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A review of SLMACC agricultural greenhouse gas mitigation projects

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A review of SLMACC agricultural greenhouse gas mitigation projects

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Contents

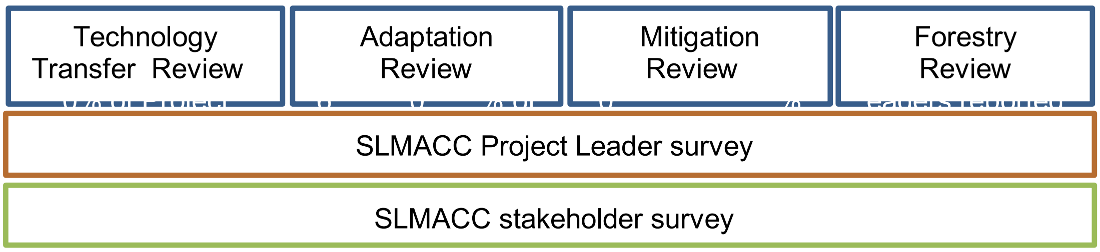
Executive Summary

Background

The Sustainable Land Management and Climate Change (SLMACC) research programme ('fund') was created in 2007 and has been administered by the Ministry for Primary Industries (MPI). Between 2007 and 2018 the fund has invested more than $51 million into research that aims to address impacts of, and adaptation to, climate change, mitigation of agricultural greenhouse gases (GHG), and improvements of forest sinks. To assess the effectiveness of the investment, MPI commissioned reviews of different components of the SLMACC funding programme.

This report covers the review of the $17 million of 'Mitigation' research funded by SLMACC (2007 – 2017). It was conducted jointly by AgResearch Ltd and Motu Economic and Public Policy Research, and is one of four primary reports and a survey results report for the SLMACC review. These reports are intended to be read in conjunction:

1) Adaptation Review (Cradock-Henry, Flood, Buelow, Blackett & Wreford, 2018)
2) Mitigation Review (van der Weerden, Jonker, Fleming, Prescott, de Klein & Pacheco, 2018)
3) Forestry Review (Dunningham, Grant & Wreford, 2018)
4) Technology Transfer Review (Payne, Turner & Percy, 2018)
5) Project Leader and stakeholder survey results (Payne, Chen, Turner & Percy, 2018)



Accompanying this mitigation research review is also an analysis of the impact and value for New Zealand agricultural mitigation research using two specific SLMACC projects as case studies (Fleming and Preston, 2018).

Objective of this Review

The objective of this review was to evaluate the impact of the SLMACC agricultural GHG mitigation research programme in relation to developing options for reducing on-farm enteric CH_4 and N_2O emissions; to identify science gaps; to identify barriers and enablers of adoption; and to provide recommendations for improvements to the SLMACC fund for agricultural GHG mitigation.

The mitigation projects aimed to develop a range of options for reducing agricultural enteric methane (CH_4) and nitrous oxide (N_2O) emissions, which account for 49 percent of New Zealand's greenhouse gases.

The review grouped projects into five general mitigation options, or 'clusters'. The five clusters were:

- ***CH_4 inhibitors/vaccines***: these projects aimed at discovering and developing compounds or antibodies to inhibit growth of microbes in the rumen (the first stomach of ruminants), called methanogens, that are responsible for CH_4 production in farmed ruminant animals such as cattle, sheep and deer.
- ***Low GHG animals***: these projects sought options to breed animals that emit less methane (e.g. low CH_4 sheep).
- ***Low GHG feeds***: these projects aimed to identify diets and feeds that result in reduced animal GHG emissions (e.g. forage rape).
- ***Reduced N_2O from soil/plants***: these projects aimed to identify soil management options and additives such as nitrogen process inhibitors (compounds that slow the conversion of nitrogen (N) from one form to another) and biochar to reduce N_2O emissions from plants and soil.
- ***Management interventions***: these projects aimed to identify farm practices to improve utilisation of carbon and nitrogen into animal products (e.g. milk, meat, wool) in the farm system and consequently reduce carbon and nitrogen losses as CH_4 and N_2O, respectively.

This report presents the findings we obtained from different sources, including project outputs (reports and scientific publications), and surveys and interviews of researchers and stakeholders.

