figures were used for all regions where regional data was not available.
5. The energy requirements of the classes and sub-classes of livestock were calculated from production figures using the 1991 model methodology with the exception of sheep (see below). The energy requirements and the energy concentrations of forage were used to calculate dry matter intake, and digestible dry matter intake was calculated using climate zone and seasonal data.
6. Methane emissions were estimated from daily intakes of digestible dry matter and empirical data of methane emissions from New Zealand animals. This approach replaced the mathematical model of rumen function developed by Baldwin et al (1987) that is used in the 1991 emissions model. Clark (2001) found that the methane production values estimated by Ulyatt (1991) that averaged 32g CH$_4$ per kg digestible dry matter intake exceeded data from a number of New Zealand experimental observations (see Clark & Ulyatt, 2002) by 15-20%.

Ulyatt (Clark & Ulyatt, 2002) has concluded that methane emissions can be predicted from the amount of methane produced per kg of digestible dry matter intake that depended only on pasture quality. However, young sheep (<12 months old) produce less methane than their adult counterparts on the same ration. Data was only available for sheep and lactating dairy cows. For inventory calculations, goats are assumed to be the same as sheep, beef cattle the same as dairy cattle, and deer an average of sheep and cattle.

The main points of difference in the proposed methodology as compared with the 1991 model presently used for National Inventory calculations are:

1. Replacement of fixed specific emission factors by a model that uses actual animal numbers, actual production data and empirical data on diet quality.
2. Livestock performance characteristics for each year are based on actual data.
3. A methane emission factor that is based on New Zealand empirical data.

When the enteric methane inventory is estimated using the revised model, two contradictory trends emerge. When compared to the official estimate of methane emissions for 1990 and 2000, the revised estimates are 26% and 16% lower, a difference largely explained by the lower estimates of methane emitted per kg of digestible dry matter intake. However, the revised estimates based on actual production data rather than a single emission factor show the effect of significant productivity gains in the sector, in particular in the dairy and sheep sectors with the revised 2000 methane emission estimate being about 7% higher than the revised 1990 estimate.

Davison (2000) has summarised the productivity gains in the sheep industry that have been made over the period 1986/87 to 1999/00 (Table 4.2).

**Table 4.2: Productivity Gains in the New Zealand Sheep Industry in the Period 1986/87 to 1999/00**

<table>
<thead>
<tr>
<th></th>
<th>1986/87</th>
<th>1999/00</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total sheep numbers (million)</td>
<td>67.47</td>
<td>46.08</td>
<td>-32%</td>
</tr>
<tr>
<td>Number ewes (million)</td>
<td>47.79</td>
<td>32.20</td>
<td>-33%</td>
</tr>
<tr>
<td>Lambing %</td>
<td>97.7</td>
<td>114.30</td>
<td>+16.6%</td>
</tr>
<tr>
<td>Number slaughtered (million)</td>
<td>31.63</td>
<td>25.55</td>
<td>-19%</td>
</tr>
<tr>
<td>Average weight at slaughter (kg)</td>
<td>13.2</td>
<td>16.48</td>
<td>+25%</td>
</tr>
<tr>
<td>Total bone-in meat (000 tonnes)</td>
<td>417.6</td>
<td>421.00</td>
<td>+0.8%</td>
</tr>
<tr>
<td>Average fleece weight</td>
<td>Estimated genetic gain +0.02kg/sheep/year</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: Davison, 2000*

The decline in sheep numbers is attributable to the conversion of sheep and beef farms to dairying (an estimated 2 500 000 sheep and beef stock units displaced in the past six years (Davison, 2000)) and to forestry. Nevertheless, it is clear that farmers have achieved productivity gains by growing more pasture dry matter on a smaller area of land.

The dairy industry presents a similar picture (Clark & Ulyatt, 2002). Milking cow numbers have increased by 887 864 and other dairy animals by 249 555 over the decade 1990 to 2000.
Milk yields per cow have increased by an average 747 litres and cow weights by 34 kg. Thus the increase in methane emissions from the national dairy herd are in part due to the increase in number that would be taken account of in the official estimates, and in part by the increase in liveweight and milk production that the specific emission factor understates.

Rys (2002) has also summarised the productivity gains made by the sheep, beef cattle and dairy cattle industries over the period 1990 to 2000.

The net effect is that if the revised model to estimate methane emissions is adopted as the official inventory tool, it will show an upward trend in total enteric methane emissions over the period 1990 to 2000. Clark and Ulyatt (2002) found that the revised methane emissions per animal for dairy and beef cattle sheep and deer over the period 1990 to 2000 trend fitted a linear relationship (goats were assumed to have constant emissions over the period), and used this to estimate 2010 emissions by extrapolation. The predicted total and per animal methane emissions are shown in Table 4.3.

Table 4.3: Predicted Total and Per Animal Methane Emissions for 2010 Compared with 1990 Levels

<table>
<thead>
<tr>
<th></th>
<th>Total Methane (Gg)</th>
<th>Methane per Animal (kg/year)</th>
<th>Change in Emissions since 1990 (Gg)</th>
<th>Forecast % Change since 1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy Cattle</td>
<td>446.14</td>
<td>81.9</td>
<td>+220.30</td>
<td>+97</td>
</tr>
<tr>
<td>Beef Cattle</td>
<td>237.47</td>
<td>55.7</td>
<td>+7.33</td>
<td>+3</td>
</tr>
<tr>
<td>Sheep</td>
<td>483.52</td>
<td>13.3</td>
<td>-130.27</td>
<td>-21</td>
</tr>
<tr>
<td>Deer</td>
<td>101.23</td>
<td>24.2</td>
<td>+82.95</td>
<td>+553</td>
</tr>
<tr>
<td>Goats</td>
<td>1.75</td>
<td>9.4</td>
<td>-7.9</td>
<td>-72</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1270.11</td>
<td>+172.41</td>
<td>+15.7</td>
<td></td>
</tr>
</tbody>
</table>

Source: Clark & Ulyatt, 2002

Predictions of changes in levels are sensitive to two factors, changes in animal numbers and changes in productivity (in particular changes in liveweight and in the weight of product). For example, the predicted emissions from dairy cattle assume an increase of 2 000 000 head of cattle and an increase in methane emission per head of 23% over 1990 figures. By 2000, the increase in dairy cattle numbers over 1990 was 888 000, and it is predicted that continuing conversion of sheep and beef farms to dairy farms will enable increases in dairy cattle numbers of 10 000 per year (Davison, pers comm). Whether this rate will be achieved will depend on the availability and cost of land and the market prices for dairy products. Bodeker (pers comm) considers that the rate of expansion of dairying on to sheep and beef farms will slow, but there is considerable unrealised productive capacity on the newly established farms.

The increased productivity of sheep is compensated for by a predicted continuing decline in sheep numbers as the result of conversion of sheep and beef farms to dairying or to forestry (predicted plantings are 20 000 to 60 000 per year). Deer numbers are predicted to continue to grow displacing sheep and beef cattle, but the rate will depend on market price differentials. Methane emissions per head are also expected to grow. However, actual measurement of methane emissions being undertaken at present will have an unknown impact on future per head estimates.

Clark and Ulyatt (2002) examined the sensitivity of methane emission estimates for 2010 to changes in the levels of animal performance, total animal numbers, and changes in the species mix in animal population estimates. Varying performance increases between 10 and 30%, and using 2010 population estimates, showed that total methane emissions could range from 1
127.71 to 1 322.99 Gg methane, 2.7% to 20.5% higher than 1990 levels. Since a 10% production increase has been obtained in the dairy and sheep industries in the 1990-2000 decade, and 30% is a likely upper limit, a more probable range of production increases of 15 to 25% increase would result in methane emission increases of 7 to 16% above 1990 levels. Methane emission rates were sensitive to changes in total animal numbers, but were relatively insensitive to varying the species mix in population numbers (for example reducing the estimated 2010 numbers of dairy cattle and deer and increasing the sheep numbers by a corresponding amount).

4.1.2 Methane emissions from animal manure management

Methane emissions from grazing animals is estimated by multiplying the estimated faecal dry matter output for dairy and beef cattle, sheep, goats and deer (Joblin & Waghorn, 1994) by emission factors derived from the measurement of the methane output of sheep faeces incubated at 37°C for 20 days. This experimental treatment measures the maximum rate of methane production rather than an actual rate at ambient temperatures. Thus the method probably overestimates actual methane emissions from this source.

It is thought that the faeces of most species shed on pasture decompose aerobically (National Inventory Report 1999/2000). However the form of bovine faeces may facilitate some anaerobic fermentation and the production of methane (Tate, pers comm). Further research is planned to clarify emission rates from the faeces of all animal types.

The National Inventory Report does not include emissions from pig and poultry faeces as no New Zealand specific emission factors are available. No methane emissions from dairy farm liquid manure disposal systems are reported.

4.1.3 Methane emissions from the field burning of agricultural residues

While the National Inventory Report 1999/2000 has changed the “fraction [of] land burned” from 0.05 to 0.5%, burning is not a significant source of trace gases because of the relatively small area devoted to grain crops (1.4% of total farm land), and burning of residues is not a common practice. The burning of tussock grasslands, once a common practice, is now actively discouraged for soil conservation and biodiversity reasons.

4.2 The Estimation of Nitrous Oxide Emissions from Agricultural Production Systems

The National Inventory is constructed using the six alternative animal waste management systems described in the IPCC guidelines. The elements that make up the National Inventory are illustrated in Figures 4.2 and 4.3. The keys to the figures indicate where specific New Zealand partitioning and emission factors are employed. IPCC guidelines and factors for Oceania are used for all other calculations.

The contributions that the various elements make to the nitrous oxide emission profile are summarised in Table 4.4. As would be expected in a country where 88% of agricultural land is devoted to pastoral farming, and where intensive swine and poultry farms make relatively minor contributors of animal waste, the principal sources of nitrous oxide are: emissions from urinary and faecal nitrogen deposited by grazing animals and nitrogenous fertilisers through direct emissions from agricultural soils; and indirect emissions arising from ammonia volatilisation and atmospheric deposition and leaching of nitrate to ground waters, rivers and to the sea. Other animal waste management systems and burning make only minor contributions. The relative inefficiency of use of plant nitrogen by grazing animals is a feature of the New Zealand pastoral system. Haynes and Williams (1993) reported N retention values of 16% on a typical dairy farm and 8% on a typical hill country sheep farm.
Figure 4.2: Sources of Direct Nitrous Oxide Emissions Estimated in the National Inventory

Key to Figure 4.2

Fractions

1. Animal waste (faeces and urine) deposited on pasture by grazing animals. This is made up of the entire nitrogen excretion from non-dairy cattle, sheep, goats and deer, 89% of dairy cattle output and 3% of swine output. The values for nitrogen excretion by dairy cattle, non-dairy cattle, sheep, goats and deer are New Zealand specific. Output calculations are based on McCrae and Ulyatt (1974) for sheep, Ulyatt (pers comm) for cattle, goats and deer. Oceania default values (IPCC, 1997) are used for pigs and poultry.

2. A mixture of gases is emitted through burning. IPCC values are used to calculate the amount of each gas produced. The fraction of land burned was increased from 0.05 to 0.5 for the 5th National Inventory.

3. The area of cultivated organic soils is an estimate since no data is collected. A review by Kelliher et al (2002) indicates that the area of ‘cultivated’ organic soils is larger than the currently used figure, and that the revised IPCC default emission rate of 8 kg N/ha/year be used in the future.

4. Includes nitrogen from the residues of non-nitrogen fixing crops (FRAC_{NCR0}), residues of nitrogen from nitrogen-fixing crops (FRAC_{NCRBF}), but excludes the fraction of the crop residue removed from the field (FRAC_{R}) and the fraction of residue burned in the field (FRAC_{BURN}).

5. Crop biomass multiplied by the fraction of nitrogen in the crop (FRAC_{NCRBF}).

6. Nitrogen content of applied synthetic fertiliser, but excludes the fractions that are volatilised (FRAC_{GASP}) and leached (FRAC_{LEACH}).

7. Excreta nitrogen is allocated proportionately to anaerobic lagoons, solid storage and dry lot and other systems. The nitrogen contribution from dairy cattle is based on Ulyatt (pers comm). The % nitrogen allocated to anaerobic lagoons is based on Haynes and Williams (1993). The amount spread on pasture and the amount deposited by grazing animals is considered under “soils”.

Emission factors

a) The emission factor (EF_{3} PR&P) for nitrous oxide emitted from animal waste deposited on pasture is New Zealand specific based on Carran et al (1995) and Sherlock et al (1995).

b) The emission rate (EF_{2}) is the IPCC default rate of 5 kg nitrous oxide N/ha/year. IPCC good practice guidance has updated this rate to 8 kg nitrous oxide N/ha/year since the 5th National Inventory was completed.

c) The emission factor (EF_{1}) is the IPCC rate of 0.0125 kg nitrous oxide N/kg N.

d) The IPCC emission factors are applied to the proportions of nitrogen in anaerobic lagoons, solid storage and drylot, and other storage systems.
Figure 4.3: Indirect Nitrous Oxide Emissions


Key to Figure 4.3

Nitrogen applied to soils as synthetic fertiliser (NFERT) and animal wastes (NAWMS) may be lost to the atmosphere as ammonia and nitric oxides, or lost by leaching or run-off to water bodies.

Pathway 1 represents the fractions of fertiliser nitrogen and animal waste nitrogen that are volatilised, and the proportion that is converted to nitrous oxide.

Pathway 2 represents the proportion of leached nitrogen that is emitted as nitrous oxide from water bodies. A New Zealand specific emission factor based on data from Ledgard et al (1996) and Heng et al (1991) is used.

Table 4.4: Nitrous Oxide Emissions from Agricultural Production in 2000

<table>
<thead>
<tr>
<th>SOURCE OF N</th>
<th>TOTAL N kg N</th>
<th>N₂O -N Gg</th>
<th>N₂O Gg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faeces and urine deposited on pasture (N_{EXAWMS})</td>
<td>1 210 519 849</td>
<td>12.104</td>
<td>19.022</td>
</tr>
<tr>
<td>Organic soils</td>
<td>0.830</td>
<td></td>
<td>6.679</td>
</tr>
<tr>
<td>Soils:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertiliser N (F_{SN})</td>
<td>191 400 000</td>
<td>71 159 839</td>
<td>3.420</td>
</tr>
<tr>
<td>Animal waste (F_{AW})</td>
<td>3 104 000</td>
<td>7 948 407</td>
<td></td>
</tr>
<tr>
<td>N-fixing crops (F_{BN})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop residue (F_{CR})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total direct soil emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indirect N₂O through</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaching NFERT</td>
<td>212 666 667</td>
<td>5.671</td>
<td>13.329</td>
</tr>
<tr>
<td>NAWMS</td>
<td>1 299 499 648</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indirect N₂O through</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>atmospheric deposition fraction from fertiliser</td>
<td>21 266 667</td>
<td>2.812</td>
<td></td>
</tr>
<tr>
<td>fraction from AWMS</td>
<td>259 893 930</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total indirect soil emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic lagoons</td>
<td>45 580 342</td>
<td>0.072</td>
<td></td>
</tr>
<tr>
<td>Solid storage/dry lot</td>
<td>996 507</td>
<td>0.030</td>
<td></td>
</tr>
<tr>
<td>Other AWMS</td>
<td>42 402 950</td>
<td>0.333</td>
<td></td>
</tr>
<tr>
<td>Field burning</td>
<td>2 304 000</td>
<td>0.025</td>
<td></td>
</tr>
</tbody>
</table>


The ongoing development of a robust, credible inventory based on IPCC Good Practice and Tier 2 methodology remains a high priority. Further, the bases for measuring and estimating the emissions of methane and nitrous oxide need to be sufficiently sensitive to demonstrate the impact of the introduction of abatement measures. There are a number of matters related...
to the calculation of the National Inventory that are the subject of current investigation. The research programme to support the development of the inventory is discussed in Section 5.4.

4.2.1 The effect of animal numbers and productivity

For faeces and urine deposited on pasture, nitrous oxide emissions are calculated from animal numbers*kg nitrogen excreted per animal*emission factor. The animal numbers are derived from national statistics, nitrogen excretion is based on a limited number of observations, and a single emission factor is used (de Klein et al, 2001; Ledgard, 2002).

An alternative approach is to calculate nitrogen excretion as the difference between nitrogen intake and nitrogen incorporated in the production of meat, milk, fibre etc using a nutrient balance model (OVERSEER) that employs regional livestock population statistics, regional animal production data and regional estimates of pasture dry matter production and nitrogen concentration (de Klein et al, 2001; Ledgard, 2002). When the inventory is calculated using these parameters, nitrogen excretion rates for 1990, 1999 and 2010 (estimated) were 33%, 51% and 58% higher than the official estimates. When the emission factor is applied, nitrous oxide emissions were estimated in 1999 to be 10% higher than 1990 levels and are projected to be 20-30% higher in 2010, whereas official estimates indicate a lesser increase (8%). The upward trend in emissions parallels the observations on methane emissions discussed above and the explanation is identical.

The OVERSEER model is widely used in New Zealand, both as a research tool and as a feed budgeting tool by farmers and their consultants (Ledgard, 2002). Currently, it accommodates environmental nitrogen losses and will be updated in 2003 to include greenhouse gas emissions.

4.2.2 Specific nitrous oxide emission factor

Since 1997, New Zealand has used a single country-specific emission factor to estimate nitrous oxide emissions from excreta (EF3PR&P) (Sherlock et al, 1997). The question is raised as to whether a single factor can be used to represent all excreta emissions in all regions and soil types, given the extent of variability in agricultural practices and husbandry. de Klein et al (2001) examined nitrous oxide emissions from cattle urine applied to four soils in three different regions and found emissions ranged from <0.5% to 2.6% of the urine nitrogen applied, the difference being largely attributable to soil drainage class.

When the observed rates were applied to national soil drainage class distribution data and a weighted average EF calculated, the result, 0.94%, was close to the EF currently used (1%).

Saggar (2002) is developing a denitrification-decomposition model (NZ-DNDC model) to simulate emissions from soils that takes account of climate, drainage type, grazing and excretal nitrogen inputs.

Nonetheless, there are limited observations on the similarities and differences between cattle and sheep urine (Whitehead, 1995; Barton et al, 2000), a lack of data on the partitioning of nitrogen excreted between faeces and urine, and limited data on the rate of emission from urine as compared to faeces (Yamulki et al, 2000). While it is clear that emission rates are higher from poorly drained soils, it is not yet clear how much influence, if any, the form of nitrogen application has on emission rates.

Most of the observations to date have been made on flat, relatively fertile, land. There is a lack of data on emissions in hill country that is more typical of the land grazed by sheep, beef cattle and deer. In general, this land would be expected to be less fertile with a much tighter nitrogen cycle.
4.2.3 Use of nitrogen fertiliser

While the fixation of nitrogen by pasture legumes remains the most important means of supplying nitrogen to New Zealand soils, the use of synthetic nitrogen fertiliser has been growing steadily over the past decade (Table 4.5).

Table 4.5: Nitrogen Fertiliser Use 1988 to 2002

<table>
<thead>
<tr>
<th>YEAR</th>
<th>N (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988/89</td>
<td>51 663</td>
</tr>
<tr>
<td>1989/90</td>
<td>59 265</td>
</tr>
<tr>
<td>1990/91</td>
<td>61 694</td>
</tr>
<tr>
<td>1991/92</td>
<td>70 122</td>
</tr>
<tr>
<td>1992/93</td>
<td>104 095</td>
</tr>
<tr>
<td>1993/94</td>
<td>124 131</td>
</tr>
<tr>
<td>1994/95</td>
<td>151 263</td>
</tr>
<tr>
<td>1995/96</td>
<td>153 780</td>
</tr>
<tr>
<td>1996/97</td>
<td>143 295</td>
</tr>
<tr>
<td>1997/98</td>
<td>155 467</td>
</tr>
<tr>
<td>1998/99</td>
<td>166 819</td>
</tr>
<tr>
<td>1999/2000</td>
<td>189 096</td>
</tr>
<tr>
<td>2000/01</td>
<td>248 000</td>
</tr>
<tr>
<td>2001/02</td>
<td>279 148</td>
</tr>
</tbody>
</table>

Source: Furness, pers comm, 2002

Furness (pers comm) noted that some caution should be exercised in using these figures, because in some years estimates have been used in the absence of actual figures.

There are a number of reasons for the increased use, for example, increased returns for products, tactical use to overcome seasonal feed shortages, and loss of clover in pasture due to clover root weevil. There is some evidence indicating that it is being used more strategically to ensure a steady supply of forage, and that this accounts for the sharper increase in use in the last three years. Whether the trend will continue, and how much it might be modified by the economics of farming, is difficult to determine. Ledgard (2002) has shown that nitrous oxide emissions from nitrogen fertiliser in 2000 were 117% higher than the 1990 levels and, assuming a linear extrapolation of the rate of increase over the past three years, are projected to be 178% higher in 2010.

The extent of use of nitrogen fertiliser in the future represents an area of uncertainty in estimating future nitrous oxide emissions.

4.3 Uncertainty

The National Inventory 1999/2000 notes:

“The current level of uncertainty in the inventory is very high, although a numerical value for this submission has not been included as there is currently no accurate method of assessing the uncertainty of several of the non-CO₂ key sources – particularly that of nitrous oxide.”

Animal numbers used in calculations are based on census and sample data, and do not contribute significantly to uncertainty. The uncertainty of methane emissions estimated according to the Ulyatt (1991) model as used to compile the National Inventory is considered to be about ±20% (National Inventory). The revised method of estimating emissions (Clark & Ulyatt, 2002) is believed to give a more accurate picture of emissions from grazing animals, but is not necessarily less uncertain because of the variation inherent in the biological processes being measured.
The National Inventory does not assign a numerical value to the uncertainty of nitrous oxide emission estimates for the following reasons:

- Some of the input data is highly uncertain.
- There is inconsistency in the source data for fertiliser use statistics.
- Some of the New Zealand specific emission factors are based on limited data – for example, the leaching fraction estimate is based on studies of high nitrogen input land and should be regarded as an upper limit rather than an average value.
- The area of organic soils under cultivation is not accurately known.
- The nitrogen in New Zealand soils is mostly derived from biological processes - the decay of nitrogen-fixing pasture legumes and animal excreta - and can only be estimated by indirect means.
- Some IPCC guidelines and default values do not represent New Zealand conditions or practices.

In their study of the revised method of estimating nitrous oxide emissions, de Klein et al (2001) found that the emission factor for nitrogen from faeces and urine (EF3PR&P) was most highly correlated with empirical emission rates accounting for 80% of the uncertainty. The emission factor for leachate nitrogen (EF5) was the next most influential variable accounting for 95% of the uncertainty. New Zealand’s N2O emission rate has a positively skewed distribution reflecting the skewed distribution of soil drainage classes. They are 95% confident that the emission rate is between 23 and 81 Gg per year (mean=44.3 Gg, mode=40.6 Gg).

The adoption of the revised model for estimating enteric methane, and the OVERSEER model for estimating nitrogen output by grazing ruminants, needs to be preceded by completion of the work and its publication in a peer reviewed journal. Clark and Ulyatt (2002) identified the need for methane emission measurement from a wider cross-section of the livestock sector in order to verify and expand the relationship of emissions to herbage quality, feed intake, animal, age and production characteristics. However, the inherent variability of the biological processes that lead to the formation of methane is likely to limit the degree to which measurement error can be reduced. This suggests that measurement of the scale of uncertainty should be a part of research to improve the accuracy of measurements or development of estimation models. de Klein et al (2001) have made such uncertainty estimates in their examination of the emission factor for nitrous oxide from urine.

### 4.4 Research to Improve the National Inventory

As the figures in Table 3.2 show, there has been a substantial increase in effort to improve the estimates of methane and nitrous oxide emissions from agriculture and this effort will continue (Rys, pers comm). The objectives of the research programme are to develop New Zealand specific Tier 2 emission estimates wherever appropriate, or verify that IPCC default values provide a satisfactory estimate:

- Develop robust models for estimation of emissions that reflect New Zealand farming conditions and systems
- Reduce the level of uncertainty in emission estimates as far as is practical
- Provide for estimating changes in emission rates as the result of the adoption of mitigation strategies.

The funding agencies, FRST, MAF and MfE are assisted in identifying and setting priorities by inter-institutional expert groups (‘Methanet’ and ‘N2Onet’). The groups also foster collaborative research.
The current research is summarised in Table 4.6.

**Table 4.6: Current Research to Improve the National Inventory**

<table>
<thead>
<tr>
<th>Nitrous oxide</th>
<th>2001/02</th>
<th>2002/03</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Determination of the N$_2$O emission factor from animal urine following application in summer in three regions of NZ (Lincoln University, AgResearch, Landcare)</td>
<td>Determination of the N$_2$O emission factor from dung and urine following application in spring in three regions of NZ</td>
</tr>
<tr>
<td></td>
<td>Indirect N$_2$O emissions from leached nitrogen (Crop &amp; Food, AgResearch)</td>
<td>Partitioning of nitrogen excretion by sheep, beef and dairy cattle between dung and urine</td>
</tr>
<tr>
<td></td>
<td>Evaluation of process based models (Crop &amp; Food, AgResearch, Landcare)</td>
<td>Upscaling national N$_2$O estimates: method evaluation</td>
</tr>
<tr>
<td></td>
<td>Improved estimates of nitrogen intake by grazing animals (AgResearch)</td>
<td>Recalculation of the NZ N$_2$O inventory using all new emission factors gathered to date and expert judgement for the remainder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quantification of N$_2$O emissions from soils using $^{15}$N isotopomer analysis</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Methane</th>
<th>Recalculate the 1990-2000 methane inventory using a modified version of the Ulyatt et al (1991) model and update emission predictions for 2010 (AgResearch)</th>
<th>Methane emissions from growing dairy heifers using SF$_6$ technique</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tier 2 methane inventory development (AgResearch)</td>
<td>Methane emissions from grazing deer using SF$_6$ technique</td>
</tr>
<tr>
<td></td>
<td>Quantify methane emissions from dung deposition on pastures by grazing sheep (AgResearch and others)</td>
<td>Derive generalised relationships between methane emissions from grazing ruminants and feed/animal characteristics</td>
</tr>
<tr>
<td></td>
<td>Develop a methodology to obtain spatial and temporal estimates of herbage quality using satellite imagery (Landcare, AgResearch)</td>
<td>Spatial and temporal estimates of herbage quality</td>
</tr>
<tr>
<td></td>
<td>Paddock and farm-scale N$_2$O and CH$_4$ emissions measurement (Landcare)</td>
<td>Re-calculation of the NZ CH$_4$ emissions inventory using IPCC Tier 2 approach and provision of a prototype computerised method for inventory calculations</td>
</tr>
<tr>
<td></td>
<td>Novel field-based method for measuring N$_2$O and CH$_4$ fluxes (Landcare)</td>
<td></td>
</tr>
</tbody>
</table>

*Source: MAF; FRST*
4.5 Conclusions

It is clear that grazing ruminants are responsible directly or indirectly for almost all of the methane and most of the nitrous oxide emissions from agriculture. The work of Clark and Ulyatt (2002) and Ledgard (2002) demonstrates the sensitivity of the emissions estimates, not only to animal numbers, but also to the effect of productivity gains. These gains have been significant in the dairy and sheep industries in the past decade. Revised inventory calculations, which take both animal numbers and productivity gains into account, demonstrate an upward trend in emissions that is in contrast to the trend demonstrated by the present method of making inventory calculations.

The adoption of abatement strategies, which yield both a reduced emission rate and a productivity gain, such as greater retention of carbon and nitrogen as animal tissue or product, will pose an interesting policy question as to the relative values of the increased production and the cost of emissions and who captures the benefits of productivity gains or emission reductions.

To illustrate this point, the productivity and methane output changes for an ‘average’ dairy cow and an ‘average’ ewe were compared based on the production data of Rys (2002), methane output data of Clark and Ulyatt (2002), and nitrogen excretion data of Ledgard et al (2002).

The difference in milk solids produced per cow between 1990 and 2000 is 68 kg, which at the 2002 announced price of $3.60/kg is valued at $244.80. The difference in methane output per cow is 8.5 kg methane/year or 1785 kg CO₂ equivalent/year. The difference in N₂O output is 294g/year or 91.14 kg CO₂ equivalent. At $25/tonne these emissions are valued at $6.74.

As compared to the 1990 ewe that produced 0.98 lambs at an average slaughter weight of 13.2 kg, the 2000 ewe produced 1.14 lambs at an average slaughter weight of 16.48 kg, that is, 5.85 kg more lamb meat valued at $21.90 ($3.75/kg). She also produced 0.5 kg more wool valued at $2.25 ($4.50/kg). The difference in methane output was 1.4kg/year (29.4 kg CO₂ equivalent), and the difference in N₂O production was 45g/year (13.95 kg CO₂ equivalent). Thus the increment in her emissions was valued at $1.08 at $25/tonne.
Tate Kevin (2002): personal communication.
dung and urine amendments on the isotopic content of N2O released from grasslands. Rapid
Communications in Mass Spectrometry, 14: 1356-1360.
Chapter 5
The Measurement of Agricultural Methane and Nitrous Oxide Emissions

Summary

Methods of measuring agricultural methane and nitrous oxide emissions are discussed and evaluated. While calorimetry has been the ‘gold standard’ for measurement of methane output by ruminants, it has significant disadvantages in measuring outputs to simulate the grazing animal. Sulphur hexafluoride tracer technology is the method of choice for the grazing animal.

Nitrous oxide emissions from soils are most frequently measured by chamber techniques. A modification using underground permeable pipes to sample fluxes is being tested at present.

Micrometeorological methods are likely to have principal value in monitoring emissions at a whole farm-scale or larger.

Modeling will continue to be the principal method of estimating emissions for inventory purposes. The benefits of pooling effort in model development should continue to be explored.

The importance of improving the methods for the measurement of methane and nitrous oxide emissions has been highlighted in Chapter 4. Improving the effectiveness and efficiency of measurement is a key to providing credible models that can estimate changes in emission levels in response to the adoption of abatement strategies, and to verify that abatement is occurring.

5.1 Measurement of Methane Emission

For the development of an accurate inventory, or to implement mitigation procedures, it is very important that there be confidence in the accuracy of the methane measurement technology. Many methods have been employed to estimate the methane emitted from ruminant animals and these are outlined below.

5.1.1 Calorimeter/respiration chamber

The classical standard for ruminant methane measurement by nutritionists is the respiration chamber, or calorimeter, and thousands of measurements have been made over the past 150 years, covering a wide range of diets and intake levels. There are many different designs of calorimeters (Blaxter, 1962), but the most common in use today is the open circuit calorimeter. Air is passed through a chamber containing an animal, gas flows and the difference in gas concentrations between inlet and outlet are measured, and the uptake of oxygen and the output of carbon dioxide and methane are calculated. The predominant use of calorimeters has been to measure gaseous exchange as part of energy balance measurements, methane loss being a necessary part of this procedure. Data collected in such feed evaluation experiments has been invaluable in describing relationships between methane emission and diet quality and quantity (e.g. Blaxter & Clapperton 1965; Moe & Tyrell, 1979).

While this technique is satisfactory for measuring methane emission from dried diets, there are difficulties in deriving values that are applicable to the grazing ruminant. Grazing animals select their diet, maximum feed intakes in a chamber are considerably lower than in grazing animals, fresh pasture plants continue to respire in the chamber, calorimeters are expensive to operate and the impact of variations in pasture management can not be addressed. Other
techniques are thus preferred for grazing animals, although if possible they should be calibrated against a calorimeter.

### 5.1.2 Tracer gas techniques

A method for measuring methane emission in the field, known as the sulphur hexafluoride (SF$_6$) tracer technique, was developed at Washington State University by Johnson et al (1994). A calibrated source of SF$_6$ is placed in the rumen per os prior to an experiment, the animal’s expired breath is sampled, and the ratio of methane to SF$_6$ determined. The source of SF$_6$ is a permeation tube, and the rate of release of SF$_6$ is controlled by a permeable Teflon™ membrane held in place by a porous stainless steel frit and a locking nut. Each tube is calibrated at 39°C by regular weighing for a period prior to insertion into the rumen. The tubes for sheep, typically 35 mm length by 11 mm in external diameter, are made from brass rods and weigh about 32 g. Each test animal is fitted with a halter, which supports an inlet tube that is placed so that its opening is close to the nose. The inlet tube leads via a capillary tube and shut-off valve to a PVC collection yoke that is fitted over the neck and strapped to the halter. The collection yoke is evacuated prior to use, and the rate at which air is sampled from near the animal’s nose is determined by the length and internal diameter of the capillary tube. The yoke is easily isolated for daily changing by means of a shut-off valve and quick connect fittings.

Yoke volumes are typically 1.7 and 2.5 litres for sheep and cattle respectively, and the capillary system is designed to deliver half this volume during the collection period, usually 24 hours. An identical apparatus is placed upwind each day to collect an integrated background air sample. The methane emission rate ($Q_{CH4}$) is calculated as:

$$Q_{CH4} = Q_{SF6} \times ([CH4 \text{ sample}] - [CH4 \text{ ambient}])/([SF6 \text{ sample}] - [SF6 \text{ ambient}])$$

where $Q_{SF6}$ is the calibrated rate of permeation from the SF$_6$ tube and [CH$_4$] and [SF$_6$] are concentrations in the collection yokes and background concentrations. Details of tube calibration and behaviour in sheep have been described by Ulyatt et al (1999) and Lassey et al (2001).

The validity of the SF$_6$ technique has been checked in comparisons with respiration chamber measurements. Johnson et al (1994) compared 55 measurements using the SF$_6$ technique with 25 chamber measurements of cattle, and showed that while the SF$_6$ estimates were 0.93 of those in the chamber, the difference was not significant. Pinares-Patiño (2000) in New Zealand found in one experiment with 10 sheep fed chaffed lucerne hay that methane production estimated from SF$_6$ was 0.95 chamber emission.

Similarly, Boadi et al (2002) compared estimates of methane production using the SF$_6$ tracer technique (137.4 l/d) with an open circuit hood calorimeter (130.0 l/d) using yearling beef heifers and found no significant difference ($P=0.24$). This is what might be expected, given that Murray et al (1976) estimated that greater than 98% of combined rumen and hind gut methane production is excreted via the mouth. However, a number of workers have found difficulty in matching chamber and SF$_6$ results. In two experiments with sheep, Pinares-Patiño (2000) obtained results that were extremely variable. McCrabb and Baker (cited Ulyatt et al, 1999) measured methane production from five Friesian calves fed Rhodes grass (Chloris gayana) hay, using both SF$_6$ and a confinement-type respiration chamber. The estimate of methane production made with the respiration chamber ($7.7 \pm 0.67$ l/h) was twice that ($P<0.005$) estimated using SF$_6$, either in pens ($4.1 \pm 0.35$ l/h) or in the chamber ($4.0 \pm 0.46$ l/h). Clearly there is a need to confirm that SF$_6$ reliably reflects respiration chamber estimates of methane production.
The reliability of the SF₆ technique under field conditions was assessed in the New Zealand work, where gas sampling using the SF₆ technique was attempted on several hundred sheep and cow days. The percentage of successful collections was 95% for sheep and 90% for cows. Further, estimates of methane production with the SF₆ technique (Johnson et al, 1994; Lassey et al, 1997; Baker, unpublished data) give values between 5-11% of gross energy intake. This is within the range that can be calculated using the IPCC (1995) methodology, which is based on indirect calorimetry. Despite the variation imposed by the various factors noted above, the SF₆ tracer technique and gas collection system appears to be robust.

SF₆ has also been used successfully as a tracer to estimate the total methane emission from all the cattle in a barn (Kaharabata & Schuepp, 2000).

Ethane (C₂H₆) has also been used as a marker to estimate methane emission (Moate et al, 1997; Mbanzamihigo et al, 2002) using essentially the same principle as SF₆. The major difference in the use of the two tracers is that ethane has to be bubbled from an external source into the rumen, and so is not suitable for use in grazing experiments.

5.1.3 Alternative methods for measuring methane emission in the field

There is a range of meteorological techniques that have been employed to try and validate predictions of greenhouse gas inventories. These can generally be classified as “bottom up”, or direct measurement of emissions from a known number of animals at the ground level, or “top down” techniques that infer land-based or area-based emissions from their atmospheric signature (Beswick et al, 1998; Denmead et al, 2000).

5.1.3.1 Bottom up techniques

The SF₆ tracer technique, described above, is a bottom up methodology that is often used to validate the more indirect techniques.

Two different versions of mass balance techniques have been tested recently: a portable wind tunnel and a non-intrusive enclosure technique. Lockyer and Jarvis (1995) and Lockyer (1997) described a system in which air was drawn across animals enclosed in a 4.3 x 9.9 m polythene-clad tunnel placed over pasture. Various numbers of sheep and calves were enclosed for up to 10 days, and methane emission was estimated to be on average 13-14 g/d for sheep and 74.5 g/d for calves. In both studies methane emission declined with time, probably in response to declining feed availability given the very high stocking rates employed (470 sheep or calves per ha with two animals in the tunnel and 2 818 sheep/ha with 12 sheep in the tunnel). The method is not suited to evaluating differences between imposed experimental treatments.

Denmead et al (1998), Harper et al (1999) and Leuning et al (1999) described a variant of the mass balance approach in which animals were fenced in a 22 x 22 m enclosure, and gas was sampled from many ports on a framework up to 3.5 m high surrounding the enclosure. Wind speeds were measured from anemometers at the same levels as the sample ports, and from these airflow across each boundary could be measured every 30 seconds. The advantage of this technique is that it can accommodate changes in wind direction. This technique was used by Leuning et al (1999) to measure methane emission for five days from 14 sheep grazing a grass and legume pasture. Seven of these animals were used concurrently to measure methane emission using the SF₆ tracer technique. Methane concentration from the sample ports was measured on line by high precision Fourier transform infra-red spectroscopy. The daily mean values for the two techniques were similar: 11.7 g/day for the SF₆ technique and 11.9 g/day for the mass balance measurements. With this technique, a very high stocking rate (289 sheep/ha) is required to achieve a differential in gas concentration that can be measured. It is also not suitable for experiments where treatments need to be evaluated.
5.1.3.2 Top down techniques

A range of meteorological techniques has been developed to infer areal emissions from their atmospheric signature (Denmead et al, 2000). These vary in scale from flux gradient analyses designed to measure at the paddock scale, to boundary layer techniques that integrate fluxes over larger areas of the landscape (Beswick et al, 1998; Denmead et al, 2000; Wratt et al, 2001).

5.1.3.2.1 Flux gradient techniques

Judd et al (1999) used a micrometeorological flux gradient technique to estimate methane fluxes for five days across a paddock grazed by sheep. The experimental site was on a flat coastal plain in the Manawatu with a reliable prevailing westerly wind. Samples of air were drawn from two heights (3.8 and 1.2 m) on a tower sited on the downwind boundary of the experimental area. Wind speed and direction were also measured from the tower. Four three ha paddocks upwind of the tower were stocked at 20 sheep/ha, and 11 of these sheep were used to estimate methane emission for the five days of the campaign using the SF₆ tracer technique as described by Lassey et al (1997). Thus, the conditions in the upwind measurement footprint were as close as possible to normal farming practice. The methane emission estimated by this technique was 19.5 ± 4.8 g/day, which compared well with the SF₆ tracer measurements of 19.4 ± 4.2 g/day. A similar measurement system was described by Denmead et al (2000) who found that good agreement was obtained with inventory predictions, but that the error was too high for detection of small changes that might be important for inventory, regulatory or animal science experimental purposes. The method of Judd et al (1999) is inflexible in that it requires a large fetch of undisturbed air on the upwind side of the sampling tower, it can only be used on rainless days when the wind is in one direction, and it can be affected by the movement of animals within the measurement footprint. It measures from groups of animals and thus is not suited to evaluating differences between treatments.

5.1.3.2.2 Boundary layer techniques

Variations of the boundary layer technique have been used to estimate methane emissions over larger land areas. Basically, vertical profiles of gas concentration are determined through the depth of the atmospheric boundary layer, and this data is used in various modeling techniques to infer emissions over a specified land area. Measurements within both the convective and nocturnal boundary layers have been made with this technique. In one series of experiments in Australia, a 22 m tower and an aircraft were used to collect samples of gas at different heights within the convective boundary layer, and gas budgeting techniques were used to estimate methane emissions (Denmead et al, 2000; Griffith et al, 2002). In another application in New Zealand (Lassey et al, 2000b; Wratt et al, 2001; Gimson et al, 2002) air samples were collected by light aircraft from two columns of air, one upwind and another towards the downwind boundary of the target site.

Both regional budget and source-oriented meteorological and mesoscale dispersion modeling techniques were used to estimate land-based methane emissions. Night time measurements utilising the gas concentrating effect of the nocturnal boundary layer have also been made, usually by taking gas samples at various heights up a profile using a balloon (Denmead et al, 2000; Harvey et al, 2002), or sampling from a tower (Griffith et al, 2002). Harvey et al (2002) have also proposed an isotope dilution/mass balance technique for use in conjunction with the nocturnal boundary layer method.

In a limited number of experiments methane emission has been measured simultaneously at one site with a variety of techniques from the soil, from grazing animals, by
micrometeorological flux measurements, and by nocturnal and convective boundary layer measurement (Judd et al, 1999; Denmead et al, 2000). There was reasonable agreement between methods for estimating emission, although the variability increased with scale.

Denmead et al (2000) reviewed the strengths and weaknesses of a range of meteorological flux measurement techniques. Those described above provide estimates of methane emission that have reasonable agreement with inventory estimates. However, the error was generally too high for detection of small changes that might be important for inventory, regulatory or animal science research. There are advantages with these techniques in that they give an integrated net emission of all sources in their “foot print” and they are non-invasive in terms of farm management. These techniques are, however, inflexible in terms of the limited climatic conditions in which they can operate. Despite these caveats, the methods are at an early stage of development and give promise for the future.

5.1.4 Prediction with regression equations

A number of empirical regression equations, based on the results of calorimetric experiments, have been developed for predicting methane production. The two best known equations are (a) those of Blaxter and Clapperton (1965), which are based on data from cattle and sheep and have as independent variates energy digestibility at maintenance, gross energy intake and level of feeding (multiples of maintenance); and (b) the equation of Moe and Tyrell (1979) which are based on data from Holstein dairy cows and have as independent variates the intakes of non-fibre carbohydrate, hemicellulose and cellulose. These and a number of other equations were evaluated for accuracy of prediction of methane production for Holstein cows against a set of data compiled at the USDA, Beltsville by Wilkerson et al (1995). The conclusion was that the equation of Moe and Tyrell (1979) was the most accurate for the prediction of methane production from dry and lactating cows. However, the mean absolute error of prediction (11.0% of the mean) was still high. Further, the equation is probably limited in application to dairy cows confined indoors and fed the typical high concentrate type of diet used in the US.

Recently Yan et al (2000) published a specialised equation for dairy and beef cattle offered grass silage-based diets where the independent variates are digestible energy intake, the proportion of ADF in the diet, and the level of feeding above maintenance. The $R^2$ was 0.89, indicating a reasonably good fit. Pelchen and Peters (1998) developed equations for sheep from 1 137 sets of data from the literature. There was a wide range of diet types, including a few from animals fed fresh herbage. By grouping the sets of data according to criteria such as digestibility (<65, 65-70, 70-75, >75) and crude fibre (<15, 15-20, 20-25, 25-30, >30) they derived regressions for predicting methane emission (g/d) with $R^2=0.7-0.85$. Pelchen et al (1998) developed similar regression equations for predicting methane emission from dairy cows using 729 sets of data from the literature.

The equations described above are useful in examining the relationships between dietary constituents and methane emission, however they are not accurate enough for use in determining small differences between animals in experiments. Also, being derived predominantly from animals fed indoors on preserved rations, they do not satisfactorily measure methane emission from animals grazing fresh pasture.

5.1.5 Prediction with dynamic mathematical models

Dynamic mechanistic models of rumen digestion have been developed that will predict methane emission from an input of diet intake and composition. Ulyatt et al (1991) used the model of Baldwin et al (1987) to predict methane emission for a model of the New Zealand inventory. Ulyatt et al (1991) compared the Baldwin model predictions against predictions
with the Blaxter and Clapperton (1965) and Moe and Tyrell (1979) regressions, using a standard set of input data. They found that while there was bias in the Baldwin model predictions, the bias was greater with the two regression equations. Benchaar et al (1998) challenged an updated version of the Baldwin et al (1987) model, a modified version of the Dijkstra et al (1992) dynamic model and the Blaxter and Clapperton (1965) and Moe and Tyrell (1979) regressions with 32 experimental rations with large variations in diet composition.

The Dijkstra model predicted methane production with an $R^2$ of 0.71, compared to an $R^2$ of 0.70 with the Baldwin model. However, the Baldwin model had a higher error of prediction (36.9 vs 19.9%). Predictions with the Blaxter and Clapperton (1965) and Moe and Tyrell (1979) regressions were poor, with $R^2=0.57$ and 0.42 respectively. Mills et al (2001) also developed a dynamic methane model that predicted results from the literature with $R^2=0.76$. It appears that dynamic mechanistic models can predict methane production with better accuracy than the best of the available empirical regression equations. This might be satisfactory for inventory purposes where resources are limited, however these models are very complicated and require a skilled operator. Further they are not appropriate for evaluating differences between experimental treatments.

5.1.6 Choice of a method for grazing animals

In terms of accuracy, ability to measure at the individual grazing animal level, and usefulness in evaluating experimental treatments, there can be no doubt that the SF$_6$ tracer technique is the method of choice. There are, however, issues with this technique that require attention:

- There have been concurrent comparisons with the respiration chamber, but these have generally been less than convincing. Further work is required to absolutely confirm that SF$_6$ is accurate.
- The technique is reliant for its efficacy on one experiment with one diet (Murray et al, 1976) with regard to the proportion of large intestinal methane that is absorbed and excreted via the lungs.
- The question of whether allowance should be made for excretion in the flatus, and if so how much, is still to be resolved.
- Variation between animals in methane emission appears to be much higher with the SF$_6$ technique than respiration chamber measurements (Boadi et al, 2002). Is this a true effect or is it an artefact of the SF$_6$ procedure?
- The SF$_6$ measurement is relatively expensive to conduct.
- All the above issues need addressing if the SF$_6$ technique is to become universally accepted.

5.1.7 Conclusions

Although many methods have been employed to measure or calculate methane emissions from ruminants, the method of choice for grazing animals is the SF$_6$ tracer technique. The other methods have too high an error to be able to detect the small differences that are important in inventory, regulatory or animal science research. Meteorological methods have the advantage that they can integrate over large land areas, but a lot more methodological development will be necessary before they can become accurate and routine. Further work is also needed on the SF$_6$ technique: rigorous evaluation against the respiration calorimeter; confirmation of the proportion of methane that is excreted in the flatus; and evaluation of the high variability of the technique.
References


5.2 Measuring Nitrous Oxide Emission from Soil

Emissions of nitrous oxide from soil are difficult to measure accurately because of the small amounts emitted, the large variation which occurs over the soil surface, and the marked changes which take place with time. The variability is due mainly to the variation in the factors controlling metabolism of nitrogen across the landscape such as the microorganisms, substrate for the organisms, water, temperature, oxygen and pH.

5.2.1 Chamber methods

Most of the information on rates of nitrous oxide emission from soils has been obtained by placing simple, relatively small chambers on the soil surface, and measuring the increase in nitrous oxide concentration within the chamber after a set time (Mosier, 1989; IAEA, 1992; Smith & Arah, 1992; Ryden & Rolston, 1983; Granli & Böckman, 1994; Fowler et al, 1997). A variety of chambers have been designed and labelled as closed, open, mega, and vented (Berges & Crutzen, 1996; Meixner et al, 1997; Sibbetsen & Lind, 1993; Smith et al, 1994; Velthof et al, 1997). In addition automated closed chamber methods have been developed (Meyer et al, 2001; Smith & Dobbie, 2001) which enable the determination of fluctuations in nitrous oxide fluxes not seen by manual sampling.

The nitrous oxide concentration in the chamber is usually determined by taking samples with a syringe at particular times and analysing them by gas chromatography using a Ni$^{63}$ electron capture detector operated at a temperature between 300 and 400 °C (Mosier & Mack, 1980). The concentration has also been monitored by employing an infrared gas analyser (Denmead, 1979) and Fourier transform infrared (FTIR) spectroscopy in a closed loop (Meyer et al, 2001).

Enclosure methods have the advantage of being able to detect small fluxes, are inexpensive, and are useful for short-term process studies. They have many disadvantages, including changes to the microclimate, but the main one is that measurements are obtained over a small area. When coupled with the large spatial variability in nitrous oxide emission, this makes it difficult to obtain meaningful values for emission from a field (Matthias et al, 1978; IAEA, 1992; Livingston and Hutchinson, 1995; Smith et al, 1995). The problem can be overcome to some extent by using more chambers and increasing their size (Smith et al, 1994).

Sherlock et al (2002) describe a closed chamber technique which is being used within NzOnet to measure nitrous oxide emission from pasture soils. Microplots are formed by pushing steel cylinders (24 cm diameter) into the soil. Cylindrical gas-tight lids, having a headspace height of 10 cm, and fitted with rubber septa for sampling, are attached to the steel cylinders during gas emission measurements, but are left open between measurements. The changes in headspace concentrations are used for calculating the flux of nitrous oxide. Gas samples are collected with 50 ml syringes at 0, 10 and 20 minutes after lid closure. The gas samples are injected via a 10-port sampling valve into a carrier stream of nitrogen, to a gas chromatograph equipped with a $^{63}$Ni electron-capture detector and a stainless steel column (4 m long, 3 mm internal diameter) packed with Poropak Q (80/100 mesh). Detector and column temperatures are 350°C and 20°C respectively. In general, fluxes are calculated using the logarithmic equation described by Hutchinson and Mosier (1981).

5.2.2 Micrometeorological methods

Micrometeorological methods are also employed for measuring nitrous oxide emissions from field soils, although less frequently than chamber methods. They are extremely useful in that they integrate emissions over large areas, and can assess the effect of rainfall, temperature and
wind speed on emission (Fowler & Duyzer, 1989). As with the chamber methods, a variety of micrometeorological methods are available.

The mass balance method is non-disturbing, does not require a large fetch or uniform land area, has a simple theoretical basis, and can be used to measure gas emission from small plots. The idea is to calculate gas production from a particular area by measuring the difference between the rates at which gas is transported into and out of an area. Denmead et al (2000) used such a method to determine the nitrous oxide resulting from the grazing of sheep on a lucerne (Medicago sativa)-ryegrass (Lolium rigidum) pasture in a test plot, 22 x 22 m. Measurements of atmospheric nitrous oxide concentrations were made with Fourier transform infrared (FTIR) spectroscopy. They found that the average emission over eight days was 1.87 g N₂O-N per head per day, which corresponded to 13.9% of the nitrogen excreted by the animals. Brown et al (2002) measured nitrous oxide emission from a solid dairy manure pile with a mass balance method using a tunable diode laser trace gas analyser which provided high precision concentration difference measurements. Loss from the pile was 0.42 g N m⁻² day⁻¹.

Wagner-Riddle et al (1996) used a flux-gradient method to measure fluxes of nitrous oxide from a bare soil. In this technique, changes in atmospheric nitrous oxide concentrations with height above the surface are measured. They used a tunable diode laser system for rapid measurement of nitrous oxide concentrations at only two heights, switching between them two every four seconds. Denmead et al (2000), Griffith and Galle (2000) and Griffith et al (2002) used the same approach, but measured concentrations with FTIR spectroscopy. Griffith et al (2002) measured vertical profiles of nitrous oxide every 30 minutes from the ground up to 22 m so they could use a nocturnal boundary layer method to measure nitrous oxide fluxes. In this method the rate of change in mass storage in the 0-22 m layer is combined with fluxes measured at 22 m to estimate surface fluxes. Night time fluxes of nitrous oxide were 2±3.2 ng N m⁻² s⁻¹ which were in good agreement with chamber measurements and inventory estimates based on stocking rates in the region. For comparison day time rates were 17±48 ng N m⁻² s⁻¹.

A second night time micrometeorological method has been proposed for measuring the nitrous oxide emission rate from grazed pasture (Kelliher et al, 2002). This method used Fourier-transform infrared spectroscopy to simultaneously monitor concentrations of nitrous oxide and carbon dioxide over a 97 m long, open-air absorption path at a height of 3 m in the stable boundary layer. On calm and clear nights, the formation of an inversion layer trapped surface gas emissions and led to a build-up of N₂O and CO₂ concentrations near ground level. The ratio of these concentrations was combined with the more readily measured CO₂ emission rate to calculate an area-integrated N₂O emission rate. The increases in nitrous oxide and carbon dioxide concentrations in the stable boundary layer concentration were highly correlated (r²=0.83, n=201).

References


Chapter 6
Nitrous Oxide: Production, Sources and Abatement Options

Summary

Addition of nitrogen to soil in any form (animal excreta, synthetic fertiliser, crop residues or biological fixation) results in increased nitrous oxide emissions. In New Zealand, agriculture is based largely on animals grazing grass-legume pastures, but the animals do not utilise the nitrogen they ingest efficiently. On average only 10.5% of the nitrogen in grass, silage or other feedstuff is converted into milk, meat, eggs or wool (Table 7.5,) and the remainder is excreted in dung and urine. Thus the bulk of the nitrogen added to New Zealand soils comes from the excreta of animals

(1 282 Gg N/y) and addition of fertiliser (213 Gg N/y) (Table 7.1).

Additional nitrous oxide is emitted directly from soil as a result of these inputs. It is also generated indirectly when nitrate lost by leaching or run-off is converted to nitrous oxide in water bodies, and when nitrogen from excreta and fertiliser is lost as ammonia to the atmosphere and subsequently deposited on land. During 2000, nitrous oxide emission from these sources amounted to 25.2 Gg N, compared with the 1990 base value of 24.4 Gg N.

Of the direct emissions, 53% came from excreta and 10% resulted from the application of fertiliser. Indirect leaching and run-off of nitrogen from animal excreta or fertiliser application contributed 23%, and deposition of ammonia which had been volatilised contributed a further 11%. Because of their larger numbers, sheep were responsible for the bulk of the direct nitrous oxide emissions from animal excreta (5.5 Gg N/y; 45.5% of the total), and dairy cattle (3.3 Gg N/y; 27.3%) generated more nitrous oxide than non-dairy cattle (3.0 Gg N/y; 24.8%).

It is apparent from this discussion of sources that mitigation options need to focus on limiting the direct loss of nitrogen from animal excreta and synthetic fertilisers and the indirect loss caused by leaching, run-off and ammonia volatilisation. Options are available that could result in considerable reductions in nitrous oxide emission from grazing animals and fertiliser application. These include:

Manipulating the diet of animals. Feeding dairy cattle low degradable protein and high starch diets should result in 24% less nitrogen being excreted in the urine, reduced ammonia volatilisation, and less nitrous oxide emission.

Breeding cultivars that improve nitrogen efficiency. Dairy cows fed grasses high in water soluble carbohydrate excreted 24% less nitrogen than those fed normal diets.

Keeping cattle on feed-pads during the wet autumn/winter period, so that excreta can be collected and utilised as fertiliser later in the year. Nitrous oxide emission from dairy excreta could be reduced by 25% and nitrate leaching by 40%.

Improving drainage and preventing soil compaction can reduce nitrous oxide emission by 3% each.

If these options were adopted by farmers, and the effects were additive, there is the potential for nitrous oxide emission to be reduced from the sheep, dairy cattle, and beef cattle sectors by 16% (0.9 Gg N), 28% (0.9 Gg N) and 25% (0.8 Gg N) respectively (Table 7.8).
Matching nitrogen supply with crop demand, tightening nitrogen flow cycles, and optimising tillage, irrigation and drainage could reduce nitrous oxide missions from fertiliser use by 19% (0.6 Gg N).

Nitrate leaching can be reduced by lowering fertiliser application rates, synchronising nitrogen supply to plant nitrogen demand, growing cover crops and using buffer zones.

If the total reduction of 3.2 Gg N was achieved, it would reduce the emissions calculated for the year 2000 to 22 Gg N (i.e. 2.43 Gg below the 1990 base value).

However, even if nitrous oxide emissions were reduced below the 1990 level by implementing these options, it will only be maintained at that level if nitrogen inputs remain static. This means that fertiliser nitrogen use and animal numbers can not increase. Production could only increase by increasing the efficiency of nitrogen use by sheep and cattle.

If the options proposed for reducing emissions from fertiliser use were implemented they would increase rather than decrease farmer’s income. If fertiliser nitrogen is used more efficiently, less money will be spent on fertiliser.

The options proposed for reducing nitrous oxide emission from animals could only be implemented at a cost to the farmer, and thus may not be accepted. However, making more efficient use of animal manures and slurries will have numerous indirect benefits.

6.1 Introduction

When ammonia is produced in or added to soil by the breakdown of organic matter, addition of fertiliser or animal wastes it undergoes a series of reactions (Figure 6.1) and nitrous oxide is produced.

<table>
<thead>
<tr>
<th>Nitrous oxide</th>
<th>Ammonia $\rightarrow$ Nitrite $\rightarrow$ Nitrate $\rightarrow$ Nitric oxide (gas) $\rightarrow$ Nitrous oxide (gas)</th>
</tr>
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<tr>
<td>$\uparrow$</td>
<td>$1$ $\rightarrow$ $2$ $\rightarrow$ $3$ $\rightarrow$ $4$ $\rightarrow$ $5$ $\rightarrow$ $6$ $\rightarrow$ $7$</td>
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**Figure 6.1: Production of Nitrous Oxide by Nitrification and Denitrification**

Source: Crutzen, 1974; Johnston, 1972

When atmospheric scientists first expressed concern that nitrous oxide emissions into the atmosphere as a result of fertiliser use would lead to destruction of the ozone layer (Crutzen, 1974; Johnston, 1972), it was thought that nitrous oxide was produced mainly from the denitrification, under anaerobic conditions, of nitrate produced (reactions 4, 5 and 6, CAST, 1976). However, research in 1978 showed that significant nitrous oxide was emitted from aerobic soils during the oxidation of ammonia to nitrate (called nitrification; reactions 1 and 2; Bremner & Blackmer, 1978, Freney et al, 1978), and subsequent work has shown that nitrification is a major source of nitrous oxide in upland soils (Bremner, 1997).

It is accepted that an increase in the amount of nitrogen being cycled will result in an increase in the emission of nitrous oxide. The production of nitrous oxide and nitrogen gases by these two processes can be compared with gases leaking from a pipe (Figure 6.2; Firestone & Davidson, 1989). The greater the flow through the pipe (the nitrogen being cycled), the greater is the fraction leaking through the holes (the emission of nitrous oxide).
The nitrification reaction can be carried out by either autotrophic organisms which do not require organic matter as a source of energy (Bremner & Blackmer, 1978), or heterotrophic organisms which require organic matter for energy (Papen et al, 1989). In autotrophic nitrification, ammonia (or ammonium) is oxidised to nitrite and nitrate in a two step reaction where Nitrosomonas is responsible for the first step and Nitrobacter performs the second. Nitrous oxide appears to be formed by a reductive side reaction involving nitrite (Firestone & Davidson, 1989). Heterotrophic microorganisms oxidise ammonium to nitrite or nitrate in the presence of oxygen and an organic substrate, and they appear to be important in soils which are too acidic for autotrophic nitrifiers (Schimel et al, 1984). The relative importance of autotrophic and heterotrophic organisms for the production of nitrous oxide can not be readily determined because it is difficult to separate autotrophic and heterotrophic nitrification (Robertson & Kuenen, 1991). In well-aerated soils, nitrification appears to be the main production mechanism for nitrous oxide, but in poorly aerated, nitrate rich soils significant emissions result from denitrification (Smith & Arah, 1992).

Denitrification is the reduction of nitrate and nitrite to produce nitric oxide, nitrous oxide and dinitrogen by a diverse group of bacteria, in the absence of oxygen (Tiedje, 1988). The most abundant denitrifiers are heterotrophs which require organic matter for metabolism. Production of nitrogen gas predominates in more anoxic sites, such as flooded soils, while nitrous oxide production is greater under more aerobic conditions. In addition to the free living denitrifiers, symbiotically living Rhizobia in root nodules of legumes are able to denitrify nitrate and produce nitrous oxide (O’Hara & Daniel, 1985).

Nitrous oxide can also be formed in soils when nitrite decomposes. This reaction is termed chemodenitrification (Chalk & Smith, 1983). Although nitrite is not normally present in soils at concentrations greater than 1 µg N g soil⁻¹, it does accumulate when nitrogen fertilisers which form alkaline solutions on hydrolysis are banded in soil (Chalk & Smith, 1983). However, even though nitrous oxide has been identified as a product of chemodenitrification in soils, the amounts produced are small compared with the amounts of nitric oxide and dinitrogen formed, and there is no evidence that significant amounts of nitrous oxide are formed as a result of this reaction in soils (Bremner, 1997).

Figure 6.2: A conceptual Model of the Two Levels of Regulation of Nitrous Oxide Production by Nitrification and Denitrification: (i) The Flow of Nitrogen through the Process Pipes, and (ii) The Holes in the Pipes through which the Nitrous Oxide Leaks

Source: Firestone & Davidson, 1989

Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions
6.2 Factors Controlling the Formation of Nitrous Oxide

As nitrous oxide is formed mainly by microorganisms, its rate of production is controlled by factors which affect the growth of microorganisms viz substrate, temperature, pH, and water content (Sahrawat & Keeney, 1986). However, because two microbial processes, nitrification and denitrification, which have different environmental requirements are involved, the production of nitrous oxide depends on conditions which vary in space and time. Nitrification is an aerobic process, requiring oxygen, whereas denitrification is an anaerobic process which proceeds in the absence of oxygen. As nitrification is an aerobic process the rate of nitrification declines as oxygen becomes limiting, but in most soils the availability of ammonium is the most important factor controlling nitrification. Availability of ammonium is controlled by fertilisation, animal wastes, mineralisation and immobilisation rates, plant uptake, ammonia volatilisation, cation exchange and diffusion. Water is required for the growth of the organisms, but the content also affects the rate of diffusion of ammonium and oxygen. The nitrifiers are active over a wide range of temperatures (2-40°C), and the optimum pH lies between 7 and 9 (Schmidt, 1982). Little autotrophic nitrification occurs below pH 4.5 (Haynes, 1986).

The general requirements for biological denitrification include: the presence of microorganisms with denitrifying capacity; nitrate (or other nitrogen oxides) and available organic matter; restricted oxygen supply; and a suitable pH and temperature environment (Firestone, 1982). The restricted oxygen supply is usually brought about by excess water, and denitrification generally occurs at soil water contents >60% of water-filled pore space (Linn & Doran, 1984). In aerobic soils denitrification can occur in anaerobic microsites in soil aggregates (Parkin, 1987), or in areas of high carbon content where active microbial activity rapidly consumes all of the available oxygen (Firestone, 1982). The other important variables which regulate denitrification, pH and temperature, are generally not the principal constraints in soils where crops are grown because plants have similar pH and temperature requirements (Aulakh et al, 1992). Other factors such as vegetation, crops, cropping pattern, soil type, soil texture and rainfall can influence denitrification by interacting with the main controls mentioned above.

Nitrogen gas production predominates in more anoxic sites, while nitrous oxide production seems to be greater in more aerobic conditions. The ratio of nitrous oxide to dinitrogen formed is determined by the factors controlling the functioning of the enzymes in the denitrification pathway, and ranges from negligible to 20 under field conditions (Delwiche, 1981). Nitrous oxide is usually a larger fraction of the total gaseous products of denitrification when the nitrate concentration is high relative to the available carbon supply (Delwiche, 1981; Weier et al, 1993), and when pH and moisture are low (Arah & Smith, 1990). Soil structure and water content, which affect the balance between diffusive escape of nitrous oxide and its further reduction to nitrogen gas, are important in determining the proportions of the two gases.

6.3 Biomass Burning

During combustion the nitrogen in biomass can be converted into gaseous forms such as ammonia, nitric oxide, nitrous oxide, dinitrogen and hydrogen cyanide (Galbally & Gillett, 1988). According to IPCC, agriculture accounts for half of the biomass burned every year, and it is estimated that 0.7 ± 0.3% of the nitrogen in biomass is lost as nitrous oxide during burning (Lobert et al, 1990; Hurst et al, 1994). Biomass burning not only produces nitrous oxide instantly, but nitric oxide and ammonia are emitted which serve as indirect sources of nitrous oxide when deposited on soil.
Burning also results in a longer-term increase in the production of nitrous oxide in soil. Measurements of nitrous oxide emissions from soils before and after a controlled burn showed that significantly more nitrous oxide is emitted after the burn through alteration of the chemical, biological and physical processes in soil (Anderson et al, 1988; Winstead et al, 1991).

6.4. Nitrogen Inputs to Agriculture

Formation in, and emission of nitrous oxide from, most soils is enhanced by an increase in mineral nitrogen through increased rates of nitrification and denitrification. Therefore, addition of nitrogen in any form eventually leads to an increase in nitrous oxide emissions. This input may come from synthetic fertiliser, animal wastes, increased biological fixation, mineralisation of crop residues, and increased mineralisation through the cultivation of organic soils. Nitrous oxide can be emitted directly from soil, animal confinements or waste management systems as a result of these inputs.

The inputs may also result in the indirect formation of additional nitrous oxide when: (i) nitrogen emitted as ammonia and nitric oxides is deposited on land; (ii) nitrate is lost by leaching or run-off into water bodies; or (iii) nitrogen in food stuffs is converted to sewage.

In New Zealand, agriculture is based largely on pastoral systems, livestock (sheep, cattle, deer, goats and horses) are grazed on pastures all year round, and the bulk of the nitrogen added to soil comes from the excreta of these animals. Animals deposited ~1 211 Gg N/y directly on to pastures as dung and urine, and a further ~71 Gg N/y was applied to agricultural soils as animal waste (Table 6.1).

Table 6.1: Input of Nitrogen to New Zealand Soils in 2000.

<table>
<thead>
<tr>
<th>Source</th>
<th>Gg N/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excreta deposited during grazing¹</td>
<td>1211</td>
</tr>
<tr>
<td>Legumes in pastures²</td>
<td>901</td>
</tr>
<tr>
<td>Synthetic fertilisers</td>
<td>213</td>
</tr>
<tr>
<td>Animal wastes¹</td>
<td>71</td>
</tr>
<tr>
<td>Crop residues¹</td>
<td>8</td>
</tr>
<tr>
<td>Nitrogen fixing crops¹</td>
<td>3</td>
</tr>
<tr>
<td>Atmospheric deposition¹</td>
<td>281</td>
</tr>
<tr>
<td><strong>Total input</strong></td>
<td><strong>2688</strong></td>
</tr>
</tbody>
</table>

¹From New Zealand Greenhouse Gas Inventory, 2002
²S Ledgard, pers comm, 2002

While some fertiliser nitrogen is used to boost production on pastures for dairy cattle, the bulk of the nitrogen in pastures is fixed biologically by white clover (901 Gg N/y). Relatively little fertiliser nitrogen is used in New Zealand (213 Gg N out of a global total of 85 Tg N in 2000), but usage has increased greatly since 1990 (Figure 6.3). Before 1990, New Zealand’s production of urea from natural gas was sufficient for the country’s needs and an export market, but now it is necessary to import fertiliser to meet the demand (Furness, pers comm).
It is also apparent from Table 6.1 that a large quantity of nitrogen (281 Gg N/y) is deposited on New Zealand’s soils as a result of volatilisation of ammonia and emission of nitric oxides. In addition 227 Gg N/y is leached or lost by run-off from New Zealand soils.

## 6.5 Nitrous Oxide Emissions from New Zealand Agriculture

Estimates of nitrous oxide emissions from New Zealand agriculture, calculated using IPCC (1997) guidelines, but with emission factors and other parameters more appropriate to New Zealand conditions (see Chapter 5), showed that ~48% of the nitrous oxide emitted came from excreta deposited during grazing, ~34% originated from atmospheric deposition, leaching and run-off, and ~10% was derived from synthetic fertilisers (Table 6.2).

### Table 6.2: Nitrous Oxide Inventory for New Zealand in 2000\(^1\)

<table>
<thead>
<tr>
<th>Source</th>
<th>Nitrous oxide emitted (Gg N/y)</th>
<th>(% of total emissions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct emissions from soil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic fertilisers</td>
<td>2.4</td>
<td>9.5</td>
</tr>
<tr>
<td>Animal manure</td>
<td>0.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Biological nitrogen fixation</td>
<td>0.04</td>
<td>0.2</td>
</tr>
<tr>
<td>Crop residues</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Cultivated histosols</td>
<td>0.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Direct emissions from animal production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wastes from housed animals</td>
<td>0.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Excreta deposited during grazing</td>
<td>12.1</td>
<td>47.9</td>
</tr>
<tr>
<td>Indirect emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric deposition</td>
<td>2.8</td>
<td>11.1</td>
</tr>
<tr>
<td>Nitrate leaching and run-off</td>
<td>5.7</td>
<td>22.6</td>
</tr>
<tr>
<td><strong>Total emission</strong></td>
<td><strong>25.2</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

\(^1\) New Zealand Climate Change Project, 2002

Under New Zealand’s extensive pastoral system, the majority of animal waste is excreted on to pasture and is decomposed aerobically. However, there are liquid-based systems where
waste is decomposed anaerobically. This is largely from dairy shed effluent and is discharged into effluent ponds. The land disposal method encourages the aerobic breakdown of the waste, which results in lower emission of nitrous oxide than other systems such as the two pond system (Ministry for the Environment, 2002).

6.6 Management Practices to Decrease Nitrous Oxide Emission

Nitrous oxide is mainly produced in soil by the processes nitrification and denitrification, which are controlled directly by factors such as nitrogen availability and moisture (Mosier et al, 1996) and indirectly by environmental or management factors. Some of the factors that control nitrous oxide emission such as soil type, rainfall, season and temperature are outside the farmer's control, but there are others that the farmer can influence. These include, soil aeration (affected by tillage methods), water status (controlled by irrigation and drainage), fertiliser type, amount, method and time of application, soil pH adjusted by application of lime (Stevens & Laughlin, 1998), supply of organic matter (Granli & Bøckman, 1994), and compaction of soil by animals and farm machinery (Abbasi & Adams, 1999).

Most of the research effort on mitigating nitrous oxide emissions worldwide has been devoted to reducing the emissions from cropped soils (Cole et al, 1996; Cole et al, 1997; Granli & Böckman, 1994; Freney, 1997b; McTaggart et al, 1994; Mosier et al, 1996; Mosier et al, 1998a; Seneviratne, 2001; Smith et al, 1997, 1998). Many of the techniques proposed are not considered to be applicable to the New Zealand pastoral scene where relatively little synthetic nitrogen fertiliser is used (Clark et al, 2001). However, the rate of fertiliser nitrogen use has increased rapidly during the last 10 years (Figure 6.3.), and it is expected that this will continue (Furness, pers comm), and thus the impact of techniques to reduce the emission of nitrous oxide following fertiliser application is likely to increase. Consequently, options to mitigate emissions following the application of synthetic fertiliser nitrogen also need to be considered in this review.

As mentioned above (Table 6.2), nitrous oxide is emitted from soils in New Zealand: (i) directly as a result of the application of synthetic fertilisers, animal manure or crop residues, biological nitrogen fixation, and the cultivation of histosols; (ii) directly during animal production, as wastes from housed animals, animal waste management systems, or excreta deposited during grazing; and (iii) indirectly after atmospheric deposition of ammonia and nitric oxides, or leaching and run-off of nitrate. Options to reduce the emission of nitrous oxide from each of these categories are considered below.

6.6.1 Direct emissions from soil

6.6.1.1 Synthetic fertiliser and manure nitrogen

Applied nitrogen has a very low efficiency of use in agriculture, and this is caused primarily by large losses of nitrogen in gaseous form (Peoples et al, 1995). Nitrous oxide emission is directly linked to the processes which cause loss of nitrogen from soil, and it has been demonstrated directly that any strategy which increases the efficiency of use of applied nitrogen will reduce emissions of nitrous oxide (Bronson et al, 1992; Minami et al, 1997). In general, nitrous oxide emissions can be decreased by management practices which optimise the crop's natural ability to compete with processes whereby plant-available nitrogen is lost from the soil-plant system (i.e. ammonia volatilisation, nitrification-denitrification, leaching and run-off). If nitrogen is used more efficiently by the crop or pasture, then less nitrogen will need to be supplied to meet the demand for food, less nitrogen will be lost, and less nitrous oxide will be produced.
The undesirable effects of fertiliser use on increased nitrous oxide production can be mitigated by agricultural management without decreasing production, and probably reducing rather than increasing costs which is important to the farmer (Bøeckman & Werner-Olfs, 1998). Knowledge gained on the importance and timing of the loss processes, and the factors controlling them has been utilised to develop strategies to decrease nitrogen loss and the impact to the environment. Cole et al (1996) reported that some combination of the management practices listed in Table 7.3 would be expected to improve synthetic fertiliser and manure nitrogen use efficiency, and significantly reduce nitrous oxide emission into the atmosphere.