Evaluation method and results

The method used for evaluating the SLMACC-funded research programme involved an evaluative criteria rubric, which enabled i) a qualitative assessment of mitigation projects against the key aims of the SLMACC fund; and ii) the outcomes and desired impacts to be articulated in a programme logic for the SLMACC fund[1].

[1] Further detail about the evaluative criteria rubric and programme logic model can be found in the Technology Transfer Review (Payne, Turner & Percy, 2018).

Key evaluation findings

As shown in Table 1, the SLMACC agricultural GHG mitigation projects, aggregated at the cluster-level of mitigation options, were evaluated as meeting four of the six evaluative criteria to a **moderate** extent; except for Influence on Science, which scored **high**, and 'Engagement and networks', which scored **low**. This low score may have been partly a reflection of the fact that GHG mitigation was not a 'front of mind' issue for farmers and industry between 2007 and 2017.

Table 1: Summary of performance ratings for mitigation (evaluative rubric)

Evaluative criteria	**Overall rating**
Build science capacity and capability enhancement	Moderate degree
Influence on science	High degree
Engagement and networks	Low degree
Learning, awareness and knowledge exchange among next users, farmers and industry	Moderate degree
Usability of research for next users, farmers and industry	Moderate degree
Influence on stakeholders and impact for New Zealand	Moderate degree

Rubric ratings					
1 **Low degree** (Never or seldom with clear weakness)	**2** Moderate degree **(Mostly, or sometimes with few exceptions)**	**3** High degree **(Always to almost always)**	**IE** Insufficient evidence	**E** Emergent	**N/A** Not applicable **(e.g. not asked for by SLMACC)**

Build science capacity and capability enhancement: Moderate. The evaluation suggested that the SLMACC fund has had a moderate impact on science capacity. As noted by one of the interviewed stakeholders, "*SLMACC funding has enabled key capabilities to be maintained in New Zealand*". This is also reflected in the number of scientific publications produced from SLMACC-funded projects, which represent, on average approximately 10% of the total number of publications generated in New Zealand across the research clusters. The fund has also contributed to building capability through the development of early career scientists, particularly in the area of low GHG feeds.

Influence on science: High. The science impact of SLMACC-funded research has been high and supported the international positioning of New Zealand organisations addressing cutting-edge research into GHG mitigation. As noted by one of the interviewed stakeholders, in the early days "*SLMACC really filled an important gap when more funding was needed*". The fund has contributed to scientific knowledge across a wide range of agricultural GHG mitigation options, and has been a strong advocate of collaboration across research providers. The fund has played a critical role in funding some of the development research at an international scale, e.g. the development of CH_4 inhibitors, with some of this research now being supported by other funding bodies e.g. New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC) and the Pastoral Greenhouse Gas Research consortium (PGgRc).

Engagement and networks: Low. While the agricultural GHG mitigation research activities ranged from development to applied research, there was no strong focus on knowledge exchange with end-users. This was not surprising as the projects were generally not designed to guide stakeholder engagement or use participatory processes because the focus was to research a particular science knowledge gap. The low score may also be a reflection of the fact that GHG mitigation was not a ‘front of mind’ issue for farmers and industry between 2007 and 2016. Despite this, surveyed researchers suggested there was good engagement with stakeholders in SLMACC-funded projects. The view from stakeholders was that the SLMACC programme projects generally aligned well with the interests of next users (researchers), especially in the early years of the programme.

Learning, awareness and knowledge exchange among next users, farmers and industry: Moderate. Research activities were often in specific areas, leading to knowledge exchange and next user research funded by other organisations such as NZAGRC and PGgRc. Examples of such research activities included CH_4 inhibitors and farm systems research into stacked mitigation options.

However, SLMACC-funded projects had generally little communication or extension with the general public and farmers/industry. It should be noted that this was often not an objective of most individual projects. Since 2017, however, the results from GHG mitigation research have been increasingly used to raise awareness of the issues and potential solutions at industry-led GHG roadshows, dairy leaders’ training events and GHG courses.

Usability of research for next-users, farmers and industry: Moderate. The SLMACC Programme has aligned well with next-users' issues, concerns or demands in terms of funding new research areas or by supporting the development of 'proof of concept' projects. High next-user (researchers) usability is evidenced by the rubric evaluation of 'Influence on Science', which received a high rating (see above). Research findings from SLMACC-funded work has been made accessible to next-users through multiple publications in peer-reviewed journals and dissemination at conferences.