**Table 6.3: Practices to Improve Efficiency of Use of Synthetic Fertiliser and Manure Nitrogen in Agriculture**

<table>
<thead>
<tr>
<th>Match N supply with crop demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Use soil/plant testing to determine fertiliser nitrogen needs</td>
</tr>
<tr>
<td>(b) Minimise fallow periods to limit mineral nitrogen accumulation</td>
</tr>
<tr>
<td>(c) Optimise split applications</td>
</tr>
<tr>
<td>(d) Reduce production goals</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tighten N flow cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Integrate animal and crop production systems to use manure to supply plant nitrogen</td>
</tr>
<tr>
<td>(b) Maintain plant residue on the production site</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Use advanced fertilisation techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Use controlled release fertilisers</td>
</tr>
<tr>
<td>(b) Place fertiliser below the soil surface</td>
</tr>
<tr>
<td>(c) Apply fertiliser to foliage not to soil</td>
</tr>
<tr>
<td>(d) Use nitrification inhibitors</td>
</tr>
<tr>
<td>(e) Match fertiliser type to seasonal precipitation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimise tillage, irrigation and drainage</th>
</tr>
</thead>
</table>

1Modified from Cole et al (1996)

### 6.6.1.1.1 Match nitrogen supply with crop demand

- Use soil/plant testing to determine fertiliser nitrogen needs
- Minimise fallow periods to limit mineral nitrogen accumulation
- Optimise split applications of fertiliser
- Reduce production goals and excessive use of fertiliser

Low levels of mineral nitrogen should be maintained in the soil when there is little or no plant growth and sufficient nitrogen should be provided when the plant is developing rapidly (Ortiz-Monasterio et al, 1996).

a) Soil and plant testing should be used to determine the requirements of the plant for nitrogen (Johnkutty & Palaniappan, 1996). This will allow for mineralisation of nitrogen from soil, legumes, manures, organic wastes, and any mineral nitrogen added by irrigation water or atmospheric deposition.

b) Agricultural systems that provide continuous plant cover should be utilised whenever feasible to minimise leaching and denitrification of nitrate associated with bare soil fallow (Wagner-Riddle & Thurtell, 1998). Nitrate accumulates in the soil during fallow periods between cropping seasons as a result of mineralisation of soil organic matter and nitrification of the ammonium so formed. The nitrate accumulated during fallow is more
susceptible to loss by denitrification than that which is produced when plants are present. The amount of fertiliser nitrogen used and the timing of application should have a goal of leaving as little residual nitrogen as possible in the soil during the non-cropped periods of the year. Any unnecessary long periods when ammonium can undergo nitrification without competition from plant uptake is likely to result in increased emission of nitrous oxide (Smith et al, 1997). Using inter-seasonal cover crops is one means of minimising the accumulation of mineral nitrogen and its loss. With this practice, mineral nitrogen does not accumulate in soil to be lost during mineralisation or flooding, but rather it is conserved within the system in plant tissue. The nitrogen can then be cycled for use by a subsequent crop through incorporation of the plant residues (Power, 1991; Townley-Smith et al, 1993).

c) The use of fertiliser nitrogen will be more efficient when the application of fertiliser coincides with the period of rapid plant uptake. Therefore, an application of fertiliser nitrogen when the crop is developed, or several applications of small amounts of fertiliser nitrogen during the growing season, would be a more effective means of supplying nitrogen for plant growth than one large dose at the beginning of the season (Ortiz-Monasterio et al, 1996). Where irrigation is used, there is the opportunity for supplying fertiliser nitrogen along with the irrigation water (Ortiz-Monasterio et al, 1996). This allows the farmer to overcome some of the limitations in supplying multiple applications of fertiliser nitrogen to crops by conventional techniques and to tune fertiliser nitrogen supply to crop requirements. This method has the advantages of simplicity, convenience and low cost (Muirhead et al, 1985).

d) Many farmers over-fertilise because they feel that the extra fertiliser nitrogen is cheaper than the production lost by under-fertilising. The most effective management practice to maximise plant uptake and minimise loss is to synchronise nitrogen supply with plant demand for nitrogen (Hellebrand & Munack, 1995).

Adoption of this some of these options would reduce nitrous oxide emission by at least 7% (Cole et al, 1996).

6.6.1.1.2 Tighten nitrogen flow cycles

- Integrate animal and crop systems by using manure to supply plant nitrogen
- Maintain plant residue on the production site

a) Over the last three decades, food production systems have changed, with animal production and meat consumption increasing much more rapidly than crop production. The increase in meat production has resulted in a further increase in nitrogen excreted from livestock, but not all of this nitrogen is being returned to the field. The reasons for this are that crop and animal production are not always conducted in the same geographical area, and the land used for crop production which is close to intensive animal production systems is not adequate to carry the animal waste input load. Return to the traditional crop and animal production systems, where animal wastes were returned to the field, would keep the nitrogen cycle tightly linked within the food production system, thus maintaining soil fertility and minimising nitrogen losses (Mosier et al, 2002).

b) Maintaining plant residues on the soil surface, instead of burning them, will allow the nitrogen contained in the residues to be reused, thus reducing the amount of external nitrogen required to produce a crop. This should directly reduce nitrous oxide production from synthetic fertiliser, and eliminate the enhancement of nitrous oxide production from soils caused by burning (Peoples et al, 1995). The presence of plant residues on the soil surface can also influence ammonia volatilisation by influencing the conditions of the
underlying soil, and by acting as a medium through which ammonia must pass before being lost to the atmosphere (Freney et al, 1992). The incorporation of residues with high C/N ratio into soils would immobilise mineral nitrogen. The immobilised nitrogen would not be lost, and would be available for later mineralisation (Aulakh et al, 1991).

c) Adoption of some of these options would reduce nitrous oxide emission by at least 4% (Cole et al, 1996).

6.6.1.1.3 Use advanced fertilisation techniques

- Use controlled release fertilisers
- Place fertiliser below the soil surface
- Apply fertiliser to foliage not to soil
- Use nitrification inhibitors
- Match fertiliser type to seasonal precipitation

a) By using specific slow release fertiliser formulations to release nitrogen in synchrony with plant growth, it should be possible to provide sufficient nitrogen in a single application to satisfy plant requirements, yet maintain very low concentrations of mineral nitrogen in the soil throughout the growing season. With this concept, any gaseous loss event would be small because of the limited substrate. Many different slow-release forms of nitrogen have been suggested (Shaviv & Mikkelsen, 1993; Shoji & Kanno, 1994; Vallejo et al, 2001) and considerable advances have been made in the formulation of these materials (Smith et al, 1997). Large reductions in the emission of nitrous oxide have been achieved using polyolefin-coated ammonium nitrate (trade name ‘Long’) and polyolefin-coated ammonium sulphate (trade name ‘Nutricote’), instead of uncoated fertiliser nitrogen (Smith et al, 1997).

b) It has been demonstrated that plant uptake of fertiliser nitrogen can be improved, and total nitrogen losses reduced from the levels achieved with surface broadcasting, by incorporation or deep placement of the nitrogen fertiliser (Rees et al, 1997). Placement of the nitrogen deep in the soil in an anaerobic zone will lower the N2O/N2 ratio when denitrification occurs. Placement beneath the soil also decreases ammonia volatilisation by providing a physical barrier in the form of a layer of soil to trap any ammonia liberated. Rees et al (1997) found that improved fertiliser placement could increase the recovery of fertiliser nitrogen by 20-30%. Relative recoveries and level of nitrogen loss can also be influenced by fertiliser composition, and the rate and timing of application (Strong et al, 1991; McTaggart et al, 1994; Smith et al, 1997).

c) Foliar fertilisation represents an alternative means of applying supplementary nitrogen during periods of rapid plant growth and nitrogen demand, or at times of critical physiological stress. Its greatest use has traditionally been with high-value crops such as fruits and vegetables, although it has been successfully used for late applications of nitrogen to cereal, leguminous and fibre crops to either increase grain protein or yield (Smith et al, 1991). As urea is rapidly absorbed it is commonly used for foliar applications of nitrogen. In wheat, around two-thirds of foliar applied urea-nitrogen was incorporated into plants within four hours of application, and almost 80% of the nitrogen applied was recovered in grain at the final harvest (Smith et al, 1991). Direct measurements of gaseous emission in such systems showed that very little nitrogen was lost from foliar applied urea unless rainfall washed unassimilated urea from the plant on to the soil (Smith et al, 1991).

d) Maintaining the nitrogen in the ammonium form in soil would prevent loss of nitrogen by both nitrification and denitrification. One method of doing this is to add a nitrification
inhibitor with the fertiliser. While this technique does not always produce increased crop yields, it does decrease nitrous oxide production (McTaggart et al, 1997a; Smith et al, 1997; Skiba et al, 1997; Dittert et al, 2001; Majumdar et al, 2002). Only a limited number of chemicals are available commercially for use as nitrification inhibitors in agriculture, and many of these compounds have limitations to their usefulness. For example, the most commonly used nitrification inhibitor, nitrapyrin, is seldom effective because of sorption on soil colloids, hydrolysis, and loss by volatilisation (Skiba et al, 1997). Using calcium carbide, coated with layers of wax and shellac to provide a slow release source of acetylene to inhibit nitrification, increased yield or recovery of nitrogen in irrigated wheat, maize and cotton, and flooded rice (Freney, 1997a). It also inhibited nitrous oxide emission from urea-fertilised maize and rice soils (Table 6.4). Since those trials were carried out with wax-coated calcium carbide, an improved product has been developed as a slow release source of acetylene. This material is a polyethylene matrix containing small particles of calcium carbide (1-200µm diameter), and various additives to provide controlled water penetration and acetylene release. This matrix inhibited nitrification for 90 days, and considerably slowed the oxidation for 180 days (Freney et al, 2000; Randall et al, 2001).

Table 6.4: Effect of Nitrification Inhibitors on Nitrous Oxide Emission (g N ha⁻¹ day⁻¹)¹

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Corn¹</th>
<th>Rice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.1ᵃ</td>
<td>38ᵃ</td>
</tr>
<tr>
<td>Control + wax-coated CaC₂</td>
<td>4.1ᵃ</td>
<td>14ᵇ</td>
</tr>
<tr>
<td>Urea</td>
<td>31ᵇ</td>
<td>73ᶜ</td>
</tr>
<tr>
<td>Urea + wax-coated CaC₂</td>
<td>5.4ᵃ</td>
<td>16ᵇ</td>
</tr>
</tbody>
</table>

¹From Mosier et al, 1994
²Numbers in each column followed by the same letter are not significantly different (p=0.05). The periods over which mean rates were calculated were 97 days for corn and 23 days for rice.

Studies by McTaggart et al (1994, 1997a) showed that dicyandiamide (DCD) was also effective for reducing emissions of nitrous oxide following applications of fertiliser nitrogen to grassland and arable crops. Annual emissions of up to 58% were achieved (Smith et al, 1997). Delgado and Mosier (1996) also found DCD to be effective for reducing nitrous oxide emission from a crop of spring barley fertilised with urea (emissions reduced by 82%).

A new nitrification inhibitor, 3,4-dimethylpyrazole phosphate (DMPP, trade name ENTEC), has been developed by the German company BASF AG (Linzmeier et al, 2001; Zerulla et al, 2001). Inhibition was achieved for 28 to 70 days with applications of 0.5-1.5 kg DMPP ha⁻¹, depending on the amount of nitrogen applied. Weiske et al (2001) showed that DMPP reduced emission of nitrous oxide by 49% (averaged over three years), which was considerably greater than DCD (average reduction 26%), without having any adverse effect on methane oxidation in soil.

Laboratory studies by Majumdar (2002) showed that Karanjin, isolated from Karanja (Pongamia glabra Vent.), was a naturally occurring nitrification inhibitor which slowed the emission of nitrous oxide from an alluvial sandy loam fertilised with urea.

Some studies have suggested that the emission of nitrous oxide varies with the type of fertiliser used, while other reports suggest that the variation has more to do with environmental conditions than type of nitrogen used (Mosier et al, 1998). It may be that both factors play a part, and thus provide scope for managing nitrous oxide emissions (Clayton et al, 1997). Thus, in situations where nitrification is the main process responsible for nitrous oxide production, a switch from urea to ammonium nitrate may be beneficial. This would
also result in a reduction in ammonia volatilisation and secondary emissions of nitrous oxide. On the other hand, where denitrification is likely to be the main process producing nitrous oxide, nitrate forms of fertiliser should not be used. Thus matching the type of fertiliser with rainfall and moisture conditions in the soil could result in appreciable reductions in nitrous oxide emissions (McTaggart et al, 1994).

Adoption of some of these options would reduce nitrous oxide emission by at least 4% (Cole et al, 1996).

6.6.1.1.4 Optimise tillage, irrigation and drainage

Reduced or no-till farming systems, in which plant residues are retained, and soil disturbance is minimised, encourage reduced rates of nitrogen mineralisation. However, there is evidence which indicates that no-till soils suffer from greater gaseous losses through denitrification than those under conventional cultivation (Ball et al, 1999; Smith et al, 2000). This may be because in no-till soils there is a larger pool of substrate-nitrogen in the surface layers (MacKenzie et al, 1998), greater bulk density resulting in reduced diffusion of air in the surface layers, larger and more anaerobic aggregates, increased water content due to greater water conservation, and greater concentrations of organic matter near the surface to increase carbon availability. These combined factors thus create a more favourable environment for denitrifying microorganisms and greater losses of nitrous oxide (Aulakh et al, 1984; Ball et al, 1999; Smith et al, 2000, 2001).

Since maximum denitrification rates are commonly observed when soil water-filled pore space is more than 90%, minimising the time a soil is saturated should limit denitrification (Linn & Doran, 1984). The aim should be to ensure that the water-filled pore space of the soil does not exceed 60% (Smith et al, 1997). It has been shown that less nitrous oxide was emitted from less frequently irrigated soils. Unfortunately, irrigating only once or twice each two weeks increased nitrate leaching (Rolston et al, 1982). Maintaining a balance between limiting denitrification or nitrate leaching and appropriate water management is difficult. Trickle or drip irrigation systems allow the delivery of nitrogen to the area of maximum crop uptake, and thus the rate of application can be matched to the plant’s requirements. With careful operation, trickle systems can reduce deep percolation, run-off and denitrification (Doerge et al, 1991). Localised variations in ground level (e.g. ridges or raised beds) or infiltration rate can cause localised wet spots which have greater rates of emission of nitrous oxide (Smith et al, 1997). They recommend that irrigation water be applied slowly so that aeration of the soil is not restricted, and that the amount applied at any one time is limited.

Barton et al (1999) reviewed work on denitrification rates in agricultural and forest soils which showed that denitrification rates were increased for longer periods in poorly drained soils. In addition, work on urine amended pasture showed that emission of nitrous oxide from poorly drained soils, as a result of denitrification, was greater than that from well drained soils (Barton et al, 2000) The results of the review (Barton et al, 1999) suggested that improved drainage could reduce nitrogen denitrification losses from 40 to <1 kg N ha⁻¹ y⁻¹ (Eckard et al, 2000), while a laboratory study indicated that nitrous oxide emission from well drained soil was only one fifth of that from poorly drained soil (de Klein, unpublished data; Clark et al, 2001).

A conservative estimate of the reduction achievable is 4% of the nitrous oxide currently emitted (Cole et al, 1966).
6.6.2 Direct emissions from animal production

6.6.2.1 Wastes from housed animals

Some of the livestock is kept in housing systems, and in cases where deep litter is used losses of nitrous oxide directly from the litter can be expected. Groenestein and Van Faassen (1993) studied deep litter systems for fattening pigs, and found substantial losses of nitrogen as nitrous oxide (14.8-20.6%; 0.6-0.8 kg N per pig) because of poor oxygen availability in the compacted deep litter. Nitrous oxide is unlikely to be produced from slurry stored indoor in pits beneath slatted floors, the usual excreta storage system for pigs and cattle (Monteny et al, 2001). Nitrous oxide is emitted from solid manure stored outside. Sibbesen and Lind (1993) reported that 0.3 g of N₂O was emitted per day per m² of farm yard manure. Monteny et al (2001) suggest that control of nitrous oxide emissions will have to rely on avoiding non-optimal process conditions for each source.

Strictly anaerobic systems like manure slurries can only lose nitrogen by denitrification when oxidised nitrogen is present. As the nitrogen in manures is essentially in reduced forms, aeration of slurries is required before nitrous oxide can be lost by nitrification-denitrification. Consequently the frequent aeration of stored liquid manure should be avoided as it will lead to increased loss of nitrous oxide.

6.6.2.2 Excreta deposited during grazing

In New Zealand the main form of land use (13 x 10⁶ ha) involves dairy cattle, beef cattle, sheep, deer and goats grazing on grass/legume pastures. These animals modify the physiology and nitrogen uptake characteristics of the pasture by grazing, change the physical characteristics of the soil by treading, and deposit excreta directly onto the pasture (Jarvis et al, 1995). Animals do not utilise the nitrogen they ingest efficiently. Very little of the nitrogen in grass, silage or other feedstuff is converted into milk, meat, eggs or wool and the remainder is excreted in dung and urine (Table 6.5; van der Hoek, 1998).

Table 6.5: Efficiency of Nitrogen Use in Global Animal Production¹

<table>
<thead>
<tr>
<th>Animal</th>
<th>Intake (Tg N)</th>
<th>Product (Tg N)</th>
<th>Efficiency of nitrogen use (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>64.417</td>
<td>4.959</td>
<td>7.7</td>
</tr>
<tr>
<td>Sheep</td>
<td>11.617</td>
<td>0.719</td>
<td>6.2</td>
</tr>
<tr>
<td>Goats</td>
<td>5.726</td>
<td>0.207</td>
<td>3.6</td>
</tr>
<tr>
<td>Pigs</td>
<td>12.230</td>
<td>2.513</td>
<td>20.5</td>
</tr>
<tr>
<td>Chickens</td>
<td>9.495</td>
<td>3.211</td>
<td>33.8</td>
</tr>
<tr>
<td>Total</td>
<td>114.355</td>
<td>12.004</td>
<td>10.5</td>
</tr>
</tbody>
</table>

¹van der Hoek 1998

Because of the inefficiency of use, large quantities of nitrogen are deposited on pasture (Table 7.6). The cattle excrete more nitrogen on to pasture than the other animals combined, even though they are fewer in number than the other animals, and dairy cattle excrete more nitrogen than the non-dairy cattle. While sheep numbers in New Zealand have declined from over 70 000 000 in 1982 to ~47 000 000, they are still responsible for almost half of the nitrogen deposited (Table 6.6). In the period from 1990 to 1998 methane emission declined by 5%, whereas the nitrous oxide emissions increased by 27%. This occurred because the driving force for methane emissions was the decline in sheep numbers, whereas nitrous oxide emission was affected more by the increase in numbers of dairy cattle and poultry (United Nations, 2001).
### Table 6.6: Amounts of Nitrogen Excreted on to Pasture in New Zealand in 1997<sup>1</sup>

<table>
<thead>
<tr>
<th>Livestock type</th>
<th>Number of animals (x 1000)&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Nitrogen excreted on to pasture (Gg N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-dairy cattle</td>
<td>4 723</td>
<td>298.0</td>
</tr>
<tr>
<td>Dairy cattle</td>
<td>4 250</td>
<td>327.9</td>
</tr>
<tr>
<td>Poultry</td>
<td>2 200</td>
<td>0.04</td>
</tr>
<tr>
<td>Sheep</td>
<td>46 888</td>
<td>553.3</td>
</tr>
<tr>
<td>Goats</td>
<td>228</td>
<td>2.2</td>
</tr>
<tr>
<td>Deer</td>
<td>1 345</td>
<td>26.5</td>
</tr>
<tr>
<td><strong>Total excreted</strong></td>
<td></td>
<td><strong>1 207.9</strong></td>
</tr>
</tbody>
</table>

<sup>1</sup> C de Klein, pers comm

<sup>2</sup> 3 year average, Statistics New Zealand, 1997

The amount of nitrogen contained in urine patches (equivalent to 500 kg N ha<sup>-1</sup> for sheep and 1 000 kg N ha<sup>-1</sup> for cattle) is much greater than the capacity of pasture plants to assimilate it (Jarvis et al, 1995; Silva et al, 1999; Cameron et al, 2002). The nitrogen can therefore be readily lost by ammonia volatilisation, nitrification-denitrification, or leaching with subsequent effects on nitrous oxide production.

Numerous techniques have been proposed for reducing the amount of nitrous oxide resulting from the grazing of animals on pastures (e.g. AEAT, 1998; Clark et al, 2001; Clemens & Ahlgrimm, 2001; Desjardins & Keng, 1999; Jarvis et al, 1996; Kammann et al, 1998; Kroeze, 1998; Kulshreshtha et al, 2000; Misselbrook et al, 1998; Oenema et al, 1997, 1998; Stevens & Laughlin, 1997; Velthof et al, 1998). These have been classified into three main groups: (i) Fertiliser Management; (ii) Grassland Management; and (iii) Livestock Production Management (Velthof et al, 1998). Proposals for reducing nitrous oxide production from fertiliser application were discussed above (6.6.1.1.) and are not repeated here. The measures for abatement of nitrous oxide which fall into categories (ii) and (iii) are summarised in Table 6.7.

### Table 6.7: Practices to decrease the emission of nitrous oxide resulting from animals grazing on pasture

#### Grassland Management

- (a) Adjust pH to more than 5 by liming
- (b) Improve drainage
- (c) Prevent soil compaction
- (d) Breed cultivars that improve nitrogen efficiency

#### Livestock Production Management

- (a) Reduce number of animals
- (b) Diet manipulation
- (c) Winter management of cattle


#### 6.6.2.2.1 Grassland management

- Adjust pH to more than 5 by liming
- Improve drainage
- Prevent soil compaction
• Breed cultivars that improve nitrogen efficiency

a) Clark et al (2001) point out that recent reports concerning the use of lime to adjust soil pH to >5 to reduce emissions of nitrous oxide are inconclusive and sometimes contradictory. Brumme and Beese (1992) found that adding dolomite to a beech forest reduced nitrous oxide emission by a factor of ~4, while Butterbach et al (1997) observed enhanced fluxes over the entire observation period after liming a spruce forest. van der Weerden et al (1999) observed that soil with a pH of ~6.3 had a significantly lower nitrous oxide/dinitrogen ratio than a more acid soil, while Ellis et al (1997) and Stevens et al (1998) found that nitrous oxide emission was maximal at pH 6.1-6.5. Wang et al (1997) measured nitrous oxide emissions from limed and unlimed soil, and found higher nitrous oxide emissions from the limed soil when the soil was wet, but lower emissions from the limed soil under dryer conditions.

The confusion may arise because of differential effects on the two mechanisms involved in the production of nitrous oxide viz nitrification and denitrification. Granli and Böckman (1994) reported that the rate of denitrification increased with pH and the nitrous oxide/dinitrogen ratio decreased. The net effect on nitrous oxide emission is not clear, although there may be a minimum in nitrous oxide emissions around pH 6. Because the reduction of nitrous oxide is inhibited more than the reduction of nitrate by acidic conditions, nitrous oxide production is enhanced and may even becomes dominant at pH < 5.5 to 6.0 (Weier & Gilliam, 1986). As the pH increases, the formation of dinitrogen seems to be favoured over the production of nitrous oxide (Focht & Verstraete, 1977). Clough et al (2002) examined the effect of liming on nitrous oxide emissions in two laboratory experiments, and found that the main effect of liming was to promote nitrification which markedly increased nitrous oxide fluxes. After 60 days, a synthetic urine treatment limed to pH 6 produced more nitrous oxide than any other pH treatment. Considerable nitrate remained in the soil at the conclusion of their experiments and little denitrification occurred. They pointed out that it is essential to study the fate of the nitrate produced before definite conclusions can be drawn on the effect of liming.

Clark et al (2001) suggest that a reduction in emissions by 3% should be achievable by applying lime.

b) Improving drainage is relevant to both cropping and grazing, and was discussed in Section 6.6.1.1.4.

c) The effects of soil compaction on nitrous oxide emission have been studied by a number of scientists in different situations (Sitaula et al, 1997; Smith et al, 1997; Abbasi & Adams, 1999; Ball & Ritchie, 1999; Ball et al, 1999). McTaggart et al (1997b) found that nitrous oxide emission from compacted grassland was more than twice that of unaffected soils. Hansen et al (1993) observed that concentrations of nitrous oxide in compacted soil were seven times greater than those in non-compact soil, but emissions from the compacted soil were only one and a half times greater. The difference may have been due to restricted diffusion of nitrous oxide in the compacted soil only, or increased reduction of nitrous oxide to dinitrogen because of the slow diffusion. It is apparent from these results that tillage and traffic should be reduced to minimise soil compaction, or the creation of plough pans, which may result in increased denitrification and nitrous oxide emission. Treading by cattle could increase emissions of nitrous oxide by a factor of two (Oenema et al, 1997).

Clark et al (2001) suggest that a reduction in emissions by 3% should be achievable by avoiding compaction,
d) Breeding “high sugar” ryegrass cultivars to improve nitrogen efficiency in dairy cattle has proved effective (Clark et al, 2001; IGER, 2002). Dairy cows fed grasses high in water soluble carbohydrate excreted ~24% less nitrogen than those fed normal diets. The grasses tended to contain less protein, but because of a better balance between energy and protein supply, milk yields and milk protein yields were improved (IGER, 2002).

The perennial ryegrass cultivars Aurora and Cariad, selected at Aberystwyth in the UK for high water soluble carbohydrate concentrations, were sown in three contrasting dairy environments in Australia (Smith et al, 1998). Preliminary investigations with the decision support system “GrazFeed” (Freer et al, 1997) suggest a 25% increase in milk production over the period summer to early autumn can be obtained with the development of high water soluble carbohydrate cultivars adapted to southern Australian conditions (Smith et al, 1998).

The water soluble carbohydrate concentration of *Phalaris aquatica* L. (phalaris) pasture had a significant influence on short-term diet selection by grazing sheep (Ciaveralla et al, 2000). When 12 to 13-month-old Merino wethers were given simultaneous access to phalaris pastures of ‘low’ (62 mg/g dry matter) and ‘high’ (126 mg/g dry matter) water-soluble carbohydrate concentration treatments, they selected 2.6-fold more high water soluble carbohydrate pasture than low water soluble carbohydrate pasture. The two pastures did not differ significantly in *in vitro* dry matter digestibility (84%), nitrogen (3.1%), or neutral detergent fibre concentration (42.4%) (Ciaveralla et al, 2000). These results, coupled with the results of previous workers (e.g. Dove & Milne, 1994; Leury et al, 1999), suggest that pastures with higher water soluble carbohydrate would result in higher dry matter intakes, improved efficiency of microbial protein synthesis (Dove & Milne, 1994), and better animal performance (Ciaveralla et al, 2000).

Clark et al (2001) assumed that feeding animals with grass high in water soluble carbohydrates would reduce nitrous oxide emission by 4%.

### 6.6.2.2.2 Livestock production management

- Reduce number of animals
- Diet manipulation
- Winter management of cattle

a) Reducing nitrogen excretion, and the associated nitrous oxide emission, by decreasing the number of animals on pasture, would be an effective mitigation option if the amount of nitrogen excreted per animal remained the same or increased at a slower rate than the rate of animal decline (Clark et al, 2001). If the production per animal could be increased then fewer animals would be needed to maintain production. Between 1990 and 1998 the total number of animals in New Zealand decreased by ~5%, but production of sheep meat, beef and processed milk increased by 9%, 34% and 48%, respectively (Clark et al, 2001; Meat and Wool Economic Service, 2000; Livestock Improvement Corporation, 2000). So gains in productivity can be made without continuously increasing animal numbers. However, we do not know whether there has been an increase in nitrous oxide emission associated with the increase in productivity. Velthof et al (1998) suggest that the nitrous oxide emitted per animal is probably higher for a more productive animal, but feel that this will be outweighed by the decrease in the number of animals needed to obtain the production required.

b) Methods proposed for manipulating the diet of animals to improve the efficiency of use of nitrogen and reduce the amount of nitrogen excreted include: (i) lowering the crude protein content of the diet (Miselbrook et al, 1998); (ii) increasing the carbohydrate
content of the diet so that more microbial protein is synthesised and less ammonia is lost from the rumen (Dove & Robards, 1974; Kebreab et al, 2001); and (iii) increasing the concentration of condensed tannins in the diet (Min et al, 2001).

Recent work showed that feeding pigs reduced protein diets decreased nitrogen excretion by 44% and ammonia emission by 50% (MAFF Environmental R&D Newsletter, 1998). Misselbrook et al (1998) made measurements of ammonia volatilisation, denitrification and nitrous oxide emission from grass/clover plots treated with slurries obtained from pigs fed a standard commercial diet (containing 205 g kg⁻¹ crude protein) or a specially formulated diet (containing 140 g kg⁻¹ crude protein). Decreasing the crude protein content of the pig’s diet had no effect on the growth rate of the pigs, but resulted in a slurry with a higher dry matter content and a lower pH and total nitrogen content. Ammonia volatilisation from the amended diet was less than half that of the standard diet (43 vs 109 kg N ha⁻¹), and loss by denitrification was 6 and 23 kg N ha⁻¹, respectively. The pattern of nitrous oxide emission was similar to that for denitrification.

Inefficient utilisation of nitrogen in ruminants grazing pasture is considered to be the result of low levels of non-structural carbohydrate relative to soluble protein (van Vuuren, 1993). Dove and Robards (1974) found that infusion of starch into sheep increased the excretion of nitrogen in faeces and decreased the amount of nitrogen excreted in the urine. The rise in faecal nitrogen has been attributed to the presence of undigested microbial protein in faeces as a result of the utilisation of starch by caecal microorganisms.

Kebreab et al (2001) made a comprehensive study on the effect of nitrogen intake, energy source, protein degradability and silage type on excretion of nitrogen in milk, faeces and urine. They point out that the increase in nitrogen excretion by dairy cows is related to the increased consumption of protein supplements, and that the increase in protein is difficult to justify, as there are marginal gains in terms of animal production, but an exponential increase in terms of pollution. Urinary nitrogen was strongly and exponentially correlated with nitrogen uptake, with the result that 80% of the nitrogen intake above 500 g N day⁻¹ was excreted in the urine. Kebreab et al (2001) show that reduction of nitrogen pollution from dairy cows can be achieved in several ways, and the most important of these is a reduction of nitrogen intake in the form of highly degradable protein. Cows that received lowly degradable protein excreted 24% less nitrogen in the urine than those fed highly degradable protein, without reducing milk output. The reduction in urine excretion would reduce ammonia volatilisation from dairy cows in the UK by as much as 12 Gg y⁻¹ (Kebreab et al, 2001). Energy supplement in the form of lowly degradable starch also reduced the amount of urinary nitrogen excretion. They concluded that nitrogen pollution can be ameliorated by using grass grown with moderate fertiliser application, and maize-based energy supplements formulated to provide lowly degradable protein and nitrogen intakes of less than 400 g day⁻¹ for average yielding cows.

In the dairy industry in New Zealand, fertiliser nitrogen is often used to provide extra feed when supplies are limiting. Replacement of the fertilised grass with maize silage to reduce excreted nitrogen has been suggested to prevent nitrate leaching (Clark et al, 2001). Clark et al (2001) evaluated this nitrous oxide mitigation option by assuming that the nitrogen excretion from dairy cows would be reduced by 10%. It was also assumed that by substituting fertiliser boosted grass with maize silage the fertiliser nitrogen input would be reduced by 90%. As a result nitrous oxide emission could be reduced by 60%.

Another technique used for achieving greater excretion of dietary nitrogen in the faeces is to include condensed tannins in the diet. This has been done by adding commercial tannins to silage (Slaw et al, 1999), or by grazing animals on plants containing elevated concentrations of condensed tannins, e.g. *Lotus corniculatus* (birdsfoot trefoil) (Waghorn & Sheldon, 1997; Min et al, 2001). Condensed tannins are found in a number of other
legumes including *Lotus pedunculatus*, *Onobrychis vicifolia* (sainfoin), and *Lespedeza cuneata* (sericea lespedeza). The condensed tannins in *Lotus corniculatus* (30-35 g kg\(^{-1}\) dry matter) have reduced protein solubility and degradation in the rumen (Min et al., 2000), increased the absorption of essential amino acids from the small intestine by 62% (Waghorn et al., 1987), and increased the flow of cysteine to body synthetic reactions (Wang et al., 1994). It also increased wool growth by 12% during summer and increased milk protein secretion by 14% from ewes during spring (Wang et al., 1996; Min et al., 1998).

Clark et al. (2001) suggest that a reduction in emissions by 4% should be achievable by growing high sugar grasses, and a similar reduction should be achievable by growing grass high in condensed tannins.

c) Nitrous oxide emission from animal excreta is likely to be highest during the wet autumn/winter period (de Klein et al., 2001). If dairy and beef cattle were kept on feedpads during these periods, and the excreta collected and re-utilised as effluent, nitrous oxide emission could be reduced. Nitrous oxide emission from soil after application of dung and urine is greater than that from effluent which has been applied properly (Oenema et al., 1997). Nitrate leaching losses would also be reduced by this measure to the extent of 45-55% (de Klein and Ledgard, 2001). However, ammonia volatilisation may be increased by this technique.

Clark et al. (2001) suggest that a reduction in emissions by 6% should be achievable by winter management of cattle.

### 6.6.3 Indirect emissions

#### 6.6.3.1 Atmospheric deposition

- Mitigating ammonia loss
- Urease inhibitors
- Slurry application

Until recently farmers in New Zealand relied almost exclusively on fixation by clover to supply nitrogen to pastures, and the main source of atmospheric ammonia was the excreta of grazing animals. Now farmers are using organic wastes (e.g. dairy shed effluent, pig slurry) at <200 kg N ha\(^{-1}\) y\(^{-1}\) to supply nitrogen to pastures and crops (Cameron et al., 1997), and are applying up to 400 kg synthetic fertiliser N ha\(^{-1}\) y\(^{-1}\) to pastures to provide feed for dairy cows (Cameron et al., 2002). These three sources add urea to pastures and result in large losses of nitrogen by ammonia volatilisation (e.g. Jarvis et al., 1995). This occurs because the plants and surface mat have high urease activity (McGarity & Hoult, 1971). Application of urea as synthetic fertiliser, effluent or slurry increases the dry matter yield of the pasture so that the stocking rate can be increased. Fertilisation also increases the concentration of nitrogen in the pasture which results in increased intake of nitrogen by the grazing animals. The combined result is increased excretion of urinary nitrogen and increased ammonia volatilisation (Bussink, 1992).

The techniques discussed earlier for increasing the efficiency of fertiliser nitrogen also apply to urea. In addition, ammonia loss from surface applications of urea can be reduced by the use of a urease inhibitor which allows urea to move into the soil before hydrolysis. The ammonia then released is retained by the soil. One compound which has been widely tested for its capacity to reduce ammonia loss from urea is the phosphoroamid N-(n-butyl) thiophosphoric triamid (NBTPT), which is marketed in the US mixed with urea under the trade name of Agrotain (Byrnes & Freney, 1996). In upland fields, Bronson et al. (1989)
found that addition of NBPT markedly reduced ammonia volatilisation from loamy sands. In 21 field experiments in the US, the addition of NBTPT with average applications of 100 kg urea-N ha⁻¹ increased grain yields of maize by an average of 750 kg ha⁻¹. The yield increase was equivalent to that obtained with an extra 80 kg N ha⁻¹ (Byrnes & Freney, 1995).

Abatement techniques for reducing ammonia loss from dairy shed effluent and pig slurry have the greatest impact if they are employed at the time of application when ammonia loss rates are fast. Erisman et al (1999) showed that mitigation techniques applied after this time had no significant effect on the emission of ammonia. It is also apparent that applying the waste at night, when temperatures and wind speeds are low, or in winter would result in reduced loss of ammonia (Sommer & Olesen, 2000). Decreasing the water content of the slurry, and delaying application until a substantial canopy has developed (to reduce wind speeds) would also appear to have a large impact on ammonia loss (Sommer et al, 1997; Sommer & Olesenm, 2000). Other techniques proposed for reducing loss of ammonia include applying during rainfall, incorporation or injection of the waste into the soil, application with trail hoses, applying in bands instead of broadcasting, acidification before application and matching nitrogen supply to the demand of the crop (Sommer et al, 1997; Stevens & Laughlin, 1997).

Bussink (1992) showed that the loss of ammonia from the plant-soil-animal system increased with the amount of fertiliser nitrogen applied, indicating that ammonia losses could be substantially reduced by limiting the amount of fertiliser added to the optimum required for grass production.

Concern that mitigation measures for ammonia may affect emissions of nitrous oxide and methane prompted Brink and his co-authors to analyse the effects on the Netherlands (Brink et al, 2001a) and Europe as a whole (Brink et al, 2001b). They did this by combining information from the ammonia module of the Regional Air Pollution Information and Simulation model (RAINS) with the IPCC method for national greenhouse gas inventories. They concluded that application of several ammonia abatement options may result in a substantial increase in nitrous oxide emissions, but would have a negligible effect on methane emissions.

6.6.3.2 Nitrate leaching and run-off

- Synchronising nitrogen supply and demand
- Cover crops
- Buffer zones

The nitrate retention capacity of New Zealand soils is low and thus nitrate is readily leached (Cameron et al, 2002). It is apparent from Table 6.2 that nitrate removed from agricultural lands by leaching and run-off is the second most important source of nitrous oxide in New Zealand, and reduction of this source will have a big impact on total emissions. The amount of fertiliser nitrogen used in New Zealand has increased greatly in the last 10 years (Figure 6.3), with the greatest increase being on dairy farms where farmers apply up to 400 kg N ha⁻¹ y⁻¹. Leaching losses are generally low when application rates are less than 200 kg N ha⁻¹ y⁻¹, but increase greatly when application rates approach 400 kg N ha⁻¹ y⁻¹ (Figure 6.4).

Strategies known to be effective for reducing nitrate leaching include reducing fertiliser nitrogen application rates, synchronising fertiliser nitrogen supply to plant nitrogen demand, balancing the input of different nutrients, growing a cover crop and use of buffer zones (Cameron et al, 2002; Di & Cameron, 2002b). Winter cover crops reduced nitrate leaching by up to 30 kg N ha⁻¹ compared to fallow, and delaying the cultivation of pasture leys until late autumn reduced the amount of nitrogen released from mineralisation which resulted in reduced leaching (Cameron et al, 2002). Application of irrigation water at the optimum rate
for plant growth increased nitrogen uptake and reduced leaching of nitrate, but may increase leaching if too much water is applied (Cameron et al, 2002).

Studies in a wide range of temperate ecosystems have shown that riparian zones and deep ditches interfacied between farms and rivers or lakes are very effective in reducing the nitrate content of run-off and groundwater reaching the water bodies (Blackwell et al, 1999; Burt et al, 1999; Groffman et al, 1998; Nguyen et al, 2002; Well et al, 2001). Schipper et al (1993) found that over 90% of the nitrate in the incoming water was removed by the riparian zone. However, there have been few studies on the production of nitrous oxide by these zones, and current knowledge on the significance of the saturated zone as a source of nitrous oxide is unsatisfactory (Groffman et al, 1998; Well et al, 2001). In addition, while there is now significant information on the nitrous oxide content of groundwater (Heincke & Kaupenjohann, 1999), little is known about the transfer of this nitrous oxide to the atmosphere (Well et al, 2001). As many of the riparian zone soils are highly anaerobic, they may act like flooded rice soils and denitrify nitrate at high rates, but produce little nitrous oxide (Freney, 1997a). It is apparent that riparian zones and deep ditches used to trap nitrate should not contain plants with the ability to transport nitrous oxide to the atmosphere through their aerenchyma (Mosier et al, 1990; Augustin et al, 1999). Further research is obviously required to determine if these areas are sources or sinks for nitrous oxide (Groffman et al, 1998, 2000).

![Figure 6.4: Relationship between Mineral Leached Per Annum and the Amount of Potentially Leachable N in the Soil](source: Di & Cameron, 2002a)

### 6.7 Modeling

- Evaluation of abatement options
- Inventory purposes

Currently there is no simple method for evaluating the effect of proposed abatement measures on nitrous oxide emission from agriculture, although it is anticipated that with the continued development of fast response sensors it should be possible to use micrometeorological methods for this purpose in the near future (Denmead, 1997). In addition, a more accurate method is required for producing an annual inventory of nitrous oxide emission from anthropogenic sources in New Zealand. At present, the IPCC default methodology and
animal population statistics are used to estimate emissions (IPCC, 1997; Mosier et al, 1998b), but there are uncertainties associated with emission factors, indirect sources and animal excretion. In a recent review of New Zealand’s greenhouse gas inventories, it was recommended that a process-based model be developed for estimating nitrous oxide emission from agricultural soils so that the annual inventory can be accurately prepared (United Nations, 2001). However, models of nitrous oxide production are complex, because they must be able to model soil chemistry, microbiology, physics, and the soil microclimate which has a large influence on nitrogen transformation and diffusion of gases (Denmead, 1997; Cameron et al, 2000).

Muller et al (1997a) employed Michaelis-Menten kinetics to predict seasonal and annual nitrous oxide fluxes from urine-affected pasture in New Zealand. Nitrous oxide emissions were partitioned between nitrification and denitrification sources, with nitrification being determined from ammonium concentrations and denitrification from nitrate concentrations.

Frolking et al (1998) simulated nitrous oxide emissions with four models [CENTURY-NGAS (Parton et al, 1996), DNDC - Denitrification-Decomposition (Li et al, 1992), ExpertN (Engel & Priesack, 1993) and the NASA-Ames version of the CASA model (Potter et al, 1997)] and compared these with year-round field measurements from five sites in three countries (Germany, Scotland and the US). All models generated similar results for the general cycling of nitrogen through the agro-ecosystems, but simulated nitrogen trace gas fluxes were quite different. In most cases the simulated fluxes were within a factor of two of the observed fluxes. The importance of denitrification in winter months is acknowledged (e.g. Müller et al, 1997b), but none of the models in this comparison have robust algorithms for winter denitrification. Recommendations for improving the current models for estimating greenhouse gas emission are given (Frolking et al, 1998).

Wang et al (1997) modified the DNDC model using field measurements made under conditions of low nitrous oxide emission. The modifications included increasing the water-filled pore space threshold to 60%, adding a sub-model to describe surface temperature and using better formulations for soil evaporation, organic carbon, plant transpiration, and growth and nitrogen uptake. Their results indicated that in semi-arid and arid regions nitrification was a more important source of nitrous oxide than denitrification.

Brown et al (2000) reviewed 60 models that have been proposed for estimating nitrous oxide emissions from soils to determine which one might be suitable for inventory purposes in the UK. They decided that the DNDC model (Li et al, 1992) was appropriate for the following reasons: (i) provided nitrous oxide output; (ii) already used in the US and China with success; (iii) can be used for small plots and regional studies; (iv) may be useful for nitrate leaching and indirect emissions; (v) and satisfied many IPCC requirements.

van der Weerden et al (2002) established the following criteria for the selection of a model for New Zealand: (i) prediction of nitrous oxide production; (ii) simulation of nitrification and denitrification; (iii) small data requirements; (iv) realistic time step as far as soil processes and data availability are concerned; (v) ability to run from Windows or MS DOS, (vi) availability of model; and (vii) development and validation of model with data from New Zealand. They selected four process-based models for evaluation: DNDC (Li et al, 1992), DAYCENT (Parton et al, 1998), NOPAS (van der Weerden & Sherlock, 2000), and ExpertN (Engel & Priesack, 1993). The DNDC model was modified to include the effects of day length on pasture growth, excretal-nitrogen from grazing animals and water-filled pore space, and tested against nitrous oxide emissions from two grazed and ungrazed dairy pastures (Saggar et al, 2002). Modification and testing of the models is still in progress (van der Weerden et al, 2002).

The nitrous oxide potential of returning marginal cropping land to perennial grassland was evaluated using an NGAS model coupled with a nitrogen and carbon cycling model to
simulate annual nitrous oxide emissions (Mummey et al, 1998). Model estimates suggested that conversion of 10 500 000 hectares of cropland to grassland in the US has a nitrous oxide mitigation potential of 31 Gg N₂O-N per year.

**6.8 Costs and Benefits of Adopting Mitigation Options**

Mitigation options are available that could result in considerable reductions in nitrous oxide emission from agricultural systems if they were adopted by farmers (Table 6.8). In many cases there will be a cost to the farmer for the implementation of the measure. In others there will be a direct benefit to the farmer, for example, if the options proposed for reducing emissions from fertiliser use (match nitrogen supply with crop demand, utilisation of excreta, use advanced fertilisation techniques, and optimise tillage, irrigation and drainage) were implemented, they would be more likely to increase rather than decrease farmers’ income. If fertiliser nitrogen is used more efficiently, the amount applied could be reduced, less nitrous oxide would be produced, and less money would be spent on fertiliser. If the options were additive, which has been suggested (Cole et al, 1996), then a reduction of ~19% would be achieved, which is equivalent to 0.6 Gg N as nitrous oxide. As fertiliser use in New Zealand is increasing rapidly, the effect of these mitigation options is likely to be more pronounced in the future.

Management options that reduce the amount of nitrogen excreted by animals (especially diet manipulation for dairy cows) have a big effect on nitrous oxide emission. However, the supplementary feed is likely to be costly for the farmer. Substitution of maize silage for nitrogen fertilised grass has the potential to reduce the total amount of nitrogen excreted on pasture and the amount excreted in urine. This would impact on nitrous oxide emission in two ways; according to Yamulki et al (2000) less nitrous oxide is produced from dung than urine, so there is a direct lowering of emissions, and less ammonia would be volatilised to be deposited elsewhere and produce nitrous oxide indirectly. Growing maize for silage on a small area of the farm would produce the same amount of dry matter for the animals to eat, but result in less fertiliser nitrogen use than applying fertiliser to the whole farm (Velthof et al, 1998), again reducing nitrous oxide emission.

Clark et al (2001) point out that winter management of cattle has promise as a mitigation option for nitrous oxide emission. Animal excreta collected and stored during the autumn and winter months is applied to pasture in spring. Use of nitrogen in this way means that less fertiliser nitrogen will be required to grow grass or crops. If this material is applied correctly it will result in lower emissions than if it had been excreted directly on to pasture (Oenema et al, 1997).

We do not know if a combination of the options will produce an additive effect. Jarvis et al (1996) and Velthof and Oenema (1997) made a quantitative analysis of the nitrogen flows and nitrous oxide losses from dairy farms, and concluded that a package of measures to improve efficiency of nitrogen would reduce nitrous oxide emission by up to 70% (Table 6.8). The package of options included refined fertiliser application, reduction of ammonia volatilisation, restricted grazing, and use of maize silage (Velthof et al, 1998). Further analysis of this measure is certainly warranted. If the various options are additive, then nitrous oxide emission from dairy farms, non-dairy farms and sheep farms could be reduced by 28%, 25% and 16% respectively, resulting in a decrease of 2.6 Gg nitrous oxide nitrogen.
Table 6.8: Potential Costs and Benefits of Mitigation Options Applied to Main Sources of Nitrous Oxide

<table>
<thead>
<tr>
<th>Component &amp; N₂O loss</th>
<th>Options available</th>
<th>Costs and benefits</th>
<th>Reduction (%)</th>
<th>Total reduction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser &amp; manure (3.3 Gg N)</td>
<td>Match N supply with crop demand</td>
<td>Reduce leaching, ammonia loss &amp; expenditure on fertiliser</td>
<td>7</td>
<td></td>
<td>Cole et al (1996)</td>
</tr>
<tr>
<td></td>
<td>Tighten N flow cycles</td>
<td>“”</td>
<td>4</td>
<td></td>
<td>Cole et al (1996)</td>
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<tr>
<td></td>
<td>Use advanced fertilisation techniques</td>
<td>“”</td>
<td>4</td>
<td></td>
<td>Cole et al (1996)</td>
</tr>
<tr>
<td></td>
<td>Optimise tillage, irrigation and drainage</td>
<td>“”</td>
<td>4</td>
<td></td>
<td>Cole et al (1996)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19% (0.6 Gg N)</td>
<td></td>
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<tr>
<td>Dairy cattle (3.3 Gg N)</td>
<td>Use decision support systems</td>
<td>Reduce leaching, ammonia loss &amp; expenditure on fertiliser</td>
<td>70?</td>
<td></td>
<td>Jarvis et al (1996)</td>
</tr>
<tr>
<td></td>
<td>Winter management</td>
<td>Costs of slab and management. Reduce leaching by 4%</td>
<td>6</td>
<td></td>
<td>Clark et al (2001)</td>
</tr>
<tr>
<td></td>
<td>Prevent soil compaction</td>
<td>Management costs</td>
<td>3</td>
<td></td>
<td>Clark et al (2001)</td>
</tr>
<tr>
<td></td>
<td>Growing grass high in ‘sugars’</td>
<td>Costs associated with grass production. 25% increase in milk production &amp; 24% decrease in ammonia loss</td>
<td>4</td>
<td></td>
<td>Clark et al (2001)</td>
</tr>
<tr>
<td></td>
<td>Improve drainage</td>
<td>Installation costs</td>
<td>3</td>
<td></td>
<td>Clark et al (2001)</td>
</tr>
<tr>
<td></td>
<td>Buffer zones</td>
<td>Installation costs. Reduce leaching by up to 90%</td>
<td>?</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28% (0.9 Gg N)?</td>
<td></td>
</tr>
<tr>
<td>Non-dairy cattle (3.0 Gg N)</td>
<td>Winter management</td>
<td>Costs of slab and management Reduce leaching by 4%</td>
<td>6</td>
<td>Clark et al (2001)</td>
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<td>Prevent soil compaction</td>
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<td></td>
<td>Growing grass high in 'sugars'</td>
<td>Costs associated with grass production. 24 % decrease in ammonia loss</td>
<td>4</td>
<td>Clark et al (2001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improve drainage</td>
<td>Installation costs</td>
<td>3</td>
<td>Clark et al (2001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Growing grass high in condensed tannins</td>
<td>Costs associated with grass production. Decrease in ammonia loss</td>
<td>4</td>
<td>Clark et al (2001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sheep (5.5 Gg N)</td>
<td>Addition of lime</td>
<td>Cost of lime. Prevents soil acidification</td>
<td>5</td>
<td>Clark et al (2001)</td>
</tr>
<tr>
<td></td>
<td>Growing grass high in 'sugars'</td>
<td>Costs associated with grass production. Increase wool growth &amp; decrease ammonia loss by 24%</td>
<td>4</td>
<td>Clark et al (2001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improve drainage</td>
<td>Installation costs</td>
<td>3</td>
<td>Clark et al (2001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Growing grass high in condensed tannins</td>
<td>Costs associated with grass production. Increase wool growth by 24%</td>
<td>4</td>
<td>Clark et al (2001)</td>
<td></td>
</tr>
</tbody>
</table>

Source: Jarvis et al, 1996; Velthof and Oenema, 1997.9

Conclusions
In response to nitrogen applied in the form of animal excreta, fertiliser, crop residues, biological nitrogen fixation or other human-related activities, soil produces considerable nitrous oxide. It is apparent that the easiest way to reduce nitrous oxide emission is to reduce the amount of nitrogen added to soil. This is much more effective than attempting to control the individual processes within complex biological systems that produce nitrous oxide, and it means that all forms of nitrogen pollution are reduced at the same time.

The greenhouse gas inventory for New Zealand indicates that mitigation options need to focus on limiting the direct loss of nitrogen from animal excreta and synthetic fertilisers (responsible for 53% and 10% respectively of the nitrous oxide emitted from agriculture). The indirect loss originating from these sources after nitrogen is removed from pasture or crop land by leaching and run-off (23%), or ammonia volatilisation (11%).

Many options have been discussed above for reducing nitrous oxide emissions including reducing animal numbers, increasing efficiency of use of nitrogen by animals, changing from animals with low efficiency (cattle 7.7%, sheep 6.2%) to those with high efficiency of nitrogen use (swine 20.5%, poultry 33.8%), feeding dairy cattle low degradable protein and high starch diets, using a systems approach, winter management of cattle, breeding grasses high in water soluble carbohydrate or condensed tannins, improving drainage, preventing soil compaction, matching nitrogen supply with crop demand, tightening nitrogen flow cycles, optimising tillage, irrigation and drainage, reducing nitrate leaching and ammonia volatilisation.

Reducing nitrogen emissions will require adjustments to normal farm practice, and its implementation will depend on guidance and possibly legislation. Encouraging farmers to focus more closely on efficient resource use, particularly with respect to animal manures and slurries, will have numerous indirect benefits.

Clemens and Ahlgrimm (2001) observe that animal husbandry will always produce greenhouse gases. There is also ample evidence that the increase in nitrous oxide emission and nitrogen use are directly related to crop production, animal production and human population growth, and that in the end the only way to limit nitrous oxide production is to limit population growth. The alternative is for someone to pay for the costs associated with emission reduction. This may be for purchasing nitrification inhibitors or supplementary rations for dairy cattle, the costs associated with reducing animal numbers or accepting lower profit margins, or it may mean that the consumer pays extra taxes.

6.10 Research on Nitrous Oxide Emission and Mitigation in New Zealand

In October 2000, a research plan was designed to develop priority actions and a strategic approach to improve the nitrous oxide inventory calculations and to develop methods for reducing nitrous oxide emissions. The strategy was to build on the ongoing research without duplication of effort. NzOnet, a cooperative group of New Zealand scientists drawn from across institutional boundaries, was established to plan and conduct the research. The current research on nitrous oxide is tabulated in Appendix 2 and summarised here.

6.10.1 Processes

Studies in progress or planned include: (i) examining sub-soil denitrification and the concentration of nitrous oxide in the soil profile to improve knowledge of indirect emission; (ii) studying the different emission mechanisms from soil; (iii) determining the fate of labelled nitrogen applied to soil; (iv) assessing the contribution of bacteria and fungi on emission; and (v) developing techniques to measure the effects of adopted mitigation strategies.
6.10.2 Inventory
Research to refine the emission factor for urine and faeces deposited during grazing in different regions and seasons is being undertaken cooperatively by scientists from Lincoln University, Landcare Research, Crop and Food Research, AgResearch, NIWA and the New Zealand Dairy Research Institute. Results to date suggest that adopting a single emission factor (currently 1% of nitrogen excreted) is inappropriate. Emission factors measured ranged from <0.03 to >2.5% of the nitrogen applied in urine and varied with soil and weather conditions.

They are also comparing emission factors for urine and faeces, and are improving the database so they can develop and validate process based models for estimating nitrous oxide emission from soils. Studies are also in progress to quantify the contribution of effluent irrigation on farm-scale inventories, to assess the contribution of mitigation measures on the inventory, and to reduce the uncertainty in the inventory.

6.10.3 Mitigation
Various mitigation options for reducing the emission of nitrous oxide have been proposed in New Zealand and overseas, and the ones most suitable for New Zealand’s current pastoral agriculture are being studied. These include studies on both grassland management and animal management. In the first category research is in progress evaluating the effects of fertiliser timing, soil liming, nitrification inhibitors, soil drainage, and soil compaction on nitrous oxide emission, and the use of riparian zones and drainage ditches to limit nitrate leaching and run-off. In the second category, the effect of strategic de-stocking, diet manipulation, forage winter grazing, and the impact of high tannin and high sugar producing plants on soil emissions is being studied.

6.10.4 Modeling
Models are being developed to reduce uncertainty in New Zealand’s inventory of nitrous oxide emissions from soils, to simulate the effect of treading damage on emission, pasture composition and growth, and to understand the implications of farm management practices on emission. In addition, the OVERSEER model is being upgraded to estimate nitrous oxide emission.

6.10.5 Farming systems
Studies on the relative contributions of grazing, fertiliser nitrogen and dairy farm effluent applications to nitrous oxide emission are being undertaken so that the results can be used to develop dairy farm management practices to reduce nitrous oxide emission. Farm-level decision-support systems and strategies that optimise economic, social, and greenhouse gas outcomes are being developed. Abatement scenarios using a process-based ecosystem model, capable of predicting emissions at the farm-scale, are being assessed.
References


Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions


Weiske A, Benckiser G & Ottow JCG (2001): Effect of the new nitrification inhibitor DMPP in comparison to DCD on nitrous oxide (N$_2$O) emissions and methane (CH$_4$) oxidation during three years of repeated applications in field experiments. *Nutrient Cycling in Agroecosystems*, 60: 57-64.


Chapter 7
Methane: Sources, Processes and Abatement Options

Summary

The predominant source of methane in New Zealand is the fermentation of pasture plants in the rumen of farm animals. Methane is synthesised from H₂ and CO₂ at the end of the microbial digestion chain by the methanogenic archaea, a group of microorganisms that is widely distributed in nature and is also responsible for methane synthesis in manure, effluent ponds and the soil. If H₂ is allowed to accumulate in the rumen it depresses digestion, so the archaea remove it as methane. Management of H₂ in the rumen is the key to controlling ruminant methane emissions.

There is limited data available in the world literature on methane emission from animals grazing pasture. The best set is from New Zealand, where measurements have been made over a range of pasture types and management scenarios using the SF₆ tracer technique. There is good agreement that mature dairy cows and sheep grazing high quality pastures (>75% DM digestibility) produce about 26 g methane per kg DM digested (DDMI). On poorer quality diets, dairy cows and sheep produce about 35 g methane per kg DDMI. Other sources of methane such as manure, dairy effluent ponds and the soil appear to be trivial compared to enteric digestion. The soil in fact is a major sink for methane through oxidation by methanotrophic bacteria.

Several major nutritional factors are known to have an influence on methane emission. Methane emission increases with feed intake, but the relationship is not strong because of the high degree of variation between individual animals. However, there is a stronger negative relationship between methane emitted per unit of feed intake and feed intake. So there is an advantage, in terms of methane emission, to feed animals on as high an intake as possible. It is generally accepted that digestion of cell wall carbohydrates produces more methane than the digestion of soluble carbohydrates. Protein and lipids appear to have a negative effect on methane production, but the effects are variable, and in the case of lipids toxicity to the rumen microbes can be a problem.

Many technologies have been proposed for mitigating ruminant methane emission. Livestock numbers are the major determinant of emission at the national scale. While it might be considered politically naïve to advocate reducing livestock numbers, sheep farmers over the last 15 years have reduced numbers by 33% without compromising total production. This shows that farming has the inherent flexibility to respond to a meaningful economic incentive.

There are possibilities for reducing methane via improvements in animal efficiency. All animals have an obligatory maintenance requirement that results in no production, yet has an associated methane emission. The strategy must be to dilute the effects of maintenance by various measures such as increasing feed intake, manipulation of dietary composition to increase feed quality (e.g. decrease cell wall carbohydrate), increasing metabolic efficiency and genetic improvement. Dairy cows that have been selected for feed conversion efficiency produce less methane on the same diet. These efficiency improvements should form the basis for on-farm strategies to reduce methane in the short-term.

A wide range of feed additives have been proposed to reduce methane. These include alternative hydrogen acceptors (e.g. malate, fumarate), halogenated methane analogues (e.g. chloroform, bromoethanesulphonic acid), antibiotics (e.g. monensin, mevastatin), defaunating agents (e.g. manoxol, teric), and probiotics, bacteriocins and naturally occurring plant compounds (e.g. condensed tannins). There are problems with these compounds, such as
toxicity to the microbes and the animal, short-lived effects due to microbial adaptation, volatility, expense and failure to meet consumer acceptance. With grazing animals, other than dairy cows, a delivery system would be required to ensure regular delivery into the rumen. Delivery by breeding into pasture plants is possible, but the time needed to get a viable plant established in the national pasture should not be underestimated.

Immunisation of animals against methanogens has been suggested by Australian scientists. This is a good concept, but we are still a long way from the delivery of an efficacious vaccine.

There are many possibilities available for manipulating the rumen microbial ecosystem to achieve methane reduction. These include targeting methanogens with microbial antibiotics, bacteriocins or phage, removing protozoa, and developing alternative sinks for H2 such as acetogenic bacteria. Development of mitigation technologies from this type of research are well in the future because of the need to first understand the complexities of the rumen microbial ecosystem.

Investment on research into methane mitigation should cover a suite of technologies that range in their potential delivery time from short-term (on-farm systems research) to long-term (rumen microbial manipulation). A successful technology will deliver a win/win result with respect to methane reduction and increased animal production.

There are three sources of methane associated with pastoral agriculture: ruminant animals (the largest), faeces or manure (on pasture and in effluent ponds [dairying]), and the soil (which can be a source or a sink). Because enteric fermentation in animals is the predominant source of agricultural methane, this chapter will concentrate on this aspect. It will cover the processes involved in the production of methane, the sources of methane, factors affecting methane emission and possible mitigation strategies, all in the context of the grazing ecosystem.

7.1 Processes

7.1.1 Digestion in the rumen

7.1.1.1 Physiological parameters of the rumen

In ruminant animals methane is produced by microbial fermentation of the diet mainly in the reticulo-rumen (rumen) with a smaller amount in the large intestine. The rumen is essentially a fermentation vat, containing a variable amount of digesta (4-7 kg in sheep and 50-80 kg in dairy cows), determined by a balance of the input (feeding) and outflow rates. Buffering is achieved by the secretion of large volumes of saliva containing bicarbonate and phosphate, and pH is normally within the range 5.5-6.5. The temperature is closely controlled at around 39°C. Feed particulate matter is reduced in size, predominantly by chewing during eating and rumination, and these two processes expose the plant internal structures for microbial attack. The digesta is mixed by strong regular contractions of the organ, which also aid the passage of undigested feed residues from the rumen via the reticulo-omasal orifice. Digesta particle size must be reduced to 1.0-2.0 mm in sheep and 2.0-4.0 mm in cattle before passage can occur. Mean residence time for DM in the rumen generally varies between 8 hours for a highly digestible diet to 24 hours for a hay of low digestibility. The main end products of the fermentation are the volatile fatty acids (acetic, propionic, butyric), ammonia, microbial cells and methane. The rumen can therefore be regarded as a well regulated, variable but continuous flow fermenter. Methane produced in the rumen is removed by eructation via the oesophagus and mouth.
7.1.1.2 Microbial synthesis of methane in the rumen

Methanogenesis is carried out by a specialised group of microorganisms that are not true bacteria, but are a sub-group of the archaea which are widely distributed in nature. Archaea differ from bacteria in that they lack the peptidoglycans characteristic of bacterial cell walls, their lipids are composed of glycerol joined by an ether linkage to polyisoprenoid side chains rather than glycerol esters of fatty acids, and they have distinctive ribosomal RNA sequences (Miller, 1995). Although over 66 species of archaea have been isolated from a range of anaerobic habitats, only a few have been isolated from the rumen (McAllister et al, 1996). *Methanobrevibacter* and *Methanomicrobium* have been found in large numbers in the rumen and small numbers of *Methanosarcina* are also present (Baker, 1998; Jarvis et al, 2000). However, non-culture methods based on 16S rRNA indicate that there is a far greater diversity of methanogenic archaea in the rumen than has previously been recognised (Whitford et al, 2001).

Details of the biochemistry of methanogenesis are given by Miller (1995) and McAllister et al (1996). This review will concentrate on the essential elements that have a bearing on possible mitigation strategies. Rumen methanogens preferably synthesise methane from H2 and CO2 to generate their energy requirements for growth (Miller 1995) according to the reaction:

\[4H_2 + CO_2 \rightarrow CH_4 + 2H_2O\]

They have also have the ability to synthesise methane from formate and, to a lesser degree, methanol, mono-, di- and tri- methylamine and acetate, but it is the reduction of CO2 that is the preferred pathway. The anaerobic conversion of organic matter to methane in the rumen involves a consortium of rumen microorganisms, with the final step effected by the methanogens (McAllister et al, 1996). Primary digestive microorganisms such as bacteria, protozoa and fungi hydrolyse dietary starch and plant cell wall polysaccharides producing sugars, volatile fatty acids (VFA), CO2 and H2. The sugars and protein are then fermented by secondary microorganisms to volatile fatty acids, ammonia, hydrogen and CO2.

Methanogens then facilitate the efficiency of processes, such as cell wall degradation, by preventing the accumulation of hydrogen (NADH) through interspecies hydrogen transfer (Wolin et al, 1997). The importance of interspecies hydrogen transfer has been demonstrated many times in *in vitro* co-culturing experiments (McAllister et al, 1996). For example, Williams et al (1994) showed that addition of the methanogen *Methanobrevibacter smithii* to cultures of *Ruminococcus flavefaciens* increased the rate of xylan digestion compared to *R flavefaciens* alone. Interspecies hydrogen transfer has also been demonstrated with rumen fungi and protozoa as well as cellulytic bacteria (Bauchop & Mountfort, 1981; Joblin et al, 1990). One very important symbiotic association is that between methanogens and host ciliate protozoa: both as ecto- and endosymbionts (Hegarty, 1999). These microbes living on and in the protozoa may be responsible for up to 37% of rumen methane emissions (Hegarty, 1999). The process of rumen microbial digestion is a complex and finely balanced ecosystem in which the methanogenic archaea fill an important niche.

One important consequence of hydrogen utilisation by the methanogens is that they maintain a low partial pressure of hydrogen in the rumen. If hydrogen accumulates in the rumen, re-oxidation of NADH is inhibited, reduced fermentation end-products such as lactate accumulate, and forage digestion and microbial growth are reduced (Wolin et al, 1997). For digestion to proceed normally to produce acetate, propionate and butyrate as nutrients for animal production, the partial pressure of hydrogen in the rumen needs to be kept low. Consequently, reduction or elimination of methanogenesis would require other routes of electron transfer if the animal were to benefit. Otherwise hydrogen would act as an inhibitor in the fermentation process and prevent further degradation of organic matter. Management of hydrogen in the rumen is the key to controlling ruminant methane emissions (Joblin, 1999).
The type of carbohydrate in the diet has an effect on methanogenesis (van Nevel & Demeyer, 1996). High starch-containing diets lower rumen pH, and methanogens are inhibited at low pH. Few of the starch-fermenting bacteria produce hydrogen. High starch diets therefore lead to a low proportion of the gross energy diet being converted to methane. Further, the acetate/propionate ratio in the rumen is generally decreased because high starch diets result in higher propionate production. Conversely, high fibre diets tend to produce a high acetate/propionate ratio and increased methane.

There is another group of rumen microorganisms, the acetogenic bacteria, which have the capacity to convert hydrogen into acetate, one of the main nutrients of the ruminant animal. Over 10 acetogenic bacteria have been isolated from the rumen (Joblin, 1999). The affinity of methanogens for hydrogen is 10 to 100 times higher than the affinity of the reductive acetogens, so the acetogens cannot compete with the methanogens in the rumen because the partial pressure of hydrogen is normally too low (Nollet et al, 1997). The nutritional requirements of the acetogens are not as limiting as those for the methanogenic archaea, so they are able to utilise numerous other substrates such as carbohydrates and aromatic compounds for their growth (Fonty & Morvan, 1996). However, when no methanogenic activity is present, the acetogens can activate their ability to utilise hydrogen and produce acetate.

### 7.1.2 Large intestinal methane production

Detailed reviews of large intestinal fermentation are given by Miller (1995), Immig (1996) and Moss et al (2000). The caecum and proximal large intestine can account for about 5 to 25% of digestible energy, depending on diet. The proportion digested in the large intestine generally increases when a poor quality diet is fed. Digesta flows in an intermittent pulsatile manner from the terminal ileum into the caecum, which is a blind sac, and then to the proximal and other regions of the colon. Fermentative digestion occurs mainly in the caecum and proximal colon. Residence time for digesta is much lower than for the rumen. The large intestine accounts for about 12 to 17% of VFA production and 6 to 14% of the animal’s daily methane production (Immig, 1996). Murray et al (1976) showed in sheep fed 800 g lucerne chaff per day, that while 87% of methane was produced in the rumen and 13% in the lower digestive tract, >98% was excreted via the mouth and about 2% in the flatus. Of the methane produced in the lower digestive tract, 89% was absorbed and expired from the lungs. Compared to the rumen, the large intestine does not seem to produce as much methane per mole of VFA (Immig, 1996). It is likely that reductive acetogenesis occurs to some extent in the large intestine (Miller, 1995; Immig, 1996). The biochemical reactions involved in methanogenesis seem to be the same as for the rumen (Immig, 1996). Our knowledge of transactions in the large intestine is however, far from adequate.

### 7.1.3 Methane emission from the degradation of faeces (manure)

Conservatively 50 000 t (DM) of undigested feed residues are voided via the faeces daily in New Zealand from sheep and cattle. Except for the case of dairy shed effluent, most faeces are deposited on pasture. Methane will be emitted from these faeces in three ways: release of trapped methane originating from gastro-intestinal digestion; some residual digestion by intestinal microbes, though these are very sensitive to oxygen and reduced temperature (Williams, 1993); and, a slow subsequent release due to invasion by soil methanogenic archaea. Most of the carbon in the deposited faeces will be dispersed through oxidation to carbon dioxide by aerobic bacteria of soil origin. In the case of dairy shed effluent, there will be some anaerobic methanogenic digestion of organic matter, the amount depending on the extent to which oxidative processes are built into the effluent pond design. The biochemical reactions of anaerobic methanogenesis in deposited faeces and effluent ponds are likely to be
similar to those of the rumen, although because the reaction rate will be slower there may be some switching to acetogenesis and possibly methane production from acetate.

7.1.4 Soil as a source or sink for methane

Depending mainly on its moisture status, the soil can be either a source or a sink of methane. In flooded soils fermentation of organic matter occurs, with the main products being ethanol, acetate, lactate, propionate, butyrate, H₂, N₂, CH₄ and CO₂. Methane is formed by the reduction of CO₂ with H₂, with fatty acids or alcohols as the hydrogen donor, and the transmethylation of acetic acid or methyl alcohol by the methanogenic archaea (Mosier et al., 1998). The period between flooding and the onset of methanogenesis can vary with different soils.

Microbial oxidation of methane occurs in soil and aquatic environments, where it modulates emission and is a negative feedback on the increase in atmospheric methane (Mosier et al., 1998). All methanotrophs are obligate aerobes because the enzyme responsible for the initial step in methane oxidation is a monoxygenase enzyme (MMO) that requires molecular oxygen. The affinity of a methanotroph for methane governs its ability to compete for methane at low concentrations. The MMO of methanotrophs and the ammonia monooxygenase of nitrifying bacteria have similar substrate specificities, and apparently methane and ammonia are competitive substrates for both enzymes.

7.2 Sources of Methane

7.2.1 Ruminant animals

Enteric emissions from the grazing ruminant are responsible for about 87% of New Zealand’s total methane emissions (NZCCP 2001). The only other significant sources are solid waste disposal on land (7.3%) and fugitive fuel emissions (2.7%). Within agriculture, enteric emissions account for about 99% of emissions and manure management 1% (NZCCP, 2001). The inventory of ruminant methane emissions revised by Clark and Ulyatt (2002) for the 2000 year was (Gg): dairy cows 340, beef cattle 248, sheep 541, deer 40 and goats 1.8. The inventory figures are based on emission factors inferred from a limited set of data, because very few measurements of methane emission have been made from grazing ruminants. Most data available in the international literature is from the evaluation of dried feeds in experiments conducted in calorimeters. There are limitations in this data with respect to the grazing situation. The grazing animal has fresh feed, it selects its feed, it is subject to peer pressure, and its behaviour is modified by the farmer’s grazing management style. Fresh pasture is metabolised with a different efficiency to the same feed that has been dried (Ekern et al, 1965). Further, animals confined indoors rarely consume as much as animals grazing the same feed outdoors (Ulyatt et al, 1988). So it is doubtful that data derived from dried feeds in a calorimeter would apply to the grazing situation. The advent of the sulphur hexafluoride (SF₆) tracer technique (Johnson et al, 1994) has meant that for the first time measurements of methane emission can be made from grazing animals.

Most of the measurements made from grazing animals to date in New Zealand using the SF₆ technique, where DM intake was also measured, are listed in Table 7.1. The ewes were mainly consistent, averaging 30.8 g/d, 19.9 g/kg DMI (DM intake) and 26.1 g/kg DDMI (digestible DM intake). The wethers grazing high (≥75%) digestibility pastures emitted 25.9 g/d, 15.5 g/kg DMI and 19.8 g/kg DDMI, while those grazing poor quality pastures (<61% digestible DM) had a lower total emission (18.5 g/d), a higher emission per DMI (19.3 g/kg DMI) and a substantially higher emission per DDMI (33.4 g/kg DDMI). The dairy cows’ emissions ranged from 137-431 g/d, were similar at 21.0 g/kg DMI, but like the wethers emitted 25.9 g/kg DDMI for high quality diets and 35.8 g/kg DDMI for the poor quality diets. Cows
fed perennial ryegrass and *Lotus corniculatus* silages (Woodward et al, 2001) were not included in the above analysis because the diets were changed three days before the measurements and this could have led to the unusually high emissions found. Judd et al (1999) estimated 19.5 g/d for wether sheep made with a micrometeorological technique and using animal data from Ulyatt et al (unpublished; Table 7.3).