While SLMACC has not directly produced mitigation products for on-farm use, one interviewed stakeholder highlighted that the programme has ".. *contributed to either the development of products that are in the pipeline or provided information that's been useful in deciding whether practices are useful practices to promote*." It is the view of most industry stakeholders that, because many of the mitigation options are still at the discovery and/or development stage of research, it has not been possible to observe significant uptake and use of research results by farmers and/or industry bodies yet. Development of many mitigation options are still in progress with support from other funding bodies such as PGgRc and NZAGRC. For other mitigation options that are close to or are market-ready (e.g. forage rape), uptake has been low, possibly due to a lack of information on the implications of this option for farm management, environmental and/or financial outcomes for farmers.

The lack of uptake by farmers reflects that most of the SLMACC agricultural mitigation funded research has aligned with governmental rather than farmer or industry objectives at the time of procurement. As noted by one stakeholder: "*A lot of our farmers have been concentrating on water quality… because there are rules going to be in place … so climate change has been seen as something a little bit further down the track*". However, the SLMACC investment has helped to filter out mitigation options that would not have an on-farm use: "*What they have done is added to the development of a number of practices and actually shown that some practices that we thought might be promising weren't promising*." Research projects that have not resulted in successful mitigation products have still provided insights that are seen as useful by innovators in the field: "*You actually sometimes learn more from failures than you do from successes."*

Influence on stakeholders and impact for NZ: Moderate. According to one of the stakeholders interviewed, the SLMACC fund has ensured the government could take the lead on some of the mitigation research areas and stay ahead in the field globally, which has been "*strategically very important for New Zealand.*". The benefits in terms of water quality and GHG improvements, they said, are significant to our national brand.

It is important to note that some of the research efforts have improved our understanding of co-benefits of mitigation strategies. These include the potential for improved water quality through uptake of specific GHG mitigation practices, for example reduced feed N intake will reduce N_2O and also reduce N leaching to water. This type of information provides the necessary data for potential overseas branding of New Zealand's products under the 'Product Environmental Footprint' initiative of the European Commission.

Science gaps

Future science research gaps were identified at the cluster-level, with between two and four research ideas spanning each cluster's research pipeline (across discovery, development and applied research). Key examples of gaps are shown in Table 2: further detail can be found in Section 6.

Table 2: Examples of science gaps identified for each mitigation 'cluster'

Mitigation cluster	**Science Gaps**
CH_4 inhibitors/vaccines	- Identify specific bio-active compounds that are naturally present in forages or food industry by-products that lead to reduced CH_4 production in the rumen.
Low GHG animals	- Develop a suitable low-cost method to identify cattle with lower emissions.
Low GHG feeds	- Identify mechanism(s) in forage rape responsible for reduced CH_4 to allow possible transfer of these mechanisms to other forages/diets.
Reduced N_2O from soil/plants	- Improve our understanding of mechanism(s) responsible for 'biological nitrification inhibition' to enable identification or transfer of the functionality to other plants.
Management interventions	- Evaluate multiple on-farm mitigation strategies that are designed to address both GHG emissions and water quality.

A further six research ideas that did not fit within one of the five clusters were also identified by the review team for consideration for future SLMACC funding. Two key examples include:

1. Land use diversification: Changing from livestock production-dominated agriculture to more diverse land uses that have smaller total GHG footprints while adhering to water quality regulations, community values and providing financial security.

2. Capturing CH_4 emissions by ruminants: investigating opportunities to capture, filter or oxidise CH_4 emitted in ruminant breath prior to it being exhaled into the atmosphere.

Enablers of and barriers to adoption of agricultural GHG mitigation options

There are three **key enablers or strengths** to encouraging adoption of agricultural GHG mitigation options. The SLMACC programme has funded a **diverse portfolio of potential mitigation strategies**, with a strong focus on the key sources of biological emissions, i.e. enteric CH_4 and N_2O from soils. Funding has supported mitigation studies ranging from discovery research through to developmental and applied research. Much of this science investigation has been **conducted collaboratively across research institutes**, which has been a critical enabler for the exchange of ideas and advancing scientific knowledge. The SLMACC programme procurement process itself has been a key enabler, as it has led to the **development of high quality science for next-users** (e.g. researchers) to advance further. Research contracts were typically awarded to research teams that could demonstrate how their research would meet the goals of the SLMACC programme and whether their research was of high science quality and built science capability. A further requirement was the ability to deliver results, evidenced by existing track records.