Table 7.1: Measurements of Methane Emission from Various Classes of Grazing Ruminants in New Zealand Made with the SF$_6$ Tracer Technique. BW = body weight, Dig = DM digestibility, CH$_4$ = methane, DMI = dry matter intake, DDMI = digestible dry matter intake, MY = methane yield (MJ/100 MJ gross energy intake). Dominant pasture species: PR = perennial ryegrass, WC = white clover, BT = brown top, CF = cocksfoot, Drought = completely dried off pasture, Dsa = summer grass.

<table>
<thead>
<tr>
<th>Pasture</th>
<th>BW (kg)</th>
<th>Dig (%)</th>
<th>DMI (kg/d)</th>
<th>CH$_4$ (g/d)</th>
<th>CH$_4$/DMI (g/kg)</th>
<th>CH$_4$/DDMI (g/kg)</th>
<th>MY</th>
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<td>PR/WC: Sept$^1$</td>
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<td>1.51</td>
<td>30.6</td>
<td>20.3</td>
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</tr>
<tr>
<td>Nov$^1$</td>
<td>54</td>
<td>72</td>
<td>1.46</td>
<td>33.2</td>
<td>22.7</td>
<td>31.5</td>
<td>6.9</td>
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<tr>
<td>Mar$^1$</td>
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<td>75</td>
<td>1.35</td>
<td>27</td>
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<td>27.0</td>
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<td>6.4</td>
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</tr>
<tr>
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<td>19.8</td>
<td>19.8</td>
<td>4.6</td>
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<tr>
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<td>19.8</td>
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<td>15.2</td>
<td>18.6</td>
<td>4.5</td>
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<tr>
<td>PR/WC: Nov$^6$</td>
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<td>77</td>
<td>1.81</td>
<td>34.3</td>
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<td>6.0</td>
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<td>14.0</td>
<td>17.9</td>
<td>4.2</td>
</tr>
<tr>
<td>PR/WC: Feb$^6$</td>
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<td>82</td>
<td>2.42</td>
<td>31.2</td>
<td>13.7</td>
<td>16.7</td>
<td>4.1</td>
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<tr>
<td>Kikuyu: Feb$^7$</td>
<td>35</td>
<td>61</td>
<td>0.76</td>
<td>15.6</td>
<td>20.7</td>
<td>33.8</td>
<td>6.3</td>
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<tr>
<td>Drought: Feb$^2$</td>
<td>47</td>
<td>54</td>
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<td>21.4</td>
<td>17.8</td>
<td>32.9</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Cows</strong></td>
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<td></td>
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<td>PR/WC: Sept$^1$</td>
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<td>82</td>
<td>19.3</td>
<td>431</td>
<td>22.4</td>
<td>27.3</td>
<td>6.8</td>
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<tr>
<td>PR/WC/hay: Jun$^1$</td>
<td>489</td>
<td>63</td>
<td>6.8</td>
<td>137</td>
<td>20.2</td>
<td>25.9</td>
<td>6.1</td>
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<tr>
<td>PR/WC: Mar$^4$</td>
<td>483</td>
<td>77</td>
<td>12.9</td>
<td>263</td>
<td>20.4</td>
<td>26.4</td>
<td>6.2</td>
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<tr>
<td>Kikuyu: Feb$^7$</td>
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<td>61</td>
<td>15.6</td>
<td>363</td>
<td>23.4</td>
<td>38.2</td>
<td>7.1</td>
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<tr>
<td>Dsa/RG: Mar$^7$</td>
<td>585</td>
<td>67</td>
<td>18.9</td>
<td>422</td>
<td>22.3</td>
<td>33.3</td>
<td>6.7</td>
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<tr>
<td>NZ pasture/ Sep$^8$</td>
<td>497</td>
<td>82</td>
<td>17.2</td>
<td>307</td>
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<td>22.0</td>
<td>5.3</td>
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<tr>
<td>Dec$^8$</td>
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<td>17.0</td>
<td>376</td>
<td>22.2</td>
<td>28.3</td>
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<tr>
<td>Mar$^8$</td>
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<td>15.0</td>
<td>353</td>
<td>23.8</td>
<td>30.4</td>
<td>7.0</td>
</tr>
<tr>
<td>OS pasture/ Sep$^8$</td>
<td>588</td>
<td>82</td>
<td>17.7</td>
<td>267</td>
<td>15.1</td>
<td>18.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Dec$^8$</td>
<td>601</td>
<td>74</td>
<td>17.6</td>
<td>345</td>
<td>19.9</td>
<td>26.8</td>
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</tr>
<tr>
<td>Mar$^8$</td>
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<td>78</td>
<td>16.3</td>
<td>379</td>
<td>23.4</td>
<td>30.1</td>
<td>6.9</td>
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</tbody>
</table>

$^1$Ulyatt et al, 2002a  
$^2$Ulyatt et al, unpublished  
$^3$Lassey et al, 1997  
$^4$Pinares-Pantiño, 2000  
$^5$Pinares-Pantiño et al, 2003a  
$^6$Pinares-Pantiño et al, 2003b  
$^7$Ulyatt et al, 2002b  
$^8$Waghorn et al, 2002
For comparison, New Zealand data on methane emission from animals fed indoors is presented in Table 7.2. For the wethers, with those fed Lotus excluded, methane emission was 24.9 g/d, 18.7 g/kg DMI and 26.4 g/kg DDMI. The reason for excluding the wethers fed Lotus was that this diet appeared to suppress methane emission. It was thought that this was due to the presence of condensed tannins (CT) in the Lotus pedunculatus diet. However, dosing the sheep with polyethylene glycol, which inactivates CT, had little effect. Further, other plants with known CT or CT-like activity, such as sulla and chicory, did not produce a marked depression in methane emission. This observation suggests that there is something other than CT that reduces methane emission in animals fed Lotus. The dairy cows fed TMR in Table 7.2 had methane emissions of 437.6 g/d, 20.3 g/kg DMI and 25.9 g/kg DDMI.

### Table 7.2: Methane Emission from Sheep and Dairy Cows Fed a Range of Diets Indoors, Determined with the SF6 Tracer Technique.

<table>
<thead>
<tr>
<th>Diet</th>
<th>BW (kg)</th>
<th>Dig (%)</th>
<th>DMI (kg/d)</th>
<th>CH4 (g/d)</th>
<th>CH4/DMI (g/kg)</th>
<th>CH4/DDMI (g/kg)</th>
<th>MY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wethers</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pasture1</td>
<td>57</td>
<td>73</td>
<td>1.26</td>
<td>25.0</td>
<td>19.8</td>
<td>27.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Lucerne hay1</td>
<td>59</td>
<td>59</td>
<td>1.08</td>
<td>18.7</td>
<td>17.3</td>
<td>29.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Lucerne hay1</td>
<td>43</td>
<td>64</td>
<td>1.18</td>
<td>18.8</td>
<td>15.9</td>
<td>24.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Pasture2</td>
<td>33</td>
<td>74</td>
<td>1.12</td>
<td>28.7</td>
<td>25.7</td>
<td>34.7</td>
<td>7.8</td>
</tr>
<tr>
<td>Lucerne2</td>
<td>38</td>
<td>71</td>
<td>1.47</td>
<td>30.2</td>
<td>20.6</td>
<td>29.0</td>
<td>6.2</td>
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<td>Sulla2</td>
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<td>73</td>
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<td>26.3</td>
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<td>Sulla/lucerne2</td>
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<td>71</td>
<td>1.67</td>
<td>31.8</td>
<td>19.0</td>
<td>26.7</td>
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<td>79</td>
<td>1.12</td>
<td>18.1</td>
<td>16.2</td>
<td>20.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Sulla2</td>
<td>36</td>
<td>63</td>
<td>1.17</td>
<td>20.5</td>
<td>17.5</td>
<td>27.7</td>
<td>5.3</td>
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<td>Chicory/sulla2</td>
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<td>71</td>
<td>1.37</td>
<td>23.1</td>
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<td>23.8</td>
<td>5.1</td>
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<td>Red clover2</td>
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<td>76</td>
<td>1.76</td>
<td>31.2</td>
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<td>10.8</td>
<td>11.5</td>
<td>16.4</td>
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<tr>
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<td>Lucerne hay1</td>
<td>35</td>
<td>64</td>
<td>0.90</td>
<td>11.5</td>
<td>14.8</td>
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<td><strong>Dairy cows</strong></td>
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<td>NZ/TMR: Sep3</td>
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<td>72</td>
<td>21.4</td>
<td>422</td>
<td>20.3</td>
<td>27.3</td>
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<tr>
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<td>583</td>
<td>81</td>
<td>19.7</td>
<td>435</td>
<td>22.0</td>
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<tr>
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<tr>
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<td>16.0</td>
<td>21.5</td>
<td>4.4</td>
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<tr>
<td>Dec3</td>
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<td>80</td>
<td>23.0</td>
<td>448</td>
<td>19.5</td>
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<td>13.1</td>
<td>253</td>
<td>19.5</td>
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<td>6.1</td>
</tr>
</tbody>
</table>

1Pinares-Pantirlo, 2000  
2Waghorn et al, 2002a  
3Waghorn et al, 2002b  
4Woodward et al, 2002

If the emissions of the grazing and the indoor fed animals are compared there are some interesting similarities. When data from the two groups of sheep and two groups of cows grazing the high fibre kikuyu, drought and subtropical Digitaria-dominant pastures were omitted, the mean emissions of the grazing ewes and cows and indoor wethers and cows were 26.1 ± 4.94 (sd), 26.2 ± 3.83, 26.4 ± 3.65 and 25.9 ± 2.50 g/kg DDMI respectively. There was
remarkable consistency, which has implications for inventory development. The grazing wethers emitted 19.8 ± 3.63 g/kg DDMI, which was lower than their indoor fed counterparts. The reason for this is unknown. When data from the two groups of sheep and two groups of cows grazing the high fibre pastures was analysed, their emissions were 33.4 and 35.8 g/kg DDMI for the wethers and cows respectively. The high fibre ryegrass in the work of Woodward et al (2002; Table 8.2) also fits this pattern. This suggests that the higher fibre, lower DM digestibility pastures resulted in more methane emitted per unit of feed digested, which is in line with the findings of Blaxter and Clapperton (1965) and Moe and Tyrell (1979).

There are a few estimates of methane emission from grazing animals published outside New Zealand. Lockyer and Jarvis (1995) and Lockyer (1997) estimated emissions of 13-14 g/d for sheep and 74.5 g/d for calves confined in a polythene tunnel on pasture in England, while Leuning et al (1999) using a mass balance and SF$_6$ respectively measured 11.9 g/d and 11.7 g/d in sheep in Australia. McCaughey et al (1997) used the SF$_6$ technique to measure the emission from steers and beef cows grazing lucerne/grass pasture mixtures in Canada (Table 7.3). While the total emissions (g/d) were within the range of similar animals measured in calorimeters (e.g. Vermorel, 1995), the values per unit of DMI, DDMI, or MY were very high for the beef cows compared to New Zealand data (Table 8.1). The reason appears to be their DMIs, which are dependent on their estimates of *in vitro* digestibility. The extremely low digestibilities for the beef cows would result in low DMIs and high estimates of methane emission per unit of intake. This data emphasises the crucial importance of obtaining reliable estimates of DM intake when methane measurements are made.

### Table 7.3: Methane Emission Measurements Made Under Grazing Conditions with the SF$_6$ Tracer Technique by McCaughey et al (1997) and McCaughey et al (1999)

<table>
<thead>
<tr>
<th></th>
<th>DMI (kg/d)</th>
<th>BW (kg)</th>
<th>Dig (%)</th>
<th>CH$_4$ (g/d)</th>
<th>CH$_4$/DMI (g/kg)</th>
<th>CH$_4$/DDMI (g/kg)</th>
<th>MY (MJ/100 MJ gross energy intake)</th>
</tr>
</thead>
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<tr>
<td>HiSR</td>
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<td>392</td>
<td>60</td>
<td>188</td>
<td>12.6</td>
<td>21.0</td>
<td>4.1</td>
</tr>
<tr>
<td>LoSR</td>
<td>13.6</td>
<td>417</td>
<td>61</td>
<td>200</td>
<td>14.7</td>
<td>24.0</td>
<td>4.3</td>
</tr>
<tr>
<td>Continuous grazing:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HiSR</td>
<td>13.5</td>
<td>380</td>
<td>58</td>
<td>173</td>
<td>12.8</td>
<td>21.3</td>
<td>4.4</td>
</tr>
<tr>
<td>LoSR</td>
<td>13.2</td>
<td>403</td>
<td>58</td>
<td>219</td>
<td>16.6</td>
<td>28.6</td>
<td>5.2</td>
</tr>
<tr>
<td><strong>Lactating beef cows</strong>$^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lucerne/grass</td>
<td>11.4</td>
<td>506</td>
<td>50</td>
<td>267</td>
<td>23.4</td>
<td>46.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Grass</td>
<td>9.7</td>
<td>516</td>
<td>44</td>
<td>293</td>
<td>30.2</td>
<td>68.7</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Source: McCaughey et al, 1997

Pavao-Zuckerman et al (1999) measured methane emission from cows and steers grazing tall fescue dominant pastures in the US (Table 7.4), with management and endophyte treatments superimposed. Unfortunately they did not measure feed intake or digestibility, so it is difficult to compare their methane estimates with New Zealand data, other than to say that most of
their emissions for beef cows of around 500 kg were of the order of 140-240 g/d, compared to New Zealand dairy cows of 250-400 (Table 7.1), or the Canadian beef cows (Table 7.3) of 267-293 g/d. Steers in the work of Pavao-Zuckerman et al (1999) weighing 350-430 kg emitted 190-200 g methane per day, compared to McCaughey et al (1997; Table 7.3), where steers of around 400 kg emitted 180-220 g/d. So the Canadian and American estimates for steers are reasonably similar. The New Zealand dairy cows would be expected to have a higher methane emission than beef cows because their feed intakes would have been much higher.

Table 7.4: Measurements of Methane Emission Made With the SF₆ Tracer Technique from Cattle Grazing Tall Fescue Over Seasons at Two Sites: Blount (with (E+) and without (E-) endophyte) and Holston, where two management practices were used (unimproved pasture UP and best pasture management practices of the district BMP)

<table>
<thead>
<tr>
<th>Steers (Blount)</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW (kg)</td>
<td>CH₄ (g/d)</td>
</tr>
<tr>
<td>1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E+</td>
<td>286</td>
<td>166</td>
</tr>
<tr>
<td>E-</td>
<td>297</td>
<td>190</td>
</tr>
<tr>
<td>E+/E-</td>
<td>289</td>
<td>167</td>
</tr>
<tr>
<td>E+/clover</td>
<td>290</td>
<td>178</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E+</td>
<td>256</td>
<td>110</td>
</tr>
<tr>
<td>E-</td>
<td>264</td>
<td>120</td>
</tr>
<tr>
<td>E+/E-</td>
<td>250</td>
<td>112</td>
</tr>
<tr>
<td>E+/clover</td>
<td>268</td>
<td>119</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Season*Management (Holston)</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steer</td>
<td>352</td>
<td>201</td>
</tr>
<tr>
<td>Cow</td>
<td>494</td>
<td>239</td>
</tr>
<tr>
<td>UP</td>
<td>355</td>
<td>187</td>
</tr>
<tr>
<td>Cow</td>
<td>495</td>
<td>243</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steer</td>
<td>279</td>
<td>94</td>
</tr>
<tr>
<td>Cow</td>
<td>498</td>
<td>168</td>
</tr>
<tr>
<td>UP</td>
<td>270</td>
<td>104</td>
</tr>
<tr>
<td>Cow</td>
<td>535</td>
<td>147</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steer</td>
<td>322</td>
<td>139</td>
</tr>
<tr>
<td>Cow</td>
<td>498</td>
<td>168</td>
</tr>
<tr>
<td>UP</td>
<td>301</td>
<td>145</td>
</tr>
<tr>
<td>Cow</td>
<td>535</td>
<td>147</td>
</tr>
</tbody>
</table>

Source: Savao-Zuckerman et al, 1999

7.2.2 Faeces

There are a few estimates available indicating the amount of methane derived from the faeces of dairy cows grazing pasture. The emission per cow was estimated by Jarvis et al (1995) in England as 0.603 g/d, Yamulki et al (1999) in England as 0.28-1.95 g/d, Flessa et al (1996) in Germany as 1.037 g/d and Tate (pers comm) in New Zealand as 1.97-3.04 g/d. While there is a five-fold range in the estimates, they do indicate that methane emission from faeces appears to be trivial compared with that emitted by cattle (c.250 g/d). The faeces of sheep are usually of higher DM content than those of dairy cows, and are often of a pelleted nature and more disposed for aerobic degradation. Thus it would be expected that methane emission per gram of faecal DM would be lower in sheep. Using an average sheep faecal DM output of 375 g/d, and the methane emission factor of 0.07 mg CH₄/g faecal DM (NIR 2002), the daily methane emission from an adult sheep in New Zealand would be about 26 mg/d for a ewe producing 30 g/d. The ratio, exhaled to manure methane, is thus 250 for cows and 1 150 for sheep. For
both animals’ manure would seem to be a minor source of methane and, as expected, manure would be relatively more important as a source for dairy cows than sheep.

7.2.3 Methane from effluent ponds

There are a few estimates of methane emissions from effluent ponds. The New Zealand Climate Change Programme (2001) estimated 16.93 Gg from such ponds compared to a total of 1 399 Gg from all agricultural sources.

7.2.4 Sources and sinks of methane in the soil

New Zealand’s soils generally remove methane at a rate that is negatively related to both their level of disturbance (e.g. cultivation) and level of nitrogen input (Tate, pers comm). New Zealand’s undisturbed natural ecosystems, which generally do not receive significant external nitrogen inputs, may exhibit very strong methane sink capacity. Price et al (2000) measured methane oxidation rates at a mountain beech forest site, which if applied to all such vegetation would indicate that 63 000 t of methane could be removed from the atmosphere per year by this type of land cover. Generally lower methane oxidation rates are measured for managed ecosystems. For example, planted pine forests and pasture soils could potentially oxidise about 11 000 and 400 t methane per year respectively (Tate, pers comm). New Zealand agricultural soils appear to have very low rates of methane emission (Judd et al, 1999) and are thus not considered a significant source.

7.2.5 Conclusions

New Zealand has the best set of measurements of methane emission from grazing animals in the world. However the data are predominantly from young wether sheep under a limited range of pastoral conditions, and a few measurements from mature ewes and dairy cows. If the inventory is to be accurate, and therefore beyond reproach for international reporting, regulatory and scientific purposes, methane emission from a wider sample of animal and land classes needs to be incorporated.

7.3 Factors Affecting Methane Emission


7.3.1 Feed intake

The relationship between methane emission (g/d) and DM intake is positive, but characterised by high variability between animals (Blaxter & Clapperton, 1965; Kirchgessner et al, 1995; Lassey et al, 1997). An example of this relationship is plotted in Figure 7.1, using data from sheep grazing fresh pasture in New Zealand, showing that the absolute amount of methane emitted increases as intake increases ($r=0.373; P<0.05$) (Lassey et al, 1997). The notable thing about this relationship is that approximately 87% of the variation in methane emission is between animals, suggesting that differences in DM intake per se accounted for about 14% of the variation in methane emission.
However, when methane emission per unit of feed intake (usually expressed as MJ methane per 100 MJ gross energy intake) is plotted against DM intake for the same data (Figure 7.2), a stronger negative relationship is found ($r=-0.597; P<0.01$), indicating that as intake increases the percentage of dietary energy lost as methane decreases. This is a well established relationship for sets of data where animals are fed the same diet at both restricted and ad libitum intakes (Armstrong, 1964; Blaxter & Clapperton, 1965; Johnson & Johnson, 1995). This suggests that for efficient animal production and reduced methane emission it is advantageous to feed animals well above maintenance intake.

**Figure 7.2: Methane Emission Per Unit of Feed Intake Plotted against DM Intake in Sheep Grazing the Same Pasture**

*Source: Lassey et al, 1997*
7.3.2 Diet composition

The diet in ruminant agriculture in New Zealand is predominantly based on pasture. There is an increasing use of high starch supplements in the form of maize or maize silage in dairying and grain in drought conditions. Apart from these supplements, it is difficult to achieve large changes in pasture composition through plant breeding or pasture management. There are some opportunities for manipulation of plant composition through the introduction of novel molecular biological techniques (Hancock & Ulyatt, 2001).

The major constituents of the diet - sugars, starch, fibre, protein and lipid - appear to have varying impacts on methane emission. Kirchgessner et al (1995) concluded, from a regression analysis of the impact of crude nutrient fractions on methane emission from dairy cows, that on average crude fibre provides about 60%, nitrogen-free extract 30%, crude protein 10% and ether extract a minor proportion of total methane production. However, variations within and between the major classes of nutrients can cause major shifts in methane emission.

The type of carbohydrate fermented affects methane production, particularly starch and soluble sugars compared to the cell wall carbohydrates, cellulose and hemicellulose. With respect to starch, as its content in the diet increases rumen pH decreases, making the environment more hostile for methanogens to survive. Further, few of the starch fermenting bacteria produce hydrogen, so the supply of hydrogen for methanogenesis is limited. It would therefore be expected that less methane should be produced per unit of starch than per unit of digested cell wall carbohydrate. Johnson and Johnson (1995) claimed that the soluble sugars are more methanogenic than starch. The data of Blaxter and Wainman (1964), where sheep and cattle were fed variable portions of hay and maize at about maintenance and twice maintenance levels of intake, illustrates the effects of type of carbohydrate on methane emission. As the proportion of maize (and thus starch) increased in the diet from 0 to 100% there was a small reduction in methane at maintenance, and a decrease from about 7.0 to 3.5 MJ/100 MJ intake at twice maintenance.

Conversely, Blaxter and Wainman (1964) showed that as the proportion of hay increased from 0 to 100%, crude fibre in the diet increased from 2.2 to 33.8 % and methane (MJ/100MJ) showed a small decrease at maintenance, but increased from about 3.5 to 7.0 at twice maintenance. Moe and Tyrell (1979) also found little difference between carbohydrate sources at maintenance, but at higher intakes cell wall carbohydrates were found to be more methanogenic than soluble carbohydrates. So any method that increases the ratio of soluble/cell wall carbohydrate should decrease methane production. It should be noted, however, that the proportion of soluble carbohydrate fed by Blaxter and Wainman (1964) and Moe and Tyrell (1979) to get depression in methane production was very high. There are also reports from experiments where large changes in the starch content of the diet had little effect on methane emission (Shiao et al, 1999; Islam et al, 2000; Cammell et al, 2002). So while the weight of evidence supports reduction of methane by increasing the ratio of cell wall to soluble carbohydrate in the diet, there is evidence that the impact of carbohydrate type on methane is complicated. It must also be emphasised that many indoor studies are conducted around maintenance intake where the effect is likely to be minimal.

The effect of protein concentration in the diet is less clear. Pelchen and Peters (1998) analysed 1 137 data sets from the literature where sheep were fed in calorimeters, and developed regression equations to predict methane emission. When crude protein was included as an independent variable it had a negative sign, indicating that increasing protein in a diet would be expected to decrease methane emission. This may indicate a direct negative effect of protein on methane, or it might reflect the replacement in the diet of methanogenic carbohydrate with protein.
Addition of lipids to the diet can reduce methane emission. Three factors - the quantity, the degree of unsaturation and the chain length of the lipid - can have an effect (Czerkawski et al, 1966a, 1966b; Johnson & Johnson, 2002). It appears that the effect of degree of unsaturation is relatively small and that the effect of lipid is mainly in depressing digestion (Johnson & Johnson, 1995; Mathison et al, 1998). Certain oils, such as coconut oil, seem to reduce methane, possibly by suppressing protozoa (Machmuller et al, 1998; Dohme et al, 1999).

7.3.3 Digestibility

Compilations of data comparing methane emission at various digestibilities exhibit a high degree of variation, e.g. the relationship of Johnson and Johnson (1995) for beef cattle (Figure 7.3).

![Effect of digestibility on methane emission: world beef cattle data](image)

**Figure 7.3: Effect of Digestibility on Methane Emission: World Beef Cattle Data**

*Source: Johnson, pers. comm., 2002*

The main reason for this is that the results are confounded by the wide range of diets and intakes used in such comparisons. It has already been shown above that methane is dependent on both diet composition and intake level.

Blaxter and Clapperton (1965) calculated that the relationship between methane emission and digestibility is very dependent on intake level (Figure 7.4). When feed is given at low levels of intake, methane emission (MJ/100MJ) increases as digestibility increases, whereas with high intakes methane emission falls as digestibility increases.

7.3.4 Other factors

A number of other nutritional and physiological factors are known to influence methane emission, such as grinding and pelleting the diet, and frequency of feeding (Johnson & Johnson, 1995; Mathison et al, 1998), but are probably of little significance under grazing.
7.4 Mitigation


A wide range of possibilities for reducing the methane emission of grazing livestock has been suggested. These include reducing livestock numbers, increasing the efficiency of animal production, genetic improvement, antimethanogenic feed additives, immunisation, manipulation of the rumen microbial ecosystem and manipulation of farm management.

7.4.1 Reduction in livestock numbers

As emissions from livestock are the predominant source of methane in countries like New Zealand and Australia, reducing livestock numbers is one option for meeting FCCC commitments. However, such countries are heavily dependent on their livestock industries for generating national income, and the imposition of regulations aimed at reducing livestock numbers would not be well received by the farming industry.

There are, however, ongoing fluctuations in livestock numbers in response to the marketplace. For example, in New Zealand sheep farming has become less profitable over the past 10 years, so farmers have reduced sheep numbers and other alternative land uses such as dairying and forestry have increased. Over the period 1990 to 2000, total sheep numbers have reduced from 57 900 000 to 45 100 000, dairy cattle have increased from 3 390 000 to 4 530 000, beef cattle have changed little (4 600 000 to 4 690 000), deer have increased from 960 000 to 1 910 000 and farmed goats have declined from 1 030 000 to 190 000 (Clark & Ulyatt, 2002). The net outcome in terms of ruminant methane emission has been a small increase over the 10 years from 1 098 to 1 171 Gg/year. Given the large changes in most categories of stock induced by economic conditions over the last 10 years, it might not be too excessive to suggest that farmers might be persuaded to change livestock numbers in response to greenhouse gases if suitable economic incentives were offered.
Livestock numbers are the major determinant of methane emission from pastoral agriculture, and it is implicit that reducing numbers is the simplest way to reduce emission.

### 7.4.2 Increasing the efficiency of livestock production

#### 7.4.2.1 Introduction

The subject of efficiency of livestock production is very complicated, and efficiency related to methane emission is closely related to the maintenance requirements of the animal. The maintenance requirement of an animal is the minimum amount of energy (or feed) required to keep the animal in energy equilibrium, i.e. at constant body weight with no production. It is obligatory that the maintenance requirement must be met from the diet before any production can occur, although there are short-term exceptions such as the utilisation of tissues for milk production in early lactation in dairy cows. There is a methane emission associated with the maintenance requirement. Using the emission factor of 26 g/kg DDMI, derived from New Zealand work in Section 7.2.1 above, maintenance methane emission would be 18 g/d for a 50 kg ewe, 80 g/d for a 450 kg beef cow and 105 g/d for a 450 kg dairy cow. So the animals would emit these amounts of methane unassociated with any production. The higher the intake above maintenance, or the higher the level of production, the lower will be the methane emitted per unit of product and thus the higher the efficiency with respect to methane. Examples of this are presented in Tables 7.5 and 7.6 (below) for milk production and lamb growth. From an animal efficiency point of view, the best strategy for a farmer faced with extra feed is to increase the intake of existing animals rather than increase stocking rate. From an economic point of view, methane production and animal production per ha are the important measures of efficiency. There will be a stocking rate that maximises production per ha and minimises methane emission per ha.

#### 7.4.2.2 Increasing feed intake

Increasing feed intake decreases the methane emission per unit of feed intake as shown in Figure 8.2. This can also be seen in terms of production: as milk production (Kirchgessner et al, 1995) or liveweight gain in beef cattle (McCrab & Hunter, 1999) an asymptotic decrease in methane emission per unit of product occurs. This effect is shown in Table 8.5, where the increased intake (DDMI) of the same diet to a cow increases milk production, but decreases methane emitted per unit of milk. As intake increases, the proportion of the methane associated with maintenance declines. This is known as the dilution of maintenance as intake increases. In terms of efficiency of production it is clearly advantageous to maximise intake. A similar calculation illustrating the effect of intake on methane emission during lamb growth is shown in Table 8.6. Again, methane emission per unit of product is reduced and the proportion of methane associated with production is increased at the higher intake.

#### Table 7.5: A Calculation of the Proportion of the Methane Emission Attributable to Maintenance or Milk Production in 450 kg Grazing Dairy Cows

<table>
<thead>
<tr>
<th>DDMI (kg/d)</th>
<th>Milk yield (kg/d)</th>
<th>CH₄ (g/d)</th>
<th>% CH₄ associated with:</th>
<th>CH₄/milk (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>0</td>
<td>105</td>
<td>Maintenance</td>
<td>0</td>
</tr>
<tr>
<td>7.9</td>
<td>12</td>
<td>206</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>10.5</td>
<td>20</td>
<td>272</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>11.7</td>
<td>24</td>
<td>305</td>
<td>34</td>
<td>66</td>
</tr>
</tbody>
</table>

₁ Ulyatt et al, 1976

₂ DDMI * 26, (Section 8.2.1)
Table 7.6: A Calculation of the Proportion of the Methane Emission Attributable to Maintenance or Growth in 30 kg Growing Lambs

<table>
<thead>
<tr>
<th>DDMI (g/d)¹</th>
<th>Growth rate (g/d)</th>
<th>CH₄ (g/d)²</th>
<th>% methane associated with:</th>
<th>CH₄/growth (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maintenance</td>
<td>Growth</td>
</tr>
<tr>
<td>517</td>
<td>0</td>
<td>10.3</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>832</td>
<td>100</td>
<td>16.6</td>
<td>62</td>
<td>38</td>
</tr>
<tr>
<td>1147</td>
<td>200</td>
<td>23.0</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>1463</td>
<td>300</td>
<td>29.3</td>
<td>35</td>
<td>65</td>
</tr>
</tbody>
</table>

¹Ulyatt et al, 1976
²DDMI * 20, (Section 8.2.1)

By feeding animals *ad libitum* it is possible to both maximise efficiency and reduce methane emission per unit of product. This is because as intake increases the methane emission associated with the essential, but non-productive, requirements for maintenance is diluted.

7.4.2.3 Dietary manipulation

As described above (Section 7.3.2), decreasing dietary fibre and increasing starch and lipid will reduce methane emission. Generally, diets of higher digestibility have these characteristics. This effect can be seen in the calculation in Table 7.7 where dairy cows were given feeds of increasing digestibility to achieve the same level of milk production. The animals would have eaten less of the higher digestibility diets, and thus produced less total methane and reduced methane emitted per unit of milk produced. Improving the nutritive value of the feed given to grazing animals by balancing the diet with concentrates, or by breeding improved pasture plants, should result in reduced methane emission. The latter is considered to be a primary objective in the grazing ecosystem, yet the magnitude of the changes in composition needed to affect methane emission, e.g. the ratio of soluble to cell wall carbohydrate, might be outside the capability of plant breeding or management.

Table 7.7: A Calculation of the Effect of Feed Quality on Methane Emission of Cows at the Same Level of Milk Production

<table>
<thead>
<tr>
<th>DM digestibility (%)</th>
<th>55</th>
<th>65</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk production (kg/d)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Feed intake (kg DM/d)</td>
<td>21.6</td>
<td>17.5</td>
<td>14.6</td>
</tr>
<tr>
<td>CH₄ emission (g/d)¹</td>
<td>309</td>
<td>296</td>
<td>285</td>
</tr>
<tr>
<td>g CH₄/kg milk</td>
<td>15.5</td>
<td>14.8</td>
<td>14.3</td>
</tr>
</tbody>
</table>

¹DDMI * 26 (Section 8.2.1)

Benchar et al (2001) evaluated the effect on methane production of a range of dietary strategies using a modeling approach and predicted that a reduction of 10 to 40% can be achieved this way. Methane production (MJ/100MJ) could be reduced by increasing feed intake (-7%), increasing the concentrate proportion of the diet (-40%), replacing fibrous concentrate with starchy concentrate (-22%), with the utilisation of less ruminally degradable starch (-17%), increasing the digestibility of forage (-15%), with legume compared to grass forage (-28%) and with silage compared to hay (-20%).
7.4.2.4 Metabolic efficiency

Treatment of animals with growth promoting substances can result in increased efficiency of production. An example based on bovine somatotrophin (bST) treatment of milking cows and calculated from the data of Bauman et al (1985) is given in Table 8.8. As bST dose was increased, milk production per unit intake (efficiency) increased and methane emitted per kg milk was calculated to decrease. Growth stimulants such as steroids would be expected to have a similar effect: less feed and methane overall to achieve the same level of production. Such measures must, of course, meet the required regulatory and consumer acceptance standards.

Table 7.8: Calculated Effect of Bovine Somototrophin (bST) on Methane Emission by Lactating Cows

<table>
<thead>
<tr>
<th>bST dose (mg/d)</th>
<th>0</th>
<th>13.5</th>
<th>27.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk production (kg FCM/d)</td>
<td>27.9</td>
<td>34.4</td>
<td>38.0</td>
</tr>
<tr>
<td>NE intake (MJ/d)</td>
<td>143</td>
<td>154</td>
<td>164</td>
</tr>
<tr>
<td>kg milk/MJ NE intake</td>
<td>0.195</td>
<td>0.223</td>
<td>0.232</td>
</tr>
<tr>
<td>CH4 emission (g/d)</td>
<td>365</td>
<td>361</td>
<td>351</td>
</tr>
<tr>
<td>g CH4/kg milk</td>
<td>13.1</td>
<td>10.5</td>
<td>9.2</td>
</tr>
</tbody>
</table>

All these techniques to increase efficiency use the dilution of maintenance requirements principle to achieve reduced methane emission. Their maximum effectiveness, in terms of reducing methane emission, would be in maintaining present levels of animal production with fewer animals, or in increasing animal production with the same number of animals. This would provide the farmer with options for land use that should improve profitability.

7.4.3 Genetic improvement in animals to reduce methane emission

There are two aspects of genetic improvement with respect to methane emission: genetic improvement in the efficiency of food conversion by the animals themselves; and the possibility that there are genetic differences between animals in the amount of methane they emit at the same feed intake.

In the grazing ecosystem there has been virtually no direct selection of ruminants for improved feed conversion efficiency, which is in contrast to the situation with pigs and poultry where huge gains have been made. There has, however, been considerable indirect selection for increased milk yield in dairy cows and increased liveweight gain in fattening lambs and beef cattle. Livestock statistics presented by Clark and Ulyatt (2002) show that despite large changes in livestock numbers over the 10 years 1990 to 2000, there have also been changes in production. Dairy cow weights increased from 420 to 454 kg, and milk production increased from 2,931 to 3,678 kg/cow. Beef cow weights increased from 443 to 470, heifer weights at slaughter from 397 to 420 and male weight at slaughter from 541 to 580 kg. Sheep statistics are even more interesting. Davison (2000) showed that between 1986/87 and 1999/00 breeding ewe numbers declined by 33%, but the total lamb slaughter declined at the lower rate of 19% because there was a 16.6% increase in lambing %. In 1986/87 average lamb weights were 13.20 kg compared to 16.48 kg in 1999/00, an increase of 25%. Thus the combination of increased lambing % and higher average weights resulted in a higher lamb production by 8% in 1999/00 at a time when breeding ewe numbers had declined by 33%.
Davison (2000) stated that sheep are now fed at a higher level and stocking rates are 9% lower than in 1986/87. It is impossible to separate the effects of better feeding from genetic gain in this data, and the gains are undoubtedly due to a mixture of the two. Given that methane emission per unit of intake is lower at higher intakes (Tables 7.5, 7.6), the above statistics should have a positive impact on the ruminant methane inventory. They should also provide good input for farm-scale systems models (see Section 7.4.7).

Further evidence that genotype can influence methane emission comes from the genotype X diet experiment conducted at Dexcel by Dr E Kolver (Waghorn et al, 2002), summarised in Table 7.9. Dairy cows of US or New Zealand genotype were fed either a New Zealand pasture or a total mixed ration similar to those fed in the US. On both rations the US cows produced more milk and less methane. The US cows have been bred for efficiency of feed conversion and high feed intakes. They had considerably higher feed intakes in this experiment, and presumably this is why the methane emissions per unit of feed intake were lower. Similarly, Ferris et al (1999) found that methane emission (MJ/100 MJ GE intake) was higher for Holstein dairy cows of medium than high genetic merit. These experiments indicate that breeding for efficiency has the potential to lower methane emission.

| Table 7.9: Methane Emission (g/kg DMI) from Dairy Cows of Two Genotypes Fed Two Different Diets. TMR = Total mixed rations. |
|----------------------------------------------|------------------|------------------|------------------|
| Days of lactation | Pasture diet: | | | |
| | NZ genotype | US genotype | NZ genotype | US genotype |
| 60 | 18.0 | 15.1 | 20.2 | 16.0 |
| 150 | 22.2 | 19.9 | 22.0 | 19.5 |
| 240 | 23.8 | 23.4 | 22.3 | 21.4 |

Source: Waghorn et al, 2002

A notable feature of methane emission in experiments where large numbers of animals have been fed the same diet is that there are usually large differences in emission per unit of feed intake between animals. Between-animal differences account for 70-80% of the variance, with a lesser amount attributed to differences between measurement days. Such differences between animals are real (Blaxter & Clapperton, 1965; Lassey et al, 1997; Ulyatt et al, 1999) and can persist from three weeks (Lassey et al, 1997) to up to five months (Pinares-Patiño et al, 2003b). We have found that in any group of animals measured on pasture with the SF₆ tracer technique, approximately 10% are high and 10% low emitters, with the difference between these two groups approximately 40%. As methane is produced through microbial activity, the animal can only have an impact on methanogenesis by interacting with the microbes. This interaction could be via diet selection as the microbes respond to changes in the composition of the substrate (feed) presented to them. The animal could interact with the microbes through control of the fermenter (rumen) conditions via processes such as: saliva and/or salivary proteins, feed processing (e.g. increased comminution to allow faster microbial access to plant cell contents), changes in rumen volume and digesta flow rate. Pinares-Patiño et al (2003b) found that high methane emitting sheep tended to have large rumen volumes and slower digesta flow rates than low emitters. Ørskov et al (1988) identified cows with persistent differences in rumen outflow rate and concluded that they were probably genetic in origin. The evidence for a genetically determined influence of the animal on the rumen microbes is not strong. However, if it could be proven to be the case it may be possible to obtain genetic markers that could be used to select low methane emitters.
7.4.4 Feed additives

A wide range of chemicals are available that will reduce rumen methanogenesis (Chalupa, 1980; Mathison et al, 1998).

7.4.4.1 Alternative hydrogen acceptors

Sulphate/sulphite and nitrate/nitrite are potential alternative hydrogen acceptors. However Mathison et al (1998) concluded that their use is not feasible because of their toxic properties at the concentrations that would be needed to reduce methanogenesis.

Addition of unsaturated fatty acids to the rumen will decrease methane emission. Their effect is twofold: the unsaturated fatty acids are a potential alternative sink for hydrogen, and large doses are toxic to rumen microorganisms and depress digestion. Johnson and Johnson (1995) pointed out that the amount of hydrogen used in the biohydrogenation of unsaturated fatty acids is small, and concluded that the methane reduction effects of lipids are only likely to be substantial when basal digestion is inhibited. More recent work by Dong et al (1997) found that the addition of canola oil and cod liver oil to fermenters reduced methane but did not depress digestion, whereas coconut oil depressed digestion. Johnson and Johnson (2002) cite evidence to suggest that medium chain fatty acids may suppress methane more than long chain fatty acids.

The dicarboxylic organic acids, malate and fumarate, have been suggested as potential alternative hydrogen acceptors (Martin, 1998; Lopez et al, 1999; Carro et al, 1999; Asanuma et al, 1999; Krause 2002). Some anaerobic bacteria synthesise propionate from fumarate or malate using a reverse citric acid cycle. Malate must be converted to fumarate, which is in turn reduced to succinate, a process that requires hydrogen, and the succinate is then decarboxylated to form propionate. The tactic would be to increase the utilisation of hydrogen by rumen bacteria that can use hydrogen in the above reaction. There would be a decline in the availability of hydrogen for methanogenesis in the rumen. Most of the experiments to date have been conducted in vitro. Addition of fumarate to fermenters reduced methane, enhanced propionate production (Asanuma et al, 1999; Lopez et al, 1999), and increased the numbers of cellulolytic bacteria and increased DM digestibility (Lopez et al, 1999). Similarly, addition of malate reduced methane, increased propionate, and increased the digestibility of hemicellulose (Carro et al, 1999). Malate and fumarate are expensive chemicals, so it is doubtful that the amount required could be used as a feed additive. The concentrations of these organic acids vary naturally in plants. Whether their concentrations in pasture plants can be increased by selection or molecular genetics to the level that methanogenesis is reduced has yet to be determined.

7.4.4.2 Halogenated methane analogues

Many halogenated methane analogues such as chloroform, carbon tetrachloride, chloral hydrate, bromochloromethane and bromoethanesulphonic acid can be very potent methane inhibitors (van Nevel & Demeyer, 1996; Mathison et al, 1998). While some of these compounds are volatile and difficult to administer, McCrabb et al (1997) claimed success in inhibiting methane in cattle with bromochloromethane complexed with α-cyclodextrin, which reduced volatility. Mathison et al (1998) concluded that halogenated methane analogues have potential as methane inhibitors, provided that problems such as adaptation by rumen microbes, host toxicity and suppression of digestion can be overcome. In the pastoral environment, a cost-effective delivery system would also be needed.
7.4.4.3 Antibiotics

The effects of a wide range of antibiotics, including the ionophores, on methane production have been reviewed by van Nevel and Demeyer (1995, 1996) and Johnson and Johnson (2002). For many years antibiotics have been used routinely overseas as growth promotants at very low dose levels. Their effect on methane production has been inconsistent (van Nevel & Demeyer, 1995). However, avoparcin and the ionophores are known to inhibit methanogenesis and shift VFA patterns towards higher propionate. Monensin, an ionophore, inhibits methane in vivo by about 25% (van Nevel & Demeyer, 1995). There are, however, reports that the effect appears to be short-lived as the rumen microbes adapt to the additive within two weeks (Johnson & Johnson, 1995, 2002). Monensin has been used routinely as a bloat preventative in New Zealand for many years, but its effect on methane emission under our grazing conditions is unknown.

Miller and Wolin (2001) have recently described the in vitro inhibition of methanogen growth and methane by the two hydroxymethylglutaryl-SCoA reductase inhibitors, mevastatin and lovastatin. Archaea are unique among rumen microbes in having membrane lipids that contain glycerol joined by ether linkages to long chain isoprenoid alcohols. A key precursor in the synthesis of isoprenoid units is mevalonate, which is formed by the reduction of HMG-CoA. The enzyme HMG-CoA reductase catalyses the formation of mevalonate and is the specific target of the antibiotics mevastatin and lovastatin. These antibiotics inhibit the growth of rumen methanogens, but do not inhibit the growth of the rumen bacteria responsible for fermenting cellulose, starch and other plant polysaccharides. These drugs are also used to lower cholesterol in humans, so it is argued that they would be a harmless addition to the animal’s diet.

7.4.4.4 Defaunating agents

Methanogens living in a symbiotic relationship with protozoa can account for about 40% of rumen methane emissions (Hegarty, 1999), and defaunation results in reductions in emission of about 20-50% (Kreuzer et al, 1986). Defaunating agents such as manoxol, teric, alkanate 3SL3 and sulphosuccinate can reduce methane emission (Mathison et al, 1998). They appear to act by disrupting the close symbiotic relationship between methanogenic bacteria and protozoa. Complete defaunation is difficult to achieve on a large scale, and there is a fine line between killing the protozoa and killing the animal. The toxicity of many of these defaunating agents restricts their routine use.

7.4.4.5 Probiotics

Microbial feed additives, especially those based on Saccharomyces cerevisiae and Aspergillus oryzae, are widely used in animal feeding in the northern hemisphere, particularly with high grain diets. There are mixed reports as to whether these probiotic additives can reduce methane emission (van Nevel & Demeyer, 1995; Moss et al, 2000). It would appear that more research is needed to evaluate whether probiotics have any role in methane mitigation strategy, although it seems unlikely that they would be effective with animals grazing pasture.

7.4.4.6 Bacteriocins

Bacteriocins are antibiotics, generally protein or peptide in nature, produced by bacteria. Research is ongoing to see if these compounds can be used to manipulate the rumen ecosystem (Klieve & Hegarty, 1999; Attwood, pers comm). Callaway et al (1997) used the bacteriocin nisin, which is produced by Lactococcus lactis, to produce a 36% reduction of methane production in vitro. Further research is required to evaluate the efficacy of bacteriocins.
7.4.4.7 Naturally occurring plant compounds

There are naturally occurring compounds in some forages that appear to have antimethanogenic properties. Johnson and Johnson (2002) cite a number of plant compounds that appeared to have this effect. Gupta et al (1993) claimed that the leaves of the tropical plant *Enterolobium timbouva* defaunated the rumen of buffalo. Woodward et al (2001) found a depression of methane emission by feeding sheep and dairy cows the condensed tannin-containing legume *Lotus corniculatus*, as did Waghorn et al (2002) when *L pedunculatus* was fed to sheep and Woodward et al (2002) when *Hedysarum coronarium* was fed to dairy cows. Ulyatt et al (2002) found that under some conditions methane emission was severely reduced in sheep and dairy cows grazing kikuyu grass (*Pennisetum clandestinum*), suggesting the presence of yet unidentified suppressing compounds. Such observations suggest that there are compounds to be found in pasture plants that offer the prospect of methane reduction in the grazing environment if they can be bred into competitive pasture plants.

It is important to note that despite a huge amount of research there is not one feed additive that is currently used in commercial agriculture for the sole purpose of reducing methane. The main problems with chemical additives are that many are toxic to the animal, toxic to rumen microflora and therefore reduce digestion and food intake, have short-lived effects because the rumen microbes adapt, are volatile and thus difficult to administer, are expensive, or would fail to meet consumer product acceptance.

With grazing animals, especially under extensive conditions, slow release devices would be required to ensure regular delivery into the rumen. If the antimethanogenic agent were to be built into a pasture plant through selection or molecular genetics, the time required to achieve this and get the plant accepted and distributed through the national pasture should not be underestimated. Condensed tannins are an example. It is thirty years since CT was shown to prevent bloat in cattle (Jones et al, 1973) and have the potential to improve the efficiency of protein utilisation by the animal (Reid et al, 1974). Existing plants containing CT, such as *Lotus* species, do not compete well with temperate pasture species under high soil fertility conditions and they have been slow to improve through selection. Molecular genetic techniques have had no success in introducing genes that produce CT into more agronomically competitive plants. Thirty years on we still do not have a competitive CT-containing pasture plant.

7.4.5 Immunisation

Scientists in Australia have registered patents for immunisation procedures that are claimed to reduce methane emission. They have developed a vaccine containing an antigen derived from rumen methanogenic microorganisms (Baker, 1998), and an immunogenic preparation that reduces the activity of rumen protozoa (Baker et al, 1997). The antimethanogenic vaccine is claimed to reduce methane in *in vitro* incubations, and significantly increase DM intake and wool growth. CSIRO plan to release a suitable vaccine on the market in 2007. A vaccine would be a valuable tool in providing a cost-effective and long-acting treatment to reduce methane emission and enhance animal production under grazing.

7.4.6 Manipulation of the rumen microbial ecosystem

The methanogenic archaea, which are highly efficient scavengers of hydrogen, are the main, but not the only, agents for converting hydrogen to methane in the rumen (Joblin, 1999). There is also evidence that the rumen can function satisfactorily in the absence of methanogens (Joblin 1999). There are many potential opportunities for mitigating methane through microbial intervention in the rumen such as: targeting methanogens with antibiotics, bacteriocins, or phage; removing protozoa from the rumen; and the development of
alternative sinks for hydrogen such as reductive acetogenesis. All these opportunities are possible through microbial intervention. However, it is very early days in the realisation of these possibilities.

While production of methane in the rumen from carbon dioxide and hydrogen is carried out by the methanogenic archaea, there is a class of bacteria present in the rumen, the acetogens, which utilise carbon dioxide and hydrogen to produce acetic acid, a major nutrient of the ruminant. Acetogens do not compete well in the rumen compared to methanogens, so experiments are in progress to see if the microbial ecosystem can be manipulated to enhance acetogen activity (Joblin, 1999). One strategy is to genetically modify acetogens so that they can compete more effectively in the rumen.

### 7.4.7 Management of methane emissions at the farm-scale

There are many ways in which existing and new technologies could be applied through a farm systems approach to reduce methane emission. These very important mitigation strategies are dealt with in detail in Chapter 8.

### 7.4.8 Conclusions

The best short-term possibility for mitigating methane emissions would seem to be via improvements in animal efficiency. Various measures can be taken to dilute the amount of methane associated with the animal’s maintenance requirement, such as increasing feed intake or decreasing the proportion of cell wall carbohydrate in the diet. These factors should be evaluated with systems and farm-scale research. There are possibilities for mitigation by exploiting variation between animals via genetic selection, but these await verification of the effect and selection of markers.

A wide range of feed additives for reducing methane has been tested over the last 40 years. Not one has been incorporated into farm practice for many reasons: toxicity, adaptation by the rumen microbes, expense, and lack of a suitable delivery system. It is pointless pursuing this type of research, unless at the outset of the research a delivery system is proposed and evaluated in a cost-effective way. In the grazing situation, delivery of compounds with antimethanogenic activity via pasture plant breeding is a possibility, but the estimation of the time required must be realistic.

Immunisation against methanogens is an interesting concept, but proof of efficacy is not available. A 20% reduction in methane would be helpful, but far from optimum.

Increased understanding of rumen microbiology is the most likely pathway to control of methanogenesis, because this work will address the biosynthesis of methane by the archaea. For the reason that this remains the major unknown in the area of mitigation research, it is by default the area of research with the best chance of finding a solution. However, the rumen ecosystem is extremely complex and such research will be long-term, expensive and high risk.

### 7.5 Current Research on Methane in New Zealand

Research into methane emissions is carried out predominantly at AgResearch, NIWA and Landcare. There is an informal group, MetNet, comprising the three major players and several other interested groups that meet occasionally to discuss common interests. Current research trends are summarised below and details are given in Appendix 2.
7.5.1 Inventory
The primary driver of inventory development has been the need of MfE and MAF to report to the UNFCCC on a regular basis. Until recently, reports have been based on a model developed by Ulyatt et al (1991). In 1995 NIWA invited a team from Washington State University, led by Dr Kristen Johnson, to New Zealand to demonstrate their SF$_6$ tracer technique for measuring methane emission from grazing animals. Since that time SF$_6$ has been used to measure methane emission from cattle and sheep over a wide range of pastoral conditions in a series of collaborative experiments between NIWA and AgResearch that have also involved Landcare and Dexcel. On several occasions the opportunity has been taken to measure concurrently methane emission from soil, grazing animals ($\text{SF}_6$) and with a range of meteorological techniques. Recently, Clark and Ulyatt (2002) revised the official inventory and incorporated methane emission factors derived from the measurement programme.

Programmes to refine the inventory model by measuring emission from various types and classes of livestock and pasture types continue, led by AgResearch.

7.5.2 Mitigation
Most of the current work on methane mitigation is carried out at AgResearch, Palmerston North. The ongoing research programme will form the cornerstone of the research portfolio of the PGGRC (see Chapter 3). The AgResearch group will also be conducting collaborative work with NIWA and Dexcel in the area of forages and diet supplements, the effect of animal maturity on its methane emission, and will possibly look for genes associated with low methane emission in dairy cows with Via Lactia.

7.5.3 Methodology
There is considerable expertise in New Zealand in meteorological methods for assessing greenhouse gas emissions. This work continues to be developed at both NIWA and Landcare. These technologies are aimed at estimating large scale or regional emissions and can be used to verify inventory calculations. Satellite approaches to estimate emission that correlate with pasture quality via NIR measurements are also being investigated.

Dexcel and NIWA are looking for new methods for determining the emissions of individual animals to replace the costly SF$_6$ methodology.

7.5.4 Models and systems approaches
There is an urgent need for a decision support model that is capable of evaluating the effectiveness of both existing and new technologies for reducing methane emission. This model needs to be used in conjunction with on-farm systems experiments to test alternative strategies. Several groups within New Zealand are either working on such models or contemplating such work. Thus AgResearch have developed the methane inventory model, are evaluating an Australian dairy model and looking to adapt the existing Stockpol and OVERSEER models, while Dexcel are developing a decision support model for dairying and MOTU are developing a land use model for New Zealand. There is an urgent need for all the modeling people to collaborate to produce the minimum number of models needed to do the job effectively. The resources in a small country are not large enough for the present apparent ad hoc approach.
References


Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions


Chapter 8
The Management of Emissions through Farming Practices

Summary

There have been only a limited number of studies of whole farm management systems and strategies that aim to reduce greenhouse gas emissions. However, the available evidence points to this approach in providing medium-term gains in emission management, and in the more efficient use of carbon converted to methane by rumen microbes (6% of gross energy intake) or nitrogen that is cycled in the farm production system. More efficient capture of methane carbon or nitrogen as animal tissue or product offers a win/win situation in terms of reduced emissions and increased productivity. Further, it appears that measures to reduce losses of methane carbon and nitrogen may be complementary or even synergistic.

The continuing development of farm-scale modeling, resource accounting techniques, and complementary on-farm testing protocols to support technology-based developments of abatement strategies is seen as a high priority. Core skills and expertise to do this already exists.

8.1 Management of Methane Emissions at the Farm-scale

Any proposed methane emission strategies must be evaluated for their cost-effectiveness at the farm-scale. There appear to be two approaches:

1. A systematic review of current farm management strategies based on present knowledge to evaluate where reductions in methane emission can be achieved.

2. Management techniques required to evaluate and capture the benefits of future methane mitigation technologies.

Given the present lack of suitable technologies to reduce methane emission from the rumen, there is an urgent need to develop and evaluate on-farm strategies based on our current knowledge of other factors, such as increased feed intake or dietary manipulation that influence methane emissions. This is the area where improvements are most likely in the medium-term. Our knowledge of the role of maintenance dilution, possible dietary manipulations, and improvements in animal efficiency needs to be incorporated into farming practice. This could be tested with an appropriate systems model backed up with farm testing. Models that could be used to evaluate methane emissions at the farm-scale are available (Martin et al, 1999; Yates et al, 2001; Mills et al, 2001), including economic assessment (Zeddies et al, 2000; Velthof et al, 2002). On-farm systems experiments have also been conducted (Jarvis & Pain, 1994; Murray et al, 2001). In New Zealand, de Klein et al (2002) have used a systems approach to evaluate the effect of the addition of grain to a dairying operation on methane emission. Much more emphasis should be put on this approach to developing mitigation strategies for methane emission.

Scenarios need to be developed that will allow any new methane mitigation technologies to be assessed and evaluated at the farm-scale as they are developed. Strategies that involve reduction in methane emission offer potential benefits, both in terms of the environment and in increasing animal production. Methane represents a loss to the animal of about 6% of the gross energy in the feed. If this could be captured, it should be possible to deliver a win/win situation with respect to methane reduction and increased animal productivity.

Methane is formed from CO$_2$ and H$_2$. To capture the 6% loss, carbon and hydrogen must be diverted into products that can be utilised by the animal, such as VFAs or microbial cells. If
the carbon is not captured it is presumably released as CO₂ and exhaled, or passes undigested in the faeces, resulting in reduced digestibility and no productivity gain. How much extra productivity might result if the 6% methane loss were captured? Let us take as an example a 450 kg cow yielding 3 750 kg milk per lactation and having an average ME requirement of 151 MJ/d. The GE requirement would be 259 MJ/d and 6% of this 15.5 MJGE/d. The extra ME available for milk production would be 9 MJ/d (efficiency GE to ME of 0.58). This converts to an extra 1.64 litres of milk/d, which over a lactation of 250 d becomes 409 litres of milk, or 33.54 kg milk solids. At $3.60/kg milk solids this becomes $120/cow, or for an average 250 cow herd an extra $30,000 per lactation. A similar calculation can be made for sheep farming. Taking a simple scenario, where the 6% of energy saved from methane is used to increase stocking rate. For a ewe flock of 2 000, an additional 120 ewes could be carried. This would result in 139 extra lambs, which at $65 each would earn $9,035. Extra wool at 5 kg/ewe and $4.80/kg would increase earnings by $2,880. The total increase would be $11,915. This is the theoretical maximum that could be achieved by capturing all the methane energy.

In practice it is unlikely that all the methane carbon and hydrogen would be captured, or that the efficiency of the transformation process would be perfect. With respect to meat production, both sheep and beef, any gains made by reducing methane emission by up to 6% of gross energy intake could be utilised by the farmer in many ways. Johnson and Johnson (2002) discussed possible management opportunities in North American farming systems, and considered that there was potential for methane reduction in increasing productivity (increased milk production or liveweight gain, decreased mortality, decreased culling rate, increased calving and weaning rate), genetic selection, intensive management and enhanced forage nutrient profile.

In New Zealand there are many opportunities for efficiency gains that would reduce methane emissions. For example, sheep and beef breeding stock are essentially kept at a maintenance level of production for a large part of the year once they have reached mature weight and are not lactating. This level of production has a maintenance methane cost but no associated production. Reduction in the numbers of breeding stock carried, without compromising production such as through increased multiple births, would reduce methane emissions. Many of these on-farm strategies are likely to reduce both methane and nitrous oxide emissions. The development of systems models that would allow evaluation of strategies for reducing greenhouse gas emissions must be a high priority.

8.1.1 Conclusions
There are several nutritional and farm management strategies currently available that, if applied in a systematic manner, would be expected to reduce methane. High priority should be given to the development of appropriate decision support models that could be used as a framework to test these possibilities. The model predictions should then be evaluated with farm-scale research.

8.2 Systems Approach for Reducing Nitrous Oxide Emission
A great deal of research has been conducted on nitrous oxide emission from agricultural systems and on ways to reduce the amounts emitted. However, most of the studies have been on individual processes in the nitrogen cycle or individual components of a farming system. All of this work is important, but Jarvis et al (1995) maintain that greater gains in the efficient utilisation of nitrogen in agriculture would be achieved if an integrated approach were made.

Considerable nitrogen is cycled through a production sequence on a dairy farm and there are many opportunities for loss. For example, a dairy farm in the UK receives >25 t of nitrogen
from various sources, but only 20% of the nitrogen input to the farm ends up in product (milk or meat) and over 47% of the nitrogen is lost (Jarvis et al. 1995). Losses occur during silage production, grazing, housing and waste application (Jarvis et al., 1995). Quantitative analysis of the nitrogen flows and nitrous oxide losses in dairy farming systems indicated that the implementation of options to improve nitrogen management at each stage of production could reduce nitrous oxide emission by 70% (Jarvis et al., 1996; Velthof & Oenema, 1997).

This approach was developed further by Velthof et al. (1998) and Oenema et al. (1998), who state that controlling nitrous oxide emissions requires a thorough understanding of all sources, and interacting and controlling factors at the farm level, and show that there is considerable scope for reducing nitrous oxide by proper management. Oenema et al. (1998) presented a modeling study for three dairy farming systems differing in levels of farm management. The size, structure and output in terms of milk produced from the three farms were similar (strategic management level). They illustrate the effects of decisions at the tactical management level (i.e. decisions that have an effect over one to three years, viz grazing system, fertiliser nitrogen input, method of slurry application), and the operational management level (i.e. decisions made over days, weeks and months, viz fertiliser type and timing of application) and show a three-fold difference in nitrous oxide emissions from the three farms. Oenema et al. (1998) prepared a list of the most important options to be considered at the tactical and operational levels and this is presented as Table 8.1. The authors maintain that the best results are obtained with a combination of the most appropriate options, which should be modelled first, then tested on experimental farms and finally tested by the best farmers.

**Table 8.1: Important Options to be Considered at Tactical and Operational Levels in Farming Systems**

<table>
<thead>
<tr>
<th>Reduce accumulations of mineral N in soil</th>
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<tbody>
<tr>
<td>Restricted grazing; house animals for part of the day, and for the second half of the growing season</td>
</tr>
<tr>
<td>Properly timed slurry and fertiliser application</td>
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<tr>
<th>Increase efficiency of N utilization</th>
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</thead>
<tbody>
<tr>
<td>Increase productivity per animal and decrease the number of animals</td>
</tr>
<tr>
<td>Lower the N content of the ration so as to lower the N content of the urine</td>
</tr>
<tr>
<td>Store and utilise animal excrements effectively</td>
</tr>
<tr>
<td>Adjust fertiliser N applications:</td>
</tr>
<tr>
<td>- type: no nitrate-containing fertilisers on wet soils;</td>
</tr>
<tr>
<td>- where appropriate use nitrification inhibitors</td>
</tr>
<tr>
<td>- amount: modest amounts adjusted to crop demand</td>
</tr>
<tr>
<td>- timing: no autumn and winter spreading</td>
</tr>
<tr>
<td>- method: uniform spreading</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proper drainage, run-off control and irrigation management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevent large groundwater fluctuations</td>
</tr>
<tr>
<td>Prevent flooding</td>
</tr>
<tr>
<td>Prevent surface run-off and collect run-off material in border strips</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Proper sward and soil management</th>
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</thead>
<tbody>
<tr>
<td>Establish and maintain productive swards</td>
</tr>
<tr>
<td>Prevent soil compaction</td>
</tr>
<tr>
<td>Maintain soil pH above 5</td>
</tr>
<tr>
<td>Whenever applicable, grow cover crops during autumn and winter</td>
</tr>
</tbody>
</table>

Source: Oenema et al., 1998
In New Zealand, a nutrient budget model, OVERSEER, has been developed with the aim that it would provide reasonable estimates of inputs and outputs of nitrogen, and that it could be used to examine management practices which reduce loss of nitrogen (Ledgard et al, 2001). OVERSEER was developed using data for the key nitrogen cycling processes and was validated using data sets from New Zealand field research. It is an empirical, annual time-step model, which provides average estimates of the fate of the nutrients nitrogen, phosphorus, potassium and sulfur. The model is site-specific and requires basic information on soils (soil group), site (rainfall, slope), animal production, fertiliser rates and supplementary feed. OVERSEER contains internal databases with nutrient concentrations of fertilisers, animals, products, crops, and residues which are used to estimate inputs and outputs. OVERSEER has been used for evaluating farm systems for regional councils (Ledgard et al, 1999), and it is also valuable for comparing loss of nitrogen from different farming systems (Ledgard et al, 2000). Excellent agreement was obtained between values for nitrogen leached estimated with OVERSEER and those measured on dairy farms in Ruakura, Taranaki, Otago and Southland (Thomas et al, 2002). It has also been used to obtain improved estimates of nitrogen excreted by different animal groups in different regions of New Zealand, and to refine regional nitrous oxide emission rates (de Klein et al, 2002; Sherlock et al, 2001).

Computer spreadsheets were developed by Phetteplace et al (2001) to simulate beef and dairy cattle operations at nine locations in the US, and estimate greenhouse gas emissions from those systems. Of the beef systems, the feed lot cattle resulted in the least nitrous oxide emission per unit of product. The authors conclude that their results confirm the importance of the whole farm approach to estimating greenhouse gas emissions from agriculture and for testing mitigation strategies.

References

Methane


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Nitrous oxide


Chapter 9
A Framework for Future Research Investment

Summary

It is suggested that all future research that is related to agricultural production should have specific regard to greenhouse gas emission. However, to be considered as research on abatement, the research objectives should have some aspect of greenhouse gas abatement as its primary purpose. This research could include basic studies to understand the processes by which the gases are produced or abated, measurement and inventory development, particularly that which enables the impact of any abatement strategies to be measured, and research to develop specific abatement strategies based on technologies, products or farm practices. Research to integrate such strategies into whole farm management systems would also qualify.

A framework that is based on deriving a national research strategy from an identification of national objectives for agricultural greenhouse gas emissions is proposed.

The terms of reference for this review call for the Review Team to propose:

“[a] framework, including criteria, for identifying, considering and prioritising relevant research to maximise abatement opportunities for methane and nitrous oxide from agriculture.”

The Review Team were asked to define the types of research that can be considered as abatement research.

9.1 Definition of the Types of Research that may be Considered as Abatement or Mitigation Research

The Review Team considers that all future research that is concerned with the production performance of grazing ruminants, the improvement of forage systems, the management of animal wastes, the management of carbon and nitrogen cycles in soils and the development or improvement of farming systems should have specific regard to: the emissions of carbon dioxide; methane and nitrous oxide that may result from the adoption of the research findings; and should seek to quantify the impacts of the uptake of the research findings on emission rates.

However, to be considered as research on abatement or mitigation of greenhouse gas emissions, the objectives of the research should have identification or exploration of emission abatement or mitigation as the primary purpose. This could include research on:

Fundamental studies to provide an understanding of the processes by which methane and nitrous oxide are formed and emitted or processes or technologies that modify the production or emission of the gases. This research could be expected to have an application in the medium (5-10 years) or long-term (>10 years).

Improvement of the National Inventory through the development of measurement techniques that can operate at national, regional, farm-scale or animal/paddock levels, and emission estimation models and emission factors that reflect as closely as possible New Zealand agricultural practices and systems. An important feature of the future inventory will be the capacity to demonstrate that any abatement strategies that are adopted are delivering the expected reduction in emissions.
The abatement/mitigation of methane or nitrous oxide emissions through new technologies or products.

The abatement/mitigation of methane or nitrous oxide emissions through farm management practices.

Management at a farm-scale of soil carbon and nitrogen cycles that result in reduced GHG emissions.

Whole farm management systems that incorporate abatement strategies in a manner that encourages uptake and adoption by farmers. This could include research into farmer attitudes to the management of greenhouse gas emissions and to the acceptability/adoptability of abatement strategies.

9.2 A Framework for Identifying, Considering and Prioritising Research to Maximise Abatement Opportunities

The framework that is illustrated in Figure 9.1 is based on the assumption that the agency that administers government and agricultural industry funds for the purchase of research on agricultural greenhouse emissions will establish and publish a strategic framework on which it will base its decisions to purchase research outputs.

The objective is to provide a conceptual framework that assists in identifying the strategic objectives for future agricultural greenhouse gas emissions abatement, and the research needed to achieve those objectives at a national, regional and farm level.

It is intended that this report will contribute to the analysis of needs and opportunities on which a future research strategy could be based, identify research areas that will make up the research portfolios, and assist in identifying priorities. The Workshop “Research Priorities for Abatement of Non-Carbon Dioxide Greenhouse gases from Agriculture” will have identification of opportunities and research priorities as its primary focus. The results of the Workshop will be presented in the Review Team’s final report. This report, and the findings of the Workshop, will be used by the Review Team to formulate its recommendations in its final report.

9.3 Criteria for Identifying, Considering and Prioritising Relevant Research

An assessment of current research has been provided in Chapters 4, 5, 6, 7 and 8, and these assessments offer a basis for formulating criteria for future research. However, the Review Team will provide more specific recommendations in its final report that will take account of the conclusions to date and the findings of the Workshop. The Review Team notes that how the criteria are applied in the future will depend on the strategic direction that the future funding body chooses to take. If the research funder adopts the approach of a strategy that has short, medium and long-term elements, primary criteria to make decisions regarding the allocation of resources across the research portfolios will be important. If, on the other hand, the agency adopts a more applied approach that favours more short and medium-term problem-solving research, the criteria will need to be more specific as to what research is and is not to be funded.

Since it can not pre-judge the future research strategy, the Review Team will comment on the criteria for both approaches in its final report.
OUTCOMES SOUGHT

- Govt policy outcome: practical and economic ways to reduce GHG emissions
- Sector outcome: abatement strategies acceptable to farmers and markets
- National outcome: responsible environmental resource management

NEEDS ANALYSIS

- Drivers, imperatives
- Timeframes
- Budget
- Relative priorities

OPPORTUNITIES ANALYSIS

- An analysis of current knowledge
- Potential benefits
- Risks – at the research level, at the implementation level
- Probability of successful implementation
- Costs – research, development

NEEDS ANALYSIS

- Drivers, imperatives
- Timeframes
- Budget
- Relative priorities

OPPORTUNITIES ANALYSIS

- An analysis of current knowledge
- Potential benefits
- Risks – at the research level, at the implementation level
- Probability of successful implementation
- Costs – research, development

RESEARCH STRATEGY

PORTFOLIOS

- Research areas – see 10.1
- Balance of effort – applied vs basic

STRATEGIC RESEARCH OBJECTIVES

PRIORITIES

CRITERIA FOR RESEARCH PROPOSALS

DEVELOPMENT & IMPLEMENTATION STRATEGY

Figure 9.1: A Suggested Framework for the Development of a Greenhouse Gas Research Strategy

Source: Review Team
**Glossary of Terms, Abbreviations and Symbols**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>abatement</td>
<td>see mitigation</td>
</tr>
<tr>
<td>aerobic</td>
<td>living, active or occurring in the presence of oxygen</td>
</tr>
<tr>
<td>anaerobic</td>
<td>living, active or occurring in the absence of oxygen</td>
</tr>
<tr>
<td>anthropogenic</td>
<td>caused or produced by humans</td>
</tr>
<tr>
<td>Archea</td>
<td>a group of anaerobic microorganisms that includes the methanogens residing in the rumen</td>
</tr>
<tr>
<td>AWMS</td>
<td>animal waste management systems</td>
</tr>
<tr>
<td>biomass</td>
<td>the total quantity of living matter in a particular habitat and plant and organic waste materials</td>
</tr>
<tr>
<td>BMP</td>
<td>best management practice</td>
</tr>
<tr>
<td>bST</td>
<td>bovine somatotrophin</td>
</tr>
<tr>
<td>BT</td>
<td>brown top</td>
</tr>
<tr>
<td>BW</td>
<td>body weight</td>
</tr>
<tr>
<td>C</td>
<td>carbon</td>
</tr>
<tr>
<td>Ca C₂</td>
<td>calcium carbide</td>
</tr>
<tr>
<td>CF</td>
<td>cocksfoot</td>
</tr>
<tr>
<td>CH₄</td>
<td>methane</td>
</tr>
<tr>
<td>cm</td>
<td>centimetre</td>
</tr>
<tr>
<td>C/N ratio</td>
<td>carbon:nitrogen ratio</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>CT</td>
<td>condensed tannins</td>
</tr>
<tr>
<td>day⁻¹</td>
<td>per day</td>
</tr>
<tr>
<td>DCD</td>
<td>dicyandiamide</td>
</tr>
<tr>
<td>DDMI</td>
<td>digestible dry matter intake</td>
</tr>
<tr>
<td>Dig</td>
<td>DM digestibility</td>
</tr>
<tr>
<td>DM</td>
<td>dry matter</td>
</tr>
<tr>
<td>DMI</td>
<td>dry matter intake</td>
</tr>
<tr>
<td>DMPP</td>
<td>3,4-dimethylpyrazole phosphate, ENTEC™</td>
</tr>
<tr>
<td>DNDDC</td>
<td>denitrification-decomposition</td>
</tr>
<tr>
<td>Dsa</td>
<td>summer grass</td>
</tr>
<tr>
<td>EF</td>
<td>emission factor</td>
</tr>
<tr>
<td>eructation</td>
<td>belching</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organisation of the United Nations</td>
</tr>
<tr>
<td>FCM/d</td>
<td>fat corrected milk per day</td>
</tr>
<tr>
<td>flatus</td>
<td>flatulence</td>
</tr>
<tr>
<td>FRST</td>
<td>Foundation for Research, Science &amp; Technology</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared spectroscopy</td>
</tr>
<tr>
<td>g</td>
<td>gram</td>
</tr>
<tr>
<td>g/d, g/day</td>
<td>grams per day</td>
</tr>
<tr>
<td>GE</td>
<td>gross energy</td>
</tr>
<tr>
<td>Gg</td>
<td>giga gram; one billion grams or 10⁹ grams g/d</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas(es)</td>
</tr>
<tr>
<td>GWP</td>
<td>global warming potential</td>
</tr>
<tr>
<td>ha⁻¹</td>
<td>per hectare</td>
</tr>
<tr>
<td>H₂</td>
<td>hydrogen</td>
</tr>
<tr>
<td>HiSR</td>
<td>high stocking rate</td>
</tr>
<tr>
<td>HMG-CoA</td>
<td>hydroxymethylglutaryl-co-enzyme A</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>kg</td>
<td>kilogram</td>
</tr>
</tbody>
</table>
Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions

legume: a plant that can fix nitrogen from the air by virtue of a symbiotic relationship with a microorganism

l/h: litres per hour
LoSR: low stocking rate
m: metre
MAF: Ministry of Agriculture and Forestry
ME: metabolisable energy
methanogen: a microorganism that synthesises methane by combining hydrogen and carbon dioxide
mg: milligram
mitigation: an anthropogenic intervention to reduce the emissions or enhance the sinks of greenhouse gases; abatement
MJ: milli-joule
MJGE/d: milli-joules of gross energy intake per day
ml: millilitre
MY: methane yield
nitrification: the oxidation of ammonium to nitrite and the further oxidation of nitrite to nitrate by soil organisms
N: nitrogen
N₂: dinitrogen, nitrogen gas
N₂O: nitrous oxide
¹⁵N: isomer of nitrogen
NADH: reduced form of nicotinamide adenine dinucleotide (NAD)
NE: net energy
Ng: nanogram
NH₃: ammonia
NH₄⁺: ammonium ion
⁶³Ni: isomer of nickel
NO: nitric oxide
NO₃⁻: nitrate ion
NO₂⁻: nitrite ion
NOₓ: any of several oxides of nitrogen
N m⁻² s⁻¹: nitrogen per square metre per site
N/y: nitrogen per year
OECD: Office of Economic Cooperation and Development
PEG: polyethylene glycol
PGGRC: Pastoral Greenhouse Gas Research Consortium
ppb: parts per billion
ppt: parts per trillion
PR: perennial ryegrass
RNA: ribonucleic acid
s: second
sCoA: co-enzyme A
sd: standard deviation
SF₆: sulphur hexafluoride
t: tonne
tg: tera gram; one trillion grams or 10¹² grams
TMR: total mixed rations
UNFCCC: United Nations Framework Convention on Climate Change
UP: unimproved pasture
VFA: volatile fatty acid(s)
WC: white clover
Appendix 1: Terms of Reference

A Proposal for Joint Agricultural Sector/Government Assessment of Research Needs for Non-Carbon Dioxide Greenhouse Gas Abatement Research for Agriculture

Introduction

The government and the agricultural sector seek a critical analysis of recent (largely within the last five years) and current research undertaken in New Zealand and internationally in the public and private sectors on abatement opportunities for ruminant methane emissions and nitrous oxide generated from agricultural production systems. The analysis should comment specifically on the prospects of each area of research to provide a basis for developing practical measures for New Zealand to reduce its emissions of methane and nitrous oxide from the agricultural sector. This requires the identification of best future opportunities and research priorities in terms of abatement potential. The information should provide the basis to enable future costing of the research, and the institutional arrangements necessary to make progress to abate nitrous oxide and methane emissions from agriculture.