There were **two key barriers** to stakeholders adopting SLMACC findings and recommendations.

1. **The limited number of GHG mitigation options currently available for stakeholders or farmers to use**. Most mitigation options are either not suitable for New Zealand pastoral farming conditions or not yet ready for implementation (e.g. not validated or approved for use on farm, or practical methods for on-farm implementation require further development). This limitation is an important challenge requiring further progress in research and implementation, particularly in inhibitors and vaccines for enteric CH_4.
2. **The lack of farmer understanding of the impacts of potential policy mechanisms (e.g. financial or other incentives, or taxes) to encourage them to adopt low GHG mitigation options.** Currently there is no regulatory or non-regulatory incentive for farmers to mitigate agricultural emissions, in part because it is not clear who (if anyone) is accountable for the emissions *domestically* that New Zealand must account for internationally, i.e. under the Paris Agreement. Furthermore, farmers are unsure if they will be facing a tax or will be recognised for their efforts through incentives or other such mechanisms. This is mainly due to the fact that the government is still developing the policy mechanisms, with input provided by the Interim Climate Change Committee (ICCC). It is also unclear whether the point of obligation for GHG emissions will fall on farmers or on industry sector bodies, which

may influence the type of mitigation strategies a farmer, or the industry as a whole, might adopt. As a result, reducing GHG emissions is not at the front of mind for farmers.

Recommendations

To maximise the future value and usefulness of SLMACC funded research, the following is recommended:

1. Ensure future investment into the SLMACC-funded programme on agricultural GHG mitigation includes engagement with targeted next-users, farmers and industry bodies for relevant projects, to improve communication and extension to farmers and industry; and assist in targeting of potential practical mitigation options. To achieve this, it is recommended that extension activities (e.g. on-farm demonstrations) are co-developed with and co-funded by farmer-industry organisations such as DairyNZ and Beef and Lamb NZ.
2. Commission a project with researchers, policy agents, change agents and involved practitioners to identify existing practical mitigation knowledge that could be disseminated. Funding should then be prioritised for extension activities that support uptake of these available options.
3. Ensure that a future SLMACC-funded programme includes resources for a coordinated communication plan to report key findings of future research projects to future users and the wider public. To ensure consistent messaging and to facilitate delivery of the information, such a plan should be developed in collaboration with the NZAGRC/PGgRc, relevant industry organisations (e.g. DairyNZ and Beef and Lamb NZ) and existing industry initiatives (e.g. Dairy Industry Action for Climate Change), and also utilise existing communication and extension mechanisms such as the Climate Cloud (www.climatecloud.co.nz). We note the similarity of these recommendations with those in the companion Technology Transfer Review report.
4. In the event that agricultural GHG mitigation research is no longer funded by the SLMACC programme, the recommendations outlined above should be considered by an alternative funding vehicle e.g. NZAGRC, PGgRc.

1. Introduction

1.1 Background

New Zealand has an unusual greenhouse gas emissions profile when compared with other developed countries, as 49 percent of the country's greenhouse gas emissions come from agriculture, in the form of methane (CH_4) and nitrous oxide (N_2O) (Ministry for the Environment, 2018). Methane is a short-lived greenhouse gas with a global warming potential of 25 times that of carbon dioxide (CO_2) over a 100-year period. Nitrous oxide is a potent long-lived greenhouse gas with a global warming potential 298 times that of CO_2 over a 100-year period.

In 2016, 72 percent of agricultural GHG emissions came from ruminant farm animals (cattle, sheep, deer and goats) in the form of CH_4 (Ministry for the Environment, 2018). Methane is produced in the rumen (first stomach) of ruminants by micro-organisms called methanogens. They use hydrogen produced by bacteria and protozoa in the rumen during fermentation (microbial digestion) of ingested feed. The majority of this CH_4 (~90-95%) escapes the rumen through the mouth.

The second largest source of agricultural GHG emissions in New Zealand is N_2O from agricultural soils, representing 22 percent of agricultural emissions in 2016 (Ministry for the Environment, 2018). Dung and urine excreted by grazing livestock and N fertiliser applications are the main sources of nitrogen converted to N_2O by soil microbes. Direct N_2O emissions occur as a consequence of soil processes called nitrification and denitrification, which are often mediated by soil microbes (bacteria and fungi). Indirect N_2O emissions occur when ammonia (NH_3) that is emitted into the atmosphere is deposited onto the soil downwind, thereby becoming a nitrogen input to soils. An additional indirect N_2O source is dissolved nitrate in water bodies such as streams, rivers and lakes following losses of this contaminant from, among other sources, farming practices.