Outputs

The outputs to be produced will include:

- A report, being a critical analysis of past (largely within the last five years) and current research from New Zealand and internationally from the private and public sectors assessing both methane and nitrous oxide and linkages between the two gases. This should include: information on any broad costing involved with such research where available; sources of funding; the organisations involved and any unique institutional arrangements; and the potential or actual level of emissions abatement at a national level. The review will also define the types of research that are appropriate for consideration as abatement research for nitrous oxide and methane.
- A report on the framework, including criteria, for identifying, considering and prioritising relevant research to maximise abatement opportunities of methane and nitrous oxide from agriculture.
- An international Workshop, held jointly with Australia, on prospects for additional research to develop management practices and technologies to reduce methane and nitrous oxide in New Zealand agriculture with a summary report of outcomes. The Workshop will receive secretarial support from government agencies and Meat NZ.
- A report on priorities and strategy for future methane and nitrous oxide research, using the outcomes from the previous reports and Workshop, including the ability to enable future assessments of the costs and potential for making progress.

Reviewers

A team of three reviewers will be appointed based on their expertise that will cover both methane and nitrous oxide. One member will take overall responsibility for the reviews and Workshop.

Accountability

The reviewers will be accountable to a Steering Committee made up of government officials from the Ministry of Agriculture and Forestry, the Ministry of Research, Science and Technology and the Climate Change Project Team and agricultural industry representatives. The committee will be co-chaired by Neil Taylor, Meat NZ, and Michael Jebson, MAF, or
their representatives. The committee will be accountable to Murray Sherwin, Director-General of MAF, and Jeff Grant, Chairperson of the Primary Industries Council, who will jointly sign off any documents before forwarding to Ministers, and advise on any issues related to public release of information.

**Process**

The reviewers will base their reports on reviews of the literature, expert knowledge and interviews with relevant scientists, industry and government officials. The reviewers are to use pertinent experts, including commissioning any other work within the limits of the funding provided, to gain relevant information. Industry representatives and government officials will assist the reviewers in gaining access to all relevant information for the review.
## Appendix 2: Summary of Current Research Programmes

<table>
<thead>
<tr>
<th>Provider</th>
<th>Programme Id</th>
<th>Programme Title</th>
<th>Objective</th>
<th>Investigators</th>
<th>FTEs</th>
<th>Funders</th>
<th>Collaborators</th>
<th>Type</th>
<th>Research</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgResearch</td>
<td></td>
<td>On-farm strategies for GHG mitigation</td>
<td>Develop farm-level decision-support models and strategies that optimise economic, social, GHG outcomes. Test strategies.</td>
<td>Lambert</td>
<td>Proposed FRST and Industry R&amp;D</td>
<td>Dexcel, LandCare, Forest Research</td>
<td>5</td>
<td>Integrated with Inventory, Process Resource Accounting and Implementation research projects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Proof of function of possible methane reducing technologies</td>
<td>Ensure putative technologies, when applied to grazing animals, deliver reductions in methane emissions.</td>
<td>Waghorn, H Clark, Woodward</td>
<td>0.95</td>
<td>PGGRC, Industry</td>
<td>CSIRO, Dexcel</td>
<td>4</td>
<td>Part of PGHGRC research and Dairy Global Forage Programme</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Reducing nitrogen losses from ruminants</td>
<td>Reduce nitrous oxide emissions from pastures by reducing nitrogenous wastes from ruminants.</td>
<td>Attwood, Waghorn</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Understanding and exploiting variation in methane production between animals</td>
<td>Determine cause, persistence and heritability of between-animal differences in methane production.</td>
<td>H Clark, D Clark (proposed)</td>
<td>0.5 minimum</td>
<td>PGGRC, FRST (possible)</td>
<td>Dexcel (possible)</td>
<td>4</td>
<td>Part of PGHGRC research and FRST project. Papers already quantified size animal differences in methane production.</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Rumen microbial strategies to lower methane emissions</td>
<td>Develop rumen-focused methods to reduce CH4 formation.</td>
<td>Joblin</td>
<td>4.5</td>
<td>FRST, Pastoral Agricultural Industries</td>
<td></td>
<td></td>
<td>Part of FRST programme and Pastoral Greenhouse Gases Research Consortium</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Forage and plant inhibitors to lower methane emissions</td>
<td>Locate and identify inhibitory compounds in forage to control GHG emissions.</td>
<td>Meagher</td>
<td>2.5</td>
<td>PGGRC, FRST</td>
<td></td>
<td></td>
<td>NSOF project on condensed tannins complementary.</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Evaluation and identification of abatement options</td>
<td>Analyse abatement scenarios using process-based ecosystem model, capable of predicting emissions at farm-scale. Includes GHG functions (N2) ruminant and soil CH4.</td>
<td>Parsons, Newton, Carran, H Clark, Lambert</td>
<td>0.4</td>
<td>FRST</td>
<td>University of Melbourne, IMJ</td>
<td>1,2,5</td>
<td>Part of Global Change Programme (FRST). Research model developed over past 4 years and is used in Australia for management and environmental planning.</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Transport fuels from herbaceous plants</td>
<td>Develop plant germplasm, enzyme conversion technologies and farm systems to establish a bioethanol industry based on herbaceous feedstocks.</td>
<td>Newton</td>
<td>2</td>
<td></td>
<td>Oak Ridge National Laboratory (US)</td>
<td>5</td>
<td>This work is based on a long-term field experiment. Part of Global Change Programme (FRST).</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Sensitivity of N2O and CH4 emissions to the increasing concentration of CO2 in the atmosphere</td>
<td>Measure changes to ecosystem processes from a rise in atmospheric CO2 (including the emissions of GHGs).</td>
<td>Carran</td>
<td>0.6</td>
<td>FRST (past 3 years and future 5 years)</td>
<td></td>
<td>2.6</td>
<td>Part of Global Change Programme (FRST).</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Impact of high tannin-producing plants on soil</td>
<td>Measure whether a greater input of plant tannins to soil will modify C and N pools and fluxes. Understand mechanisms.</td>
<td>Carran</td>
<td>0.05</td>
<td>FRST</td>
<td></td>
<td></td>
<td>Part of Global Change Programme (FRST).</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Farm systems for increased N efficiency</td>
<td>Develop management practices for increased N efficiency and decreased N losses. Evaluate practices in 2 farmlet studies.</td>
<td>Ledgard</td>
<td>2.5</td>
<td>FRST, MAF, FMRA</td>
<td>Dexcel</td>
<td>5</td>
<td>Linked to use of OVERSEER and Resource Accounting models. Desktop studies highlighted benefits of winter management and diet manipulation.</td>
<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Empirical farm system/industry</td>
<td>Upgrade OVERSEER model to estimate</td>
<td>Ledgard</td>
<td>2.5</td>
<td>MAF, FRST</td>
<td>Massey; Crop and</td>
<td></td>
<td>OVERSEER upgrade -</td>
<td></td>
</tr>
<tr>
<td>Provider</td>
<td>Programme Id</td>
<td>Programme Title</td>
<td>Objective</td>
<td>Investigators</td>
<td>FTEs</td>
<td>Funders</td>
<td>Collaborators</td>
<td>Type</td>
<td>Research</td>
<td>Comment</td>
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</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Models to estimate greenhouse gas emissions</td>
<td>methane, N2O and CO2. Develop and apply Resource Accounting model to estimate resource use and emissions.</td>
<td>de Klein, Li, Sherlock</td>
<td>4.45</td>
<td>MAF, MfE</td>
<td>LandCare Research, Lincoln</td>
<td>Food Research</td>
<td></td>
<td>Includes addition of Ca, Mg budgets.</td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Refinement of N2O emission factor for animal urine and dung (EF3)</td>
<td>Determine N2O emission factor for animal excreta under different environmental conditions. Generate data sets for subsequent model development.</td>
<td>de Klein, Li, Sherlock</td>
<td>4.45</td>
<td>MAF, MfE</td>
<td>LandCare Research, Lincoln</td>
<td>Food Research</td>
<td></td>
<td>Results to date show seasonal/regional variation in N2O emission factor from animal excreta. Part of research project to refine NZ's N2O inventory, coordinated through NzOnet.</td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Effect of artificial drainage and dairy winter grazing management of Southland pastures on N2O emissions</td>
<td>Determine effect of artificial drained pasture soil, strategic destocking and forage winter grazing, on N2O emissions.</td>
<td>de Klein, Drewry</td>
<td>1</td>
<td>FRST</td>
<td></td>
<td>Food Research</td>
<td></td>
<td>Results will be used to determine effect of soil physical properties on N2O emissions. Part of larger programmes investigating winter management system. Objective 2 links to farm systems work in Waikato/Taupo.</td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Desktop evaluation</td>
<td>Evaluate effect of strategic destocking and/or diet manipulation on N efficiency, reduced N leaching, N flows and losses, and total GHG emission at farm-scale.</td>
<td>de Klein, Ledgard, H Clark</td>
<td>6</td>
<td>FRST, MAF</td>
<td></td>
<td>Food Research</td>
<td></td>
<td>Studies used knowledge obtained from (field) research projects.</td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>Methane inventory development</td>
<td>Develop inventory of ruminant methane emissions.</td>
<td>H Clark, Waghorn, Krause, Lassey, Woodward, D Clark, Brooks, Hoskin, Kalliher, Dymond</td>
<td>3.1</td>
<td>FRST, MAF</td>
<td>NIWA, Dexcel, Massey, Landcare Research</td>
<td>Food Research</td>
<td></td>
<td>Part of other (unspecified) projects.</td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>A genomics approach to identify targets for methanogen inhibition</td>
<td>Identify structural and metabolic features of rumen methanogens for inhibition of methane formation in the rumen.</td>
<td>Attwood</td>
<td>1.2</td>
<td>PGGRC</td>
<td></td>
<td>Food Research</td>
<td></td>
<td>Part of PGHGRC research.</td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>C10X0203 New opportunities from Forage Plant Genomics</td>
<td>Develop knowledge of molecular regulation of lipid biosynthesis in leaves. Aim to enhance specific fatty acids in plants to increase energy content of forage and health promoting benefits.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Contributes to the Future Biotechnology area within Advanced Biological Enterprises SPO.</td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>C10X0205 Global Change Processes in Terrestrial Ecosystems</td>
<td>Improve model for methane inventory. Quantify methane emissions from grazing ruminant livestock.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>AgResearch</td>
<td></td>
<td>C10X0205 Global Change Processes in Terrestrial Ecosystems</td>
<td>Develop capability to manage consequences of environmental change for ecosystems services.</td>
<td></td>
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</tr>
</tbody>
</table>

Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions
<table>
<thead>
<tr>
<th>Provider</th>
<th>Programme Id</th>
<th>Programme Title</th>
<th>Objective</th>
<th>Investigators</th>
<th>FTEs</th>
<th>Funders</th>
<th>Collaborators</th>
<th>Type</th>
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<tbody>
<tr>
<td>AgResearch</td>
<td>C10X0223</td>
<td>Managing Productive Landscapes for Multiple Goals</td>
<td>Develop model to simulate effect of treading damage of pasture growth and composition, N2O emission and long-term effects of treading and rate of soil recovery.</td>
<td></td>
<td></td>
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<tr>
<td>AgResearch</td>
<td>C10X0227</td>
<td>Advanced Nutritional and Phytochemical Solutions for Premium Products</td>
<td>Increase farm sustainability by developing forage cultivators with proanthocyanidins.</td>
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<td>Research</td>
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<tr>
<td>AgResearch</td>
<td>C10X0227</td>
<td>Advanced Nutritional and Phytochemical Solutions for Premium Products</td>
<td>Develop techniques and obtain information on rumen microbial processes affecting methane formation in grazing livestock, to develop technologies for lowering ruminal methane emissions.</td>
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<td></td>
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<td>Research</td>
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<tr>
<td>AgResearch</td>
<td></td>
<td>Effect of soil moisture status on N2O emissions</td>
<td>Determine effect of short changes in soil moisture of N2O emissions from grazed pasture soil and N fertiliser application.</td>
<td>de Klein</td>
<td>0.5</td>
<td>FRST and FertResearch Lincoln</td>
<td>1.5</td>
<td>Evaluation of MOLLY.</td>
<td></td>
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</tr>
<tr>
<td>Dexcel</td>
<td>DRCX0205</td>
<td>Sustainable dairy systems to meet consumer demand</td>
<td>Develop pasture based forage mixed ration systems for dairy farms that use alternative forages to balance nutrient requirements for pasture-fed cows. Reduce methane emissions and production of rumen ammonia.</td>
<td></td>
<td></td>
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<tr>
<td>Dexcel</td>
<td>DRCX0207</td>
<td>Systems approach to reducing methane emissions</td>
<td>Develop a decision-support model for methane mitigation impact prediction.</td>
<td>Woodward</td>
<td>0.55</td>
<td>FRST</td>
<td>AgR, Simon Woodward</td>
<td>2</td>
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<tr>
<td>Dexcel</td>
<td>DRCX0207</td>
<td>Systems approach to reducing methane emissions</td>
<td>Methane sensor development.</td>
<td>Clark</td>
<td>3.2</td>
<td>FRST</td>
<td>AgR, NIWA</td>
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<td>Research</td>
<td>Evaluation of MOLLY.</td>
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<tr>
<td>Dexcel</td>
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<td>Systems approach to reducing methane emissions</td>
<td>Forages and diet supplements for reduced methane emissions.</td>
<td>Woodward</td>
<td>0.85</td>
<td>FRST</td>
<td>AgR</td>
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<tr>
<td>Dexcel</td>
<td>DRCX0207</td>
<td>Systems approach to reducing methane emissions</td>
<td>Genes responsible for low methane emissions.</td>
<td>Clark</td>
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<td>FRST</td>
<td>Boviquest</td>
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<tr>
<td>Dexcel</td>
<td></td>
<td>Forages for reduced methane emissions</td>
<td>High quality forages, reduced tannins.</td>
<td>Woodward</td>
<td>0.2</td>
<td>Dairy Insight</td>
<td>AgR, NIWA</td>
<td>5</td>
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<td>Papers on Lotus and sulla</td>
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<tr>
<td>Dexcel</td>
<td></td>
<td>Methane emissions from growing dairy heifers</td>
<td></td>
<td>Woodward</td>
<td>0.45</td>
<td>MAF</td>
<td>AgR</td>
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<tr>
<td>LandcareResearch</td>
<td></td>
<td>Determination of N2O emission factor from animal excreta following application in summer in 3 regions of NZ</td>
<td>Determine N2O emission factor for animal excreta under contrasting conditions. Generate data sets for modeling development and validation.</td>
<td>Li</td>
<td>0.8</td>
<td>MAF</td>
<td>Lincoln, AgResearch</td>
<td>2.3</td>
<td>Research</td>
<td>Interim report submitted to MAF June 02</td>
</tr>
<tr>
<td>LandcareResearch</td>
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<td>Determination of the N2O emission factor from animal excreta, following application in summer in 3 regions of NZ</td>
<td>Determine the N2O emission factor for animal excreta following application in summer, under contrasting conditions. Generate data sets for modeling.</td>
<td>Li</td>
<td>0.8</td>
<td>MAF</td>
<td>Lincoln, AgResearch</td>
<td>2.3</td>
<td>Research</td>
<td>Interim report submitted to MAF June 02</td>
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<tr>
<td>Landcare Research</td>
<td></td>
<td>Paddock-scale methane emissions measurement and mitigation verification technology</td>
<td>Develop technology to measure and verify mitigation of herd-scale methane emissions from dairy cows of different genetic origin.</td>
<td>Kelliher</td>
<td>1.3</td>
<td>FRST</td>
<td>AgResearch</td>
<td>4</td>
<td></td>
<td>Part of the 'Reducing GHG emissions from the Terrestrial Biosphere' programme. Linked with AgResearch's Global Change Processes in Terrestrial Ecosystems' FRST programme.</td>
</tr>
<tr>
<td>Landcare Research</td>
<td></td>
<td>Audit soil atmospheric N2O/CH4 concentrations, surface N2O/CH4 fluxes and relative soil/weather characters in 2 Hamilton soils.</td>
<td>Model development of N2O/CH4 concentrations. Develop collection system for GHG gas measurement. Test possibility of predicting N2O surface flux. Establish farm-scale platforms for N2O/CH4 abatement/mitigation experiments.</td>
<td>Li</td>
<td>1.46</td>
<td>FRST, Landcare</td>
<td></td>
<td>2,3,5</td>
<td></td>
<td>Part of Landcare FRST GHG programme (C09X0212 Reducing Greenhouse gas emissions from the Terristrial Biosphere), and under Objective 4.</td>
</tr>
<tr>
<td>Landcare Research</td>
<td></td>
<td>Prototype farm-scale gas emission model</td>
<td>Integrate IPCC methodology for methane and nitrous oxide emissions at farm-scale. Develop framework and model for incorporation of net carbon dioxide emissions.</td>
<td>Kelliher</td>
<td>0.7</td>
<td>FRST, MAF</td>
<td>AgResearch, Lincoln</td>
<td>2.5</td>
<td></td>
<td>Price is a PhD student, under supervision from Sherlock, Kelliher and Tate. Part of the Reducing GHG emissions from the Terrestrial Biosphere' programme.</td>
</tr>
<tr>
<td>Landcare Research</td>
<td></td>
<td>A pristine NZ forest soil: Benchmark for the methane sink</td>
<td>Measure methane consumption rate by soil bacteria in a native forest (pristine site) and under controlled conditions.</td>
<td>Price</td>
<td>1</td>
<td></td>
<td>Lincoln</td>
<td>1</td>
<td></td>
<td>Price is a PhD student, under supervision from Sherlock, Kelliher and Tate. Part of the Reducing GHG emissions from the Terrestrial Biosphere' programme.</td>
</tr>
<tr>
<td>Landcare Research</td>
<td></td>
<td>Develop and maintain automated trace gas analytical facilities</td>
<td>Develop an autosampler. Maintain quality control procedures for Gas Chromatograph. Provide staff training for maintenance of GC. Provide analytic services for FRST.</td>
<td>Hedley</td>
<td>0.2</td>
<td>FRST to LCR, MAF, Lotteries Grants Commission, Landcare Research Capex</td>
<td></td>
<td>3,6</td>
<td></td>
<td>Part of 'Reducing GHG emissions from Terristrial Biosphere' FRST programme. Developed technologies for surface engineering and application of clays.</td>
</tr>
<tr>
<td>Landcare Research</td>
<td></td>
<td>Clays for rumen microbial engineering to mitigate methane emissions</td>
<td>Investigate effect of surface-engineered clays on quantity/activity of methogens and thus methane production. Effect of modified clays on methane emissions.</td>
<td>Yuan, Tate</td>
<td>1.3</td>
<td></td>
<td>AgResearch, WRONZ</td>
<td>4</td>
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<td>Linked to 'Reducing GHG emissions from Terristrial Biosphere' FRST programme. Developed technologies for surface engineering and application of clays.</td>
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<tr>
<td>Landcare Research</td>
<td></td>
<td>Nitrous oxide emission from farm effluents</td>
<td>Quantify contribution of effluent irrigation to farm-scale GHG inventory and of effluent-derived N2O to GHG emission. Develop effluent irrigation practices.</td>
<td>Bolan, Saggar, Bhandral</td>
<td>1.3</td>
<td>MFAT, Environment Waikato</td>
<td>Massey, Environment Waikato</td>
<td>1.5</td>
<td></td>
<td>Linked to 'Reducing GHG emissions from Terristrial Biosphere' FRST programme. Developed technologies for surface engineering and application of clays.</td>
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<tr>
<td>Landcare Research</td>
<td></td>
<td>Spatial and temporal estimates of herbage quality for improving the national methane emissions inventory</td>
<td>Develop a remote sensing method to monitor and map herbage quality on a national scale.</td>
<td>Dymond</td>
<td>0.3</td>
<td>MAF</td>
<td>AgResearch</td>
<td>3</td>
<td></td>
<td>Linked to 'Reducing GHG emissions from Terristrial Biosphere' FRST programme. Developed technologies for surface engineering and application of clays.</td>
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<tr>
<td>Landcare Research</td>
<td></td>
<td>Mitigation process and strategies</td>
<td>Find best land-use related mitigation solutions from the combined perspectives of CO2, N2O and CH4.</td>
<td>Baisden</td>
<td>0.89</td>
<td></td>
<td>Motu Economic and Public Policy Research Trust</td>
<td>5</td>
<td></td>
<td>Linked to 'Reducing GHG emissions from the Terristrial Biosphere' programme. Developed technologies for surface engineering and application of clays.</td>
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<td>Provider</td>
<td>Programme Id</td>
<td>Programme Title</td>
<td>Objective</td>
<td>Investigators</td>
<td>FTEs</td>
<td>Funders</td>
<td>Collaborators</td>
<td>Type</td>
<td>Research Comment</td>
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<tr>
<td>Landcare Research</td>
<td></td>
<td>Methane emissions from animal excreta</td>
<td>Develop mitigation strategies for reducing emissions. Assess contribution</td>
<td>Saggar</td>
<td>0.25</td>
<td>FRST to LCR</td>
<td>3</td>
<td></td>
<td>Part of 'Reducing GHG emissions from Terrestrial Biosphere' FRST programme.</td>
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<td></td>
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<td>to NZ inventory. Understand processes controlling methane emissions from</td>
<td></td>
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<td>Funded out of Sustainability of Productive Sector Environments SPO</td>
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<td>animal dung.</td>
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<td>Landcare Research</td>
<td></td>
<td>Nitrous oxide emissions estimates and processes</td>
<td>Develop management options for reducing nitrous oxide emissions from</td>
<td>Saggar</td>
<td>1.5</td>
<td>FRST to LCR, MAF</td>
<td>2,3,5</td>
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<td>Part of 'Reducing GHG emissions from Terrestrial Biosphere' FRST programme.</td>
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<td></td>
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<td>agricultural soils. Assess contribution to NZ inventory and reduce</td>
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<td>Funded out of Sustainability of Productive Sector Environments SPO</td>
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<td>uncertainty in inventory.</td>
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<tr>
<td>Landcare Research</td>
<td></td>
<td>The role of nitrification inhibitors in mitigating</td>
<td>Develop technology of delivering nitrification inhibitor to reduce N2O</td>
<td>Bolan, Saggar, Singh</td>
<td></td>
<td>Summit-Quinlphos to</td>
<td>4,5</td>
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<td>Part of 'Reducing GHG emissions from Terrestrial Biosphere' FRST programme.</td>
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<td></td>
<td></td>
<td>the environmental impacts of urine deposition and</td>
<td>emissions from urine spots. Develop advisory tools/best management</td>
<td></td>
<td></td>
<td>Massey</td>
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<td>Funded out of Sustainability of Productive Sector Environments SPO</td>
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<td></td>
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<td>improving nitrogen use efficiency in grazed pastures</td>
<td>practices to mitigate N-losses. Determine role of</td>
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<td>nitrification inhibitors on loss of nitrogen. Assess eff ect of</td>
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<td>nitrification inhibitors on urine-induced N2O emissions, cation</td>
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<td>reaching and acidification.</td>
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<td>Landcare Research</td>
<td></td>
<td>Soil methane sink</td>
<td>Develop mitigation tool/strategy. Test if environmental pollution has a</td>
<td>Tate, Price, Carran, Niklaus</td>
<td>1.1</td>
<td>FRST to LCR, Swiss</td>
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<td>Part of 'Reducing GHG emissions from Terrestrial Biosphere' FRST programme.</td>
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<td>contributor to increasing atmospheric CH4 concentrations by limiting soil</td>
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<td>National Science</td>
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<td>Funded out of Sustainability of Productive Sector Environments SPO</td>
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<td>sink. Assess contribution to NZ's emissions inventory.</td>
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<td>doctoral fellowship)</td>
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<td>Lincoln, AgResearch</td>
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<td>Landcare Research</td>
<td></td>
<td>The IPCC-based N2O emission factor for NZ from</td>
<td>Determine N2O emission factor for animal excreta. Generate data sets</td>
<td>Li</td>
<td>1.46</td>
<td>FRST, Landcare</td>
<td>2,3,4,5</td>
<td></td>
<td>Part of 'Reducing GHG emissions from Terrestrial Biosphere' FRST programme.</td>
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<tr>
<td></td>
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<td>animal excreta, following application in summer in</td>
<td>for subsequent modeling development.</td>
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<td>Funded out of Sustainability of Productive Sector Environments SPO</td>
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<td></td>
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<td>3 regions of NZ.</td>
<td></td>
<td>Li</td>
<td>0.8</td>
<td>MAF</td>
<td>2,3</td>
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<td>Lincoln, AgResearch</td>
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<td>Interim report submitted to MAF June 02. Project part of several through NzoNet</td>
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<td>Landcare Research</td>
<td>C09X0212</td>
<td>Reducing Greenhouse Gas Emissions from the Terrestrial</td>
<td>Develop measurement technologies for methane and NO2 emissions on-farm.</td>
<td>Kelliher</td>
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<td>Landcare Research</td>
<td>C09X0212</td>
<td>Reducing Greenhouse Gas Emissions from the Terrestrial</td>
<td>Reduce uncertainty in NZ inventory of N2O emissions from soils by</td>
<td>Kelliher, Sherlock, Buchan</td>
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<td>Biosphere</td>
<td>developing model and management options for reducing emissions.</td>
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<td>Type</td>
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<tr>
<td>Landcare Research</td>
<td>C09X0212</td>
<td>Reducing Greenhouse Gas Emissions from the Terrestrial Biosphere</td>
<td>Improve understanding of processes regulating land-atmosphere GHG exchanges to improve policy and on-ground action.</td>
<td></td>
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<tr>
<td>Lincoln</td>
<td></td>
<td>The enigma of the fate of N-labelled nitrogen applied to soil</td>
<td>Determine how/where unaccounted N occurs.</td>
<td>Sherlock</td>
<td>1.2</td>
<td>Marsden Fund</td>
<td></td>
<td></td>
<td></td>
<td>Part of Marsden funded programme</td>
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<tr>
<td>Lincoln</td>
<td></td>
<td>Sub-soil denitrification</td>
<td>Examine N2O in the soil profile and sub-soil to improve knowledge of indirect emission processes.</td>
<td>Clough</td>
<td>0.3</td>
<td></td>
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<tr>
<td>Lincoln</td>
<td></td>
<td>Investigation into the efficacy of liming pasture as an N2O mitigation strategy</td>
<td>Effect of soil liming on N2O emissions and CO2 emissions. Net effect of liming.</td>
<td>Clough</td>
<td>8.5</td>
<td>Landcare FRST subcontract</td>
<td>Centre for Soil and Environmental Quality</td>
<td></td>
<td></td>
<td>Linked to ‘Reducing GHG emissions from Terrestrial Biosphere’ FRST programme.</td>
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<tr>
<td>Lincoln</td>
<td></td>
<td>Differentiating N2O emission mechanisms from soil utilising isotopomers</td>
<td>Improve understanding of processes and soil management factors that affect N2O emissions.</td>
<td>Buchan, Clough, Sherlock</td>
<td>1.2</td>
<td>Lincoln University, MAF, AgMardt</td>
<td>University of Wollongong, Max Planck Institute Germany (possibly)</td>
<td></td>
<td></td>
<td>PhD project at an early stage.</td>
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<tr>
<td>Lincoln</td>
<td></td>
<td>Determination of the N2O emission factor from animal excreta: NzOnet seasonal/field studies</td>
<td>Establish data to refine NZ's N2O and CH4 inventories: especially emission factor EF3 PR&amp;P.</td>
<td>Sherlock</td>
<td>2.05</td>
<td>ME, MAF</td>
<td></td>
<td></td>
<td></td>
<td>Two regional/seasonal studies completed. Datasets available for N2O model development and validation.</td>
</tr>
<tr>
<td>Lincoln</td>
<td></td>
<td>Production and movement of N2O in sub-soils and indirect emissions</td>
<td>Establish data sets to understand nitrogen in sub-soils and aquifers. Refine N2O inventory and emission factors relating to indirect emissions.</td>
<td>Clough, Sherlock</td>
<td></td>
<td>FRST</td>
<td></td>
<td></td>
<td></td>
<td>Part of larger FRST programme examining N fluxes in grazed dairy systems</td>
</tr>
<tr>
<td>Lincoln</td>
<td></td>
<td>Farm management practices and N2O emissions</td>
<td>Understand implications of on-farm management practices for N2O emissions.</td>
<td>Clough, Sherlock</td>
<td></td>
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<tr>
<td>Lincoln</td>
<td></td>
<td>Organisms responsible for N2O emissions</td>
<td>Determine contribution of bacteria versus fungi on N2O emissions in NZ pastoral systems.</td>
<td>Clough, Sherlock</td>
<td></td>
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<tr>
<td>Lincoln</td>
<td></td>
<td>Verification of N2O mitigation strategies</td>
<td>Establish techniques and/or methodologies that can determine efficacy of mitigation strategy.</td>
<td>Clough, Sherlock</td>
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<tr>
<td>NIWA</td>
<td>C01X0204</td>
<td>Drivers and Mitigation of Global Change</td>
<td>Analysis of socio-economic factors relevant to GHG mitigation options</td>
<td>Lassey, Harvey</td>
<td></td>
<td>AgResearch, Dexcel</td>
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<tr>
<td>NIWA</td>
<td>C01X0204</td>
<td>Drivers and Mitigation of Global Change</td>
<td>Develop techniques and methodologies for GHG emission estimates for grazing ruminants to support mitigation strategy.</td>
<td>Lassey, Harvey</td>
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<tr>
<td>NIWA</td>
<td>C01X0204</td>
<td>Drivers and Mitigation of Global Change</td>
<td>Improving information on NZ emissions of GHG at the landscape and regional scales, to develop GHG inventories.</td>
<td>Lassey, Harvey</td>
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<td>Contributes to the Global Environmental Processes and Change SPO</td>
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<tr>
<td>NIWA</td>
<td>C01X0204</td>
<td>Drivers and Mitigation of Global Change</td>
<td>Improve understanding of evolution of non-GHG source-removal budgets.</td>
<td>Lassey, Harvey</td>
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<td>NIWA</td>
<td>C01X0204</td>
<td>Drivers and Mitigation of Global Change</td>
<td>Characterise the role of stratosphere in climate change, and effect of ozone-related chemistry on climate. Feedback by which</td>
<td>Lassey, Harvey</td>
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Abatement of Agricultural Non-Carbon Dioxide Greenhouse Gas Emissions
<table>
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<tr>
<th>Provider</th>
<th>Programme Id</th>
<th>Programme Title</th>
<th>Objective</th>
<th>Investigators</th>
<th>FTEs</th>
<th>Funders</th>
<th>Collaborators</th>
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<th>Comment</th>
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<td>NIWA</td>
<td>C01X0204</td>
<td>Drivers and Mitigation of Global Change</td>
<td>Recording CO2 in the hemisphere and relationship to climatic factors. Record changes in hemispheric budget of carbon in atmosphere. Validate predictive model for future CO2 levels.</td>
<td>Lassey, Harvey</td>
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<td>Contributes to the Global Environmental Processes and Change SPO</td>
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<td>NZ Forest Research Institute</td>
<td>C04X0206</td>
<td>Advanced Biomass Energy Systems</td>
<td>Design optimal biomass energy system through simulation models for different energy markets.</td>
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Part Three:

Joint New Zealand/Australia Workshop

Research Priorities for Abatement of Non-$\text{Co}_2$
Greenhouse Gas Emissions from Agriculture

A Summary of the Conclusions of the Workshop

10-11 December 2002
Christchurch, New Zealand
Introduction

Australia and New Zealand have unique greenhouse gas emission profiles in which emissions of methane and nitrous oxide from farms and farm animals form the largest single component of the total emissions of both countries. In Australia, production systems (including land clearing) are responsible for over one-third of national emissions, and in New Zealand they represent 55% of total emissions.

As such, the agricultural sector has an important role to play in national responses to reducing emissions. However, at present individual farmers and graziers lack effective tools to abate their emissions in a way that does not impose economic loss.

The principal challenges in reducing emissions include:

- Improving understanding of the factors controlling the emission of greenhouse gases and a better knowledge of the amounts emitted.
- Identifying relationships between agricultural management practices, rates of emission and abatement costs.
- Accounting for the high number of small enterprises employing different management practices with different greenhouse gas profiles.

The level of scientific and technical information relating to these challenges is well below what is needed to design and implement effective abatement, and substantial research and development is needed to identify additional abatement opportunities.

The Australian and New Zealand governments are initiating processes to explore the research needs and priorities for agriculture. Both countries have common interests in this area.

The New Zealand government’s preferred policy is to not charge the agricultural sector for its emissions during the first commitment period (2008-2012) but, in return, it expects the sector to contribute to the cost of the research. In order to develop a research strategy, the government and the Primary Industries Council have appointed Drs John Freney, Marc Ulyatt and Peter O’Hara to undertake a review of recent and current research on methane and nitrous oxide emissions, conduct this Workshop, and prepare a report recommending a strategy and priorities for future research. Thus the conclusions of this Workshop will form an integral part of the Review Team’s final report.

Objectives of the Workshop

The objectives of the workshop are to enable the participants to identify:

- The most promising technologies and management systems that will lead to abatement of methane and nitrous oxide from agriculture in the long-term.
- The research needed to encourage these technologies/systems to be taken up by farmers and graziers.
- The research needed to integrate the abatement technologies/systems into farming practices, land use decisions and regional or national policy making.
- The means of demonstrating that any adopted strategies are producing the expected abatement outcome.
- The research investment priorities.
- The organisational and institutional arrangements that will facilitate the conduct of the research.
- The opportunities for collaborative research within each country, between Australia and New Zealand and with other international organisations.
Opening Addresses

New Zealand

The Honourable Pete Hodgson, Convenor of the Ministerial Group on Climate Change, opened the Workshop. His address follows.