1.2 The SLMACC Fund and key stakeholders

The Sustainable Land Management and Climate Change (SLMACC) research programme ('the fund') was created in 2007 and has been administered by the Ministry for Primary Industries (MPI). Between 2007 and 2018 the fund has invested more than $51 million into research that aims to address the impacts of, and adaptation to, climate change, mitigation of agricultural greenhouse gases (GHG), and improvements of forest sinks. The investment in each of these areas between 2007 and 2017 is provided in Table 3 below.

With enteric CH_4 from ruminants and N_2O emissions from soils being the two largest contributors to New Zealand's agricultural emission profile, much of the SLMACC investment into agricultural mitigation research has concentrated on these two areas.

Key stakeholders and users of SLMACC-funded agricultural mitigation research include:

A) Government (end-users[2]), to design and implement appropriate policies and programmes to address climate change; regulate and underpin New Zealand reporting of its emissions for international commitments and contribute to New Zealand's international reputation;

B) Farmers and farming industry bodies (end-user), to apply SLMACC research findings through practical knowledge or tools on-farm, i.e. to help reduce GHG emissions from the agricultural sector; and use SLMACC evidence for potential overseas branding of New Zealand's low carbon footprint products;

C) Other scientists, in New Zealand and internationally (next-user[3]), to further advance SLMACC research and development of mitigation options and technologies, including expansion into new opportunities and on-farm evaluation.

1.3 The SLMACC Review (2007 – 2017): objectives and scope

Given the ten year timeframe since SLMACC inception and the $50+ million investment, in 2016 MPI commissioned a Review of the SLMACC funding programme.

The objective of this review was to evaluate the impact of the SLMACC agricultural GHG mitigation research programme in relation to developing options for reducing on-farm enteric CH_4 and N_2O emissions; to identify science gaps; to identify barriers and enablers of adoption; and to provide recommendations for improvements to the SLMACC fund for agricultural GHG mitigation.

The scope of this review is the $17 million investment in 31 (of 58) agricultural mitigation projects: see Table 3 below. Although the original list provided by MPI included 58 research projects in the domain of agricultural GHG mitigation, in discussion with MPI this

[2] End-users: refers to stakeholders whom the research or technology is ultimately intended for, and who will likely be a direct user, such as government, industry bodies and farmers.
[3] Next-users: The intermediary stakeholder who intends to use the research or technology, such as other scientists (or science organisations) to further advance scientific progress.

list excluded 27 projects that focused on other, indirect issues, such as improving GHG measurement/modelling methodologies and on-farm adaptation.

Table 3. SLMACC investments over the years 2007-2017

Aggregated level of investment	Total costs (NZ$, nominal values)	Number of projects	Average value per project
Mitigation of agricultural GHG emissions (58 projects)*	$ 25,039,128	58	$ 431,709
Forestry & carbon market	$ 9,847,629	29	$ 339,573
Impacts of climate change and adaptation	$ 8,036,225	36	$ 223,228
Crosscutting issues and technological transfer	$ 8,108,925	20	$ 405,446
***Total SLMACC 2007-2017* (for four review project areas)**	**$ 51,031,906**	**143**	**$ 356,866**
Reviewed (in this review) mitigation of agricultural GHG emissions projects (31 projects)	$ 17,158,818	31	$ 553,510

Source: Collated by current project team with data on SLMACC projects received from MPI. *Notes:* Monetary values are nominal. *The original list of 58 agricultural GHG mitigation projects was reduced to only 31 (values shown in last row) after projects that did not focus on research to develop mitigation options were excluded – action agreed by MPI.

1.4 Structure of this review

This report is organised as follows:

- **Section 2** describes the methods used for this review, including a description of the rubric evaluation process.
- **Section 3** provides an overview of the SLMACC projects under review.
- **Section 4** discusses the **outcomes** of the SLMACC agricultural GHG mitigation programme based on the results of the rubric evaluation.
- **Section 5** provides a general description of the mitigation knowledge gained through the SLMACC programme.
- **Section 6** identifies **gaps** in mitigation research knowledge.
- **Section 7** explores the **enablers** and **barriers** to adoption of mitigation strategies.
- **Section 8** synthesises the review **learnings** and provides **recommendations** for improvements to the SLMACC programme.