“Today is a very important day for New Zealand in its response to the global threat of climate change.

Two major steps will be taken today. One will be in Wellington, where the Prime Minister, the Rt Hon Helen Clark, will sign New Zealand’s instrument of ratification of the Kyoto Protocol.

The other is right here in Christchurch, with this Workshop and the research programme that will ultimately flow from it.

The people in this room represent many of the world’s foremost scientists in the area of agricultural greenhouse gas emissions. The New Zealand government, along with our co-hosts the Australian government, extend a warm welcome to our guests from around the world. We have representatives from Canada, the US, the UK, the Netherlands, Norway, Brazil and, of course, Australia.

Agricultural non-CO2 gases – methane and nitrous oxide – make up around 55% of all New Zealand’s greenhouse gas emissions. This is the highest proportion of any developed country.

There is therefore probably no country in the world for whom finding practical and measurable ways to reduce these emissions is more important.

Clearly then, policies to address agricultural emissions will be a key component of New Zealand’s response to climate change.

The vital importance of agriculture to New Zealand’s economy was a fundamental consideration for the government as it considered the options. Fifty-six percent of all New Zealand’s export earnings come from agriculture. It is and will remain critical to New Zealand’s economic prosperity.

At one end of the range of policy options for New Zealand was to expose the agricultural sector to the full cost of emissions. In other words, to tax farmers for having sheep and cattle and deer.

That was never a goer, even if we taxed only the increase in emissions over 1990 levels rather than the whole lot. Putting a tax on the engine room of our economy for no gain would be silly. Besides which, measuring emissions at the individual farm level is so difficult and costly that we would never be able to verify anyone’s attempt to reduce their farm’s emissions per stock unit.

At the other end of the range of policy options was the possibility of doing nothing. But this government takes the view that climate change is everyone’s issue and every sector must do something to address it.

How then to address agricultural greenhouse gas emissions positively, while maintaining an internationally competitive agricultural sector?

The government’s answer is that the agricultural sector will be exempt from price measures for methane and nitrous oxide, provided that an adequate research effort aimed at mitigating these emissions is undertaken.
Helping to make this research as effective as possible is the principal reason for this Workshop.

New Zealand already has some of the best understanding of the agricultural non-CO2 greenhouse gases under pastoral grazing systems.

If there is scope to reduce these emissions in a sustainable and economically efficient way, we must develop it and implement it. The Kyoto Protocol provides direct financial incentives for doing so.

We also know that reducing agricultural non-CO2 emissions can have significant co-benefits. Reducing methane can lead to increased food conversion efficiency from animals, and any such gains would go straight to the farmer's bottom line. Similarly, better management of nitrogen in the agricultural system can reduce leaching to waterways and the associated environmental issues are therefore directly addressed.

For these reasons New Zealand will commit significant resources over at least the next decade to identifying, researching, developing and disseminating technologies that reduce agricultural greenhouse gas emissions.

This is no simple task. It will take a substantial and sustained effort. And it is critical that this effort be well directed from the outset. We do not have time or resources to waste.

This workshop will be a crucial input into developing a research strategy for New Zealand. We hope it will also provide a solid basis for further cooperation and collaboration between researchers and policy-makers around the world. We need a hard-headed approach, weighing cost and time and the practicality of implementing the results.

We hope too that participants will take home information that will help inform the research efforts of their countries, so that the international effort to address this significant area of greenhouse gas emissions is strengthened.

The prospect of greater cooperation and collaboration is one reason why New Zealand was delighted to accept the Australian government’s offer to co-host this Workshop. We welcome this initiative as a tangible example of the close partnership between New Zealand and Australia over climate change issues. I am confident that this partnership will grow over time and add considerable value to both countries’ responses to climate change.

The terrible drought situation in Australia reminds us all of the possible negative consequences of climate change, and why it is so important that all countries do what they can to address it.

New Zealand is willing to explore areas of cooperation with any country. We have already taken steps to cooperate with the US under a framework agreement.

Of course, cooperation and collaboration have always been something scientists are renowned for. Another important outcome of this Workshop will be the ongoing relationships that will no doubt be formed from it.

I wish everyone here a most successful two days. I hope that you can also take some time to enjoy the beautiful city of Christchurch, and as much of the rest of New Zealand as you are able.

It is my pleasure to formally open the proceedings of this very important Workshop.”

Australia

The following is a summary of the presentation by Dr David Ugalde, Manager Greenhouse Science and Agriculture, Australian Greenhouse Office.
Greenhouse and Agriculture in Australia

Australian Agriculture: Social and Economic Importance

- Agricultural output worth $AUD 30 billion per year, over half exported
- 140,000 enterprises in agriculture, covering about half of Australia’s land area
- Over 400,000 people employed in agriculture
- Agriculture supports rural and regional communities

Issues for Greenhouse in Agriculture and Land Management

1. Projections of climate change
2. Impacts and adaptation
3. Emissions reduction
4. Forestry and sinks
5. Federal, State, industry and community partnerships

Emissions Projections to 2010

Estimated Emissions by Sector in 2000 (UNFCCC Accounting)

National Carbon Accounting System (NCAS)

Forest Conversion and Carbon Change Comparison

National Carbon Accounting System (NCAS) Non-CO₂

- Developing an operational capability:
  - Based on current state of knowledge
  - Builds on existing carbon cycling/emissions capability
  - Step 1: Build robust N-cycling accounting methodologies as a parallel to C-cycling
  - Step 2: Calibrate emissions (types):
    - Various models and methods to be considered
    - Additional, targeted emissions monitored
    - Define sensitivity responses

Estimated Non-CO₂ Emissions from Agriculture in 2000
Cross-jurisdictional & State and Territory Activities for Greenhouse and Agriculture
- Council of Australian Governments High Level Group on Greenhouse
- Greenhouse in Agriculture and Natural Resource Systems Working Group under the Land, Water and Biodiversity Committee (Natural Resource Management Ministerial Council arrangements)
- State and Territory greenhouse strategies and programs

Commonwealth Activities for Greenhouse and Agriculture
- Forward Strategy on Greenhouse and Climate Change
- Commonwealth Agriculture Working Group
- Prime Minister’s Science, Engineering and Innovations Committee – Beyond Kyoto Working Group
- Recommendations: Impacts and Adaptation, and Emissions from Energy, Transport, and Agriculture & Land Management
- National Research Priorities
- National Greenhouse Science Program
- Science and Agriculture program in the AGO
- CRC for Greenhouse Accounting (non-CO₂ emissions)

Forward Strategy - Four Guiding Elements -
- Strive for a more comprehensive global response to climate change
- Position to maintain a strong and internationally competitive economy with a lower greenhouse signature
- Domestic policy settings will balance flexibility with sufficient certainty to allow key decisions on investment and technology development, and also emphasise cost effectiveness
- Implement policies and programs that assist adaptation to the consequences of the climate change that is already unavoidable

Draft National Plan for Greenhouse and Agriculture: Key Elements
- To improve understanding of impacts of climate change on agriculture and managed ecosystems, and to identify and implement adaptive response measures
- To improve understanding of greenhouse gas emissions from agriculture, and to identify and implement opportunities for cost-effective abatement
- To identify opportunities for integrating greenhouse action and natural resource management outcomes
- To build coordination and capacity to deliver effectively on greenhouse and agriculture

Theme 2 Priorities: Reducing Emissions for Production and Environmental Benefit
- Modelling and decision support
- Adoption of BMP
- Carbon sequestration
- Bioenergy
- Methane from enteric fermentation
- Nitrous oxide
- Energy Use
- Market approaches
- Targeted solutions

Theme 3 Priorities: Integration and Capacity Building
- Coordinated government policies and programs
- Industry partnerships
- National research program
- Integrating greenhouse action and sustainable land management
- Integrating greenhouse action and EMS
- Information, education, skills and training
- Public awareness and acceptance

Challenge for Reducing Emissions from Agriculture
- What are the Drivers to reduce emissions of greenhouse gases from agriculture?
- What will be the Motivation for farmers to reduce emissions of greenhouse gases for the benefit of all?

New Zealand - Australia Partnerships
- Opportunities
  - Joint research agenda to address common goals
  - Sharing of expertise and resources
  - Sharing of outputs from research efforts
  - Collaborative approaches for implementation
- Opportunities for an Australia – New Zealand Climate Action Partnership

Mechanisms to Link Greenhouse Reductions to Other Drivers
- Key drivers
  - Environmental Management
  - Productivity
  - Food Safety
- Loss of greenhouse gases from agriculture is a loss of valuable resources from the production base.
- Reducing greenhouse gases has the potential to provide environmental, production, social and regional benefits.
- A challenge for this workshop is to focus on delivering solutions for multiple benefits.

Workshop Outcomes: Australia’s Expectations
- Realistic research priorities to reduce emissions of methane and nitrous oxide from agriculture and land management systems
- Stronger networks for research collaboration
- Better opportunities for implementing these research outcomes
Introductory Papers

The following are summaries of the three introductory papers. Their purpose was to set the scene for the Workshops that followed their presentation.

New Zealand's Greenhouse Gas Emissions and the Contribution from Agriculture – Dr Peter O'Hara

In 2000, the official estimates of New Zealand’s greenhouse gas emissions showed that methane and nitrous oxide represented 59.6% of total emissions in CO₂ equivalent terms, and emissions from agriculture were 55% of total emissions. Compared to 1990, methane emissions were 6.17% less, a fall largely attributable to the fall in sheep numbers, and nitrous oxide was 6.35% more.

The most important source of agricultural methane is ruminant enteric fermentation (98.7%). The most important sources of nitrous oxide are faeces and urine deposited by grazing animals on pasture, animal waste and fertiliser nitrogen in soils, and indirect emissions from atmospheric deposition and leaching. The use of nitrogen fertiliser is increasing at an exponential rate.

Research is leading to the adoption of revised models for estimating methane and nitrous oxide emissions that take into account animal numbers, animal productivity and New Zealand specific emission rates that are based on empirical data. In the decade 1990 to 2000, productivity gains have been significant, particularly in the dairy and sheep industries. The effect of the revised methodology is to show that the official estimates understate emission rates and that there is a rising linear trend in these rates. Extrapolation of the curves to 2010 indicates that methane emissions will exceed 1990 levels by 15.7% in gross terms, and nitrous oxide emissions will exceed 1990 levels by 20-30%.

Emission rates are most sensitive to changes in total animal numbers and to productivity. An emerging policy question is how the trade-off will be made between that national objective of maintaining emissions at 1990 levels and individual farmer’s objectives for the performance of their livestock. A number of abatement strategy options may confer productivity advantages as well as reduced emissions.

Current and planned research is directed at:

- Extending the range of methane emission measurements from animals.
- Improving the measurements of nitrous oxide release from excreta under a variety of soil and seasonal conditions.
- Improving the assessment of indirect emissions.
- Improving (or selecting) the models that can be used to estimate emissions in the future leading to robust estimates that conform with IPCC good practice.
- Developing methodologies that allow broad scale assessments of herbage quality and paddock/farm/locality emissions.
- Understanding the basis of enteric ruminant methane production and how to control it. It is particularly important that methods can verify that any abatement strategies adopted in the future are delivering the expected effects.

Reducing Nitrous Oxide Emissions from Agriculture – Dr John Freney

In response to nitrogen applied in the form of animal excreta, fertiliser, crop residues, biological nitrogen fixation and other human-related activities, soils produce nitrous oxide through the processes of nitrification and denitrification. Each year in New Zealand, 12.1 Gg of N₂O-N comes directly from dung and urine deposited during grazing, and 2.4 Gg of N₂O-N is emitted directly as the result of fertiliser application. Indirect emissions include 2.8 Gg
N₂O-N from the deposition of volatilised ammonia, and 5.7 Gg come from leaching and run-off of water containing nitrates.

Procedures proposed in the literature for reducing the emission of N₂O from animal nitrogen sources include: manipulation of the diet by feeding proteins with reduced degradability and increasing soluble carbohydrate levels; synchronising the availability of nitrogen and soluble carbohydrate in the rumen, including condensed tannins in the diet and grazing animals on grasses with high soluble carbohydrate levels.

Nitrous oxide emissions from fertiliser can be reduced if the efficiency of fertiliser use is increased. This can be done by matching fertiliser supply to crop demand, integrating animal and crop production, maintaining crop residues on-site, using a range of advanced fertiliser techniques, and optimising tillage, irrigation and drainage.

The indirect emissions from ammonia deposition and nitrate leaching would also be controlled by adopting such procedures.

It is apparent that the easiest way of reducing nitrous oxide emissions is to reduce the amount of nitrogen added to soil. This is much more effective than trying to control the individual processes in the complex biological systems that produce nitrous oxide, and it leads to all forms of nitrogen pollution being controlled at the same time.

**Past and Present Research on Methane Emissions – Dr Marc Ulyatt**

Methane is produced in the rumen by a consortium of microorganisms that combine to degrade feed into a range of products including volatile fatty acids, amino acids, ammonia, carbon dioxide and hydrogen. Methanogens of the family archaea reduce carbon dioxide with the hydrogen, thus maintaining low partial pressures of hydrogen which would otherwise depress digestion.

Several major nutritional factors are known to have an influence on methane emission. Methane emission increases with feed intake, but the relationship is not strong because of the high degree of variation between individual animals. However, there is a stronger negative relationship between methane emitted per unit of feed intake and feed intake. So there is an advantage, in terms of methane emission, to feed animals on as high an intake as possible. It is generally accepted that digestion of cell wall carbohydrates produces more methane than the digestion of soluble carbohydrates. Protein and lipids appear to have a negative effect on methane production, but the effects are variable, and in the case of lipids toxicity to the rumen microbes can be a problem.

Many technologies have been proposed for mitigating ruminant methane emission. Livestock numbers are the major determinant of emission at the national scale. While it might be considered politically naive to advocate reducing livestock numbers, sheep farmers over the last 15 years have reduced numbers by 33% without compromising total production. This shows that farming has the inherent flexibility to respond to a meaningful economic incentive.

There are possibilities for reducing methane via improvements in animal efficiency. All animals have an obligatory maintenance requirement that results in no production, yet has an associated methane emission. The strategy must be to dilute the effects of maintenance by various measures such as increasing feed intake, manipulation of dietary composition to increase feed quality (e.g. decrease cell wall carbohydrate), or increasing metabolic efficiency and genetic improvement. Dairy cows that have been selected for feed conversion efficiency have been shown to produce less methane. These efficiency improvements should form the basis for on-farm strategies to reduce methane in the short to medium-term.

A wide range of feed additives have been proposed to reduce methane. These include alternative hydrogen acceptors (e.g. malate, fumarate), halogenated methane analogues (e.g.
chloroform, bromoethanesulphonic acid), antibiotics (e.g. monensin, mevastatin), defaunating agents (e.g. manoxol, teric), and probiotics, bacteriocins and naturally occurring plant compounds (e.g. condensed tannins). There are problems with these compounds such as toxicity to the microbes and the animal, short-lived effects due to microbial adaptation, volatility, expense and failure to meet consumer acceptance. With grazing animals, other than dairy cows, a delivery system would be required to ensure regular delivery into the rumen. Delivery by breeding into pasture plants is possible, but the time needed to get a viable plant established in the national pasture should not be underestimated. None of these additives is used routinely to reduce methane emissions at present.

Immunisation of animals against methanogens has been suggested by Australian scientists. This is a good concept, but we are still a long way from the delivery of an efficacious vaccine.

There are many possibilities available for manipulating the rumen microbial ecosystem to achieve methane reduction. These include targeting methanogens with microbial antibiotics, bacteriocins or phage, removing protozoa and developing alternative sinks for hydrogen such as acetogenic bacteria. Development of mitigation technologies from this type of research is well in the future because of the need to first understand the complexities of the rumen microbial ecosystem.

Investment in research into methane mitigation should cover a suite of technologies that range in their potential delivery time from short-term (on-farm systems research) to long-term (rumen microbial manipulation). A successful technology will deliver a win/win result with respect to methane reduction and increased animal production.

Each of the technologies discussed was evaluated for its potential to reduce methane at the farm level over the next 10 years. The maximum abatement potential obtained from published data (expressed as a rate between 0 and 1) was multiplied by an assessed rate of adoption by farmers (scale 0-1) to give a potential reduction over 10 years. On this basis it was concluded that farm-scale systems studies based on existing knowledge (e.g diet manipulation of animals) offered the best prospects for short-term abatement of emissions. However, selection for between-animal differences and rumen microbial manipulation offered the best prospects in the medium and long-term respectively.

**Similarities and Differences in the Non-CO2 Greenhouse Gas Emission Profiles of Australia and New Zealand:**

While the majority of the outcomes of the Workshop are related to the common interests of Australia and New Zealand in the abatement of agricultural greenhouse gases, there are features of the emission profiles that are unique to each country and may require specific and local solutions.

As compared to New Zealand agriculture, the differences in Australian agriculture that are likely to be significant in requiring recognition in the National Inventory and/or requiring specific solutions include:

- The higher proportion of agricultural land devoted to cropping, particularly extensive dry-land cropping and cropping under irrigation.
- The prescribed burning of savannas as a source of methane and nitrous oxide
- Rice cultivation
- Differences in the nature of pastoral agriculture – terrain, rainfall, forage species.

These differences are reflected in the conclusions of the Workshops. Notwithstanding these differences, there are many areas of research where the interests of both countries are common and where cooperation and collaboration can be fruitful.
Workshops on Research Priorities

Workshops to examine the priorities for research on methane and nitrous oxide were set up. Each Workshop was asked to consider the following criteria in developing their views on priorities:

- **Effectiveness**
  - abatement potential?
  - is the data good enough?
- **Risks to plants, animals, soils, environment (e.g. any toxicity?)**
- **Acceptability of technology - by farmers, by consumers, wider public?**
  - Will farmers incorporate the technologies in farming practice? Economics - benefits compared to costs? Is it a convenient, feasible delivery system?
- **Research effort required**
  - What sort of research?
  - Cost and funding?
  - Time, rate of progress?
  - Likelihood of success?
- **Commercial opportunities, intellectual property?**

The Workshops also were also asked to categorise research in the following terms:

- **Fundamental studies** intended to develop better understanding of processes that might create future abatement options.
- **Currently identified abatement technologies and processes.**
- **Research** that will improve the measurement of greenhouse gases and enable verification of abatement of emissions.

Development of priorities included an exercise in ranking the abatement potential of each technology considered against technical feasibility for development, and the technology uptake/ adoption potential against public acceptability of the technology.

Reducing Nitrous Oxide Emissions from Agriculture

Chairman: John Freney
Rapporteurs: Kevin Tate, Chris Smith
Facilitator: Rhys Taylor

The Chairman outlined the purpose of the Workshop as follows:

1. Consider the opportunities for reducing the emission of nitrous oxide from agriculture and the linkage between nitrous oxide and methane emissions.
2. Will reducing nitrous oxide emissions increase methane emissions?
3. Comment on the prospects for developing practical measures for reducing nitrous oxide emissions from agriculture.
4. Identify the best opportunities and research priorities in terms of abatement potential and estimate the potential for success.
5. The information should enable the costing of the research and define the best institutional arrangements for its conduct.

The following list of approaches was discussed and amended by the participants:
Sources and processes
1. Fundamental work on the processes responsible for the production of nitrous oxide, its transformation and transfer.

Strategies for Emission Reduction
1. Animals - diet manipulation
2. Animals - reduce nitrogen in excreta or shift the balance between dung and urine in favour of dung
3. Farm management of dairy effluent
4. Feed livestock on pads in winter
5. Soil structure - optimise tillage, prevent compaction
6. Manage soil water - irrigation, drainage
7. Manage soil pH so that nitrogen is emitted as N₂
8. High sugar grasses
9. High condensed tannin grasses
10. Optimise nitrogen use by plants
11. Fertiliser timing, rates of application, tighten flow cycles
12. Nitrification inhibitors
13. Run-off management, riparian zones, drainage ditches, reed beds.

Measurement, inventory and verification
1. Inventory - need to know the relative importance of the various sources and the uncertainty attached to each.
2. Methods to determine the effectiveness of the various options - chambers, micrometeorological, modeling.

The international visitors were asked to comment on the amended list in the light of their experience in their own country. The Workshop then undertook the evaluation of the list according to the abatement potential versus technical feasibility and the adoption versus acceptability criteria. This enabled a number of approaches to be discarded and linkages to be drawn.

Resulting from this prioritisation process, three farming systems and associated technologies were identified, namely:

a) Cropping
b) Intensive livestock
c) Extensive livestock.

Technologies appropriate to each system were identified as follows:

Cropping systems
1. Optimise tillage methods and timing to prevent soil compaction.
2. Match nitrogen supply with plant requirements by timing the application of fertiliser, adjusting the rate of application, changing fertiliser type to suit climatic conditions, injecting fertiliser rather than applying it to the soil surface, using slow release fertilisers and linking soil testing and weather data/water management with fertiliser application.
3. Use nitrification inhibitors to keep nitrogen in the ammonium form.
4. Optimise crop residue management taking into account crop rotation, green manures and burning.
5. Develop decision-support systems for farmers that take into account production, market and environmental parameters.
6. Methods are required to determine the effectiveness of the suggested options and to reduce the uncertainty attached to the size of the various sources.

7. Economic analysis of the feasibility of the various options.

**Intensive animal systems**

1. Manipulate the diet to reduce nitrogen in excreta or shift the balance toward dung and away from urine.
2. Manage livestock to contain excreta and reduce leaching.
3. Keep animals on feed pads during autumn and winter when soils are wet.
4. Select pasture species for condensed tannins.
5. Research the use of riparian zones and drainage ditches to reduce the leaching and run-off of nitrate. Determine whether these areas are sources or sinks for nitrous oxide.
6. Study the movement of agricultural nitrogen into rivers, estuaries and oceans.
7. Study the optima for each farming system to determine the balance between yield and emission.
8. Develop methods to determine the effectiveness of the various abatement options.
9. Improve the efficiency of fertiliser nitrogen use in producing forage.

**Extensive livestock systems**

1. Develop flexible, holistic model of farming system/enterprise that includes production, market and environmental issues.
2. Consider land use changes.

In reviewing the draft report of the Workshop, Dr Arvin Mosier added the following comments:

“Following are a few topics that I would like to see emphasised a bit more strongly, although they are generally mentioned in the report (comments are applicable to both New Zealand and Australia):

1. Development of an integrated trace gas flux and soil carbon sequestration programme across the major agricultural systems (CO₂, CH₄, N₂O and total/net GWP) should be encouraged. This involves using comparable techniques where applicable across the different parts of the agricultural sector. The approach should integrate process based modeling (see comment 3). Where possible, conduct a set of measurements across a variety of scales (meters to regions) to provide data on which to validate model scaling. Both Australia and New Zealand have done this to some extent and these efforts should be applauded and utilised.

   Hopefully the current research funding situation, which dictates competition for funding, will not get in the way of the interdisciplinary, collaborative research efforts that are needed.

2. Wherever possible, integrate the greenhouse gas programmes with soil and water quality research.

3. Evaluate the impact of management strategies imposed to mitigate greenhouse gases with selected measurement and process based modeling programmes (suggest using two different models at the same time until the uncertainty of model results is greatly reduced from the current state-of-the-art). It is easy to discuss changes in management to theoretically reduce gas emissions, but much more difficult to verify that the changes do occur. There are currently few data to compare different livestock and crop management scenarios.

4. In both livestock and cropping systems there was little discussion of nitrogen budgets. Since N₂O emissions are only a very small part of the nitrogen budget, altering…"
management to decrease the immediate or direct emissions from a pasture or field may lead to greater nitrogen leaching or indirect N₂O emissions (N₂O produced in ground water, ponds, streams, rivers, oceans from nitrogen leached or volatilised from land areas) at some later time. I heard some discussion of very low nitrogen run-off from pastures in New Zealand, for example, and it seems difficult to believe that most of the nitrogen deposited on a pasture located on a steep slope during the wet season stays on the pasture. The data to support these observations may be very good, but I think it is important to determine if the correct kind of studies have been made to evaluate volatilisation and run-off of nitrogen from systems that are difficult to maintain and manage. A good nitrogen budget for the main systems at the field to farm basis would be quite useful.

Another example of where good nitrogen budgets are needed is the change in livestock diet to shift the nitrogen in excreta between urine and dung. This technique makes sense for limiting the immediate NH₃ emissions and N₂O production. What happens to the nitrogen in the dung later on?

5. Evaluate the fate of nitrogen and N₂O emissions in on-farm ditches and riparian areas. It is likely that a good deal of nitrogen is processed in such areas and we have little knowledge of the final fate of the nitrogen or how much N₂O is produced.

6. The concept of farm land use management to optimise production on the most productive part of the land and the use of the most non-productive lands to grow energy crops (e.g. trees, switch grass) seems an interesting approach to the net GWP problem. The extent of applicability and acceptability of such concepts may be limited.

7. Exploit farmer collaboration to conduct whole farm net GWP and economic evaluation.

8. On page 16 of the report under ‘Inventory verification’ the statement “Models to be process based and aim for 5% uncertainty” is a laudable goal, but it is highly unlikely that it could be reached. Performing on-site verification is even more unlikely.

Reducing Methane Emissions from Agriculture

Chairman: Marc Ulyatt
Rapporteurs: Harry Clark, Roger Hegarty
Facilitator: Ian Whitehouse

A provisional list of topics was provided by the Chairman as follows:

Sources and processes
1. Manipulation of the rumen ecosystem
2. 16 S r RNA probes.

Abatement technologies
1. Reduction of livestock numbers
2. Improving efficiency - feed intake, diet manipulation
3. Animal genetic improvement
4. Feed additives - inhibitors
5. Naturally occurring inhibitors
6. Immunisation
7. Farm-scale abatement systems.

Inventory, verification
1. SF₆ tracer technology
2. Feed intake estimation.

The Workshop participants added the following topics:

1. Exploit host/microbe interactions
2. Alternative land use
3. Understanding stoichiometry
4. Farm decision-support models and systems
5. Verification techniques
6. Product quality issues
7. Performance enhancers
8. Inventory methodology
9. Dilution of maintenance requirements
10. Biocontrol of protozoa and methanogens
11. Alternative electron sinks and acetogenesis
12. Animal waste management
13. Fire management
14. Rice management

These additional topics were combined with the provisional list in accordance with the three headings. The Workshop then undertook a ranking analysis considering abatement potential, feasibility, acceptability and likelihood of adoption described above. From this exercise the Workshop identified the top five priority areas and elected to devote further discussion to them. They were:

1. Rumen manipulation
2. Diet manipulation
3. Animal breeding
4. Farm-scale management systems and modeling
5. Inventory and verification matters.

Rumen manipulation

- Rumen microbial inhibitors offer potential solutions in the medium to long-term. Safe alternatives are needed.
- Defaunation is a reasonable approach in the short-term but new methods are needed to avoid toxicity. A combined strategy of defaunation and enhancement of acetogenic activity is worth following. Partial defaunation is a possibility – saponins may be effective.
- Acetogen enhancement as an alternative hydrogen acceptor is a medium to long-term possibility. Linked to inhibition of other organisms. Identification of competitive acetogens – look in other species e.g. kangaroos.
- Immunisation – the first commercial release is planned for 2008 with second generation products to follow closely. Linked to use of inhibitors to depress methanogenesis.
- Biological control – there are many options. Likely to be used in a combined strategy with inhibitors. Long-term.
- Organic acids – large dose required, therefore an issue is how to deliver the required dose. Not suitable for delivery via forage plants because of the high dose requirement. Products are available now but high cost.
Diet manipulation

- Increased feed intake by incorporating alternative plants species (medium/long-term), or genetic manipulation of current plants (long-term), changing agronomic practices (short-term), increasing legume content (short-term).
- Investigate alternative sources of soluble carbohydrate including concentrates (short-term).
- Nutrition to select for preferred rumen microbes (long-term).

Animal genetics

- Breeding may be the best way to improve methane emissions in the extensive production industries (long-term). Understand the genetic basis of traits that might lead to reduced methane production (long-term).
- Support programmes that promote improved animal efficiency (medium-term).

Farm-scale management of methane emissions

- Education is vital. Convince farmers that there is a problem. Extension is as important as research to encourage farmers to change practices. Implement change through networks such as monitor farms. Aim at developing on-farm inventories of carbon dioxide, nitrous oxide and methane.
- Decision-support models essential.
- Encourage Australia/New Zealand collaboration in modeling.

Inventory, verification

- National, regional and farm-scale inventory models (medium-term). Verification of abatement. Models to be process based and aim for 5% uncertainty.

After completing this prioritisation process, the Workshop concluded that the top priorities in descending order were:

1. Rumen manipulation
2. Inventory verification
3. Animal genetics
4. Diet manipulation
5. Farm-scale management systems.

NOTE: The results of the poll to determine the top priorities are likely to be biased by the scientific interests of the participants in the vote.
Conclusions on Strategic Issues

Participants in the Workshop arranged themselves in five groups to consider five strategic issues. The purpose of the Workshop session was to give another perspective on priorities from a different mix of the experience of the participants. Each group was asked to give their top 3-5 priorities. The questions and the responses follow.

Question A: What combination of technologies for reducing carbon dioxide, methane and nitrous oxide will produce the best overall reduction in emissions?

- The increased use of feedlots offers better waste management options (nutrient re-cycling, energy source), better utilisation of feed, and the opportunity to introduce additives that modify emission processes.
- In grazing ruminants, highly digestible forages with a balance of carbohydrate and protein.
- Targeted land use (precision farming) with intensification where suitable land is available. Whole farm models to assist decision making.

Question B: What are the needs for the successful uptake of abatement strategies in farming systems – skills, expertise, tools? Provide a farmer’s perspective and a researcher’s perspective.

- Uptake of appropriate technologies depends on farmer awareness of climate change issues. Farmer organisations need to put them at the top of their agenda. Government support of awareness programmes is essential.
- Uptake requires farmer education, the development of best management practices and environmental management codes and on-farm demonstrations.
- Education should offer principles, not recipes, and show economic and market access benefits. Results must be measurable.
- Benefits to farmers include increased profit, reduced costs, less labour, reduced environmental impact and an improved lifestyle.
- Researchers require the same awareness as farmers in addition to knowledge of the factors most important to farmers.
- Tools include decision-support systems and models and learning packages.

Question C: What combination of technologies offers the best chance of modifying ruminant CH₄ output and nitrogen excretion without compromising animal performance?

- Management systems to maintain high feed quality and re-focus towards legumes.
- Feed balanced diets that limit the nitrogen surplus to animal/ rumen microbe requirements and favour a low fibre/high soluble carbohydrate profile. Possible role of condensed tannins in modifying CH₄ output and protein digestibility. Such diets are likely to increase intake and animal performance.
- Rumen microbe modification/immunisation strategies combined with diet modification. Shift rumen environment to favour acetogens and reduce ammonia producers.
- Optimise nitrogen fertiliser use in accordance with rainfall and plant growth requirements.
- Effective extension to land users.

Question D: What research is needed to optimise the management of the nitrogen cycle in farming systems to minimise N₂O emissions? Consider the best option for each system considered.
• Generic problem, but with many site-specific controlling factors requiring concentrated, integrated, multi-site (themed) experiments designed to contribute data to a centralised modeling/analytical facility. Protocols for measurement, data storage and data sharing are needed to ensure compatibility of data with model parameters.
• Model synthesis requires an interactive sequence of modeling current knowledge, and scenario analysis to identify knowledge gaps followed by experimental work to fill the gaps and to test the model’s output in the field. For example:
  − quantification of N₂O emissions related to nitrogen application to wheat - is the relationship linear?
  − nitrous oxide emissions from grazed pastures.
• Mechanistic and decision-support models must include economic parameters.

*Question E: What research is needed to ensure that national inventories can accurately reflect the results of the adoption of abatement strategies?*

• Simple on-farm techniques for GHG measurements.
• Inventory methodologies that capture the major drivers of emissions and the impacts on these of abatement factors that take account of spatial and temporal variability.
• Scaling techniques that enable on-farm models to refine the national inventory models.
• Robust data, uncertainty estimates.
A Summary of International Experience

A panel discussion moderated by David Ugalde sought to summarise the experience of other countries represented at the Workshop in developing national responses to the issue of greenhouse gases. The UK and Canada have used a workshop approach to identify the key elements of a national mitigation strategy. The UK Workshop is being written up at present.

Canada followed their Workshop with an intensive period of policy analysis and development spear-headed by a small committee that met regularly to review progress and set direction. Targets for national GHG emissions reductions have been defined and criteria established for all sectors regardless of how small their contribution to the national totals. The Canadian government has provided $21,000,000 for a national farmer-led awareness campaign.

The Netherlands adopted a scientist-led systems analysis of all agricultural sectors to identify abatement options for nitrous oxide. Each option was evaluated against criteria that included abatement potential cost-effectiveness, risks, likely adoption rate and the capacity to verify that abatement is obtained. The priority criteria are based primarily on abatement potential.

The US programme is focused on carbon budgeting and little attention is being devoted specifically to greenhouse gases. It was noted that the American public are likely to place higher priority on health issues such as air pollution (ammonia, PM 2.5) and environmental problems such as nitrogen leaching. A recent meeting in Washington concentrated on carbon sequestration and GHG emissions from cropping. The conference theme emphasised the need to consider the environmental impacts of agricultural systems as a whole.

Keith Smith emphasised the need to distinguish between the precise requirements of research and inventory models and the capacity to make incremental gains even though knowledge may be imperfect.

David Scholefield believes that modeling supported by collaborative research to obtain multi-site data holds the key to a concerted research approach. Tim McAllister argued for ensuring research that is clearly long-term is funded for the long-term.

Magda Aparecida de Lima noted that Brazil has employed IPCC default values to construct its National Inventory to date. Ninety-two percent of Brazil’s agricultural methane emissions are from enteric fermentation, and for this reason a programme of research was begun in 2000 to develop country-specific emission factors.
Final Communiqué

The communiqué issued by the New Zealand Ministry of Agriculture and Forestry and the Australian Greenhouse Office follows:

“Australian and New Zealand scientists lead the way in agricultural emissions reduction research

A joint New Zealand and Australia Workshop, held over the past two days in Christchurch, has identified a range of research priorities for reducing emissions of greenhouse gases from agriculture and land management.

Both countries share similar issues in emissions of greenhouse gases from agriculture and both have economies heavily dependent on agricultural production. In New Zealand over half of total greenhouse emissions are a by-product of agricultural production, and in Australia 20% of emissions are likewise from agriculture. Both countries have a deserved reputation for world-class agricultural research, and there are real benefits for both countries to work more closely on addressing this issue.

The Workshop was co-sponsored by the New Zealand Ministry of Agriculture and Forestry, New Zealand's Primary Industries Council, and the Australian Greenhouse Office. Some of the world's foremost scientists in agricultural methane and nitrous oxide research came together for this Workshop. It provided opportunities for New Zealand and Australian scientists, and scientists from Canada, the US, the UK, the Netherlands, Norway and Brazil to share up-to-date approaches and the most recent scientific and technological knowledge.

The Workshop was timely as it coincided with a new phase in the New Zealand climate change programme, with the ratification of the Kyoto Protocol by the New Zealand Prime Minister last night. The New Zealand government has identified research to reduce agricultural emissions as a key part of its policy to meet New Zealand's commitments to reduce emissions under the Kyoto Protocol.

It also is timely for Australia, providing advice to the development of the Forward Strategy for Greenhouse and Climate Change - which is to set directions for greenhouse and climate change in Australia over the next 20 years. Last Thursday, the Australian Prime Minister's Science, Engineering and Innovations Committee recommended to the Australian Cabinet the need for greater research into agricultural emissions. The outcomes of the Workshop provide directions for the way forward.

Joint research developed at the Workshop covers areas that are common to both Australia and New Zealand, as well as areas that are specific to the needs of each country individually. For instance, New Zealand hill country offers unique challenges for measuring and reducing nitrous oxide emissions. Australia's cropping systems and extensive rangelands offer different challenges. But in many ways, the scientific approaches needed to address all opportunities for reducing greenhouse gas emissions from agriculture are similar.

This Workshop represents a real practical opportunity for closer partnership between the two countries to jointly explore ways to reduce emissions. Also coming out of the Workshop, both countries have identified science network coordinators and opportunities for future collaboration.”
Networking

An initiative to maintain contacts established by the Workshop has led to the establishment of a network. The New Zealand connection will be maintained by Dr Harry Clark (harry.clark@agresearch.co.nz) and Dr Tim Clough (clough@lincoln.ac.nz). The Australian link will be through Dr Richard Eckard at the newly established Climate Change CRC, University of Melbourne (rjeckard@unimelb.edu.au).

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