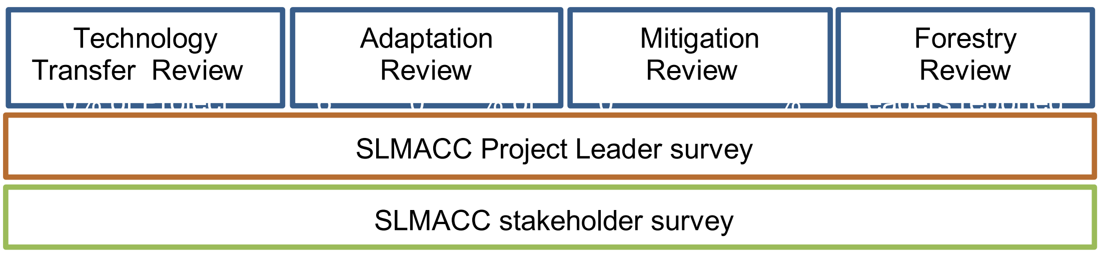
Supporting material used for this review can be found in the Appendices, including a summary of the projects included in the review (Appendix 1), a technical description of the mitigation options (Appendix 2), analysis of publication outputs (Appendix 3), results from the stakeholder interviews (Appendix 4), evaluation of the mitigation options using the five key questions presented by the Parliamentary Commissioner for the Environment (Appendix 5), results from the project leaders and stakeholder surveys (Appendix 6) and a technical summary of the mitigation effectiveness (Appendix 7).

Accompanying this mitigation review is also an analysis of the international scientific impact of the New Zealand mitigation research and the potential economic value that the mitigation options could generate, using two specific SLMACC projects as case studies (Fleming and Preston, 2018).

2. Review process and methods

This Mitigation Review was conducted jointly by AgResearch Ltd. and Motu Economic and Public Policy Research, with each organisation responsible for key aspects of the review process. This review is one of four primary reports for the SLMACC Review, intended to be read in conjunction with Fleming and Preston (2018) and the other three SLMACC review reports, and survey results report:

1) Adaptation Review (Cradock-Henry, Flood, Buelow, Blackett & Wreford, 2018)
2) Mitigation Review (van der Weerden, Jonker, Fleming, Prescott, de Klein & Pacheco, 2018)
3) Forestry Review (Dunningham, Grant & Wreford, 2018)
4) Technology Transfer Review (Payne, Turner & Percy, 2018)
5) Project Leader and stakeholder survey results (Payne, Chen, Turner & Percy, 2018)



We applied a mixed method approach to provide a robust analysis on the role that the SLMACC fund has played within the agricultural mitigation area in New Zealand.

To provide consistency across the SLMACC reviews, an evaluative criteria rubric was co-designed with members from the other review teams and MPI. The group agreed on the critical success factors (or key aims) for the SLMACC fund using an agricultural innovation systems perspective (Botha et al. 2017). This approach enabled a system-wide focus on how SLMACC projects have contributed to climate change mitigation and adaptation in New Zealand (Campbell et al. 2015) over the past decade. The evaluation rubric is described next.

2.1 The Evaluation Rubric

The evaluative criteria rubric specifically assesses six key performance areas:

1) Build science capacity and capability enhancement
2) Influence on science
3) Engagement and networks
4) Learning, awareness and knowledge exchange among next users, farmers and industry
5) Usability of research for next users, farmers and industry
6) Influence on stakeholders and impact for New Zealand

Information for populating the rubric with scores was derived from several sources:

1. Evaluation of 31 SLMACC agricultural mitigation projects and mapping of their research contribution, subdivided into five research clusters
2. An analysis of agricultural mitigation science outputs (in the form of journal publications) generated in New Zealand
3. Interviews with key stakeholders for each of the five research clusters to identify perceptions on impacts and influence of the SLMACC funded research
4. The use of a series of questions based on a Parliamentary Commissioner for the Environment (PCE) report to identify the strengths and weaknesses of the researched mitigation options in New Zealand
5. Analysis of data from project leaders and stakeholders surveys (implemented by the 'Technology Transfer' review team)
6. Review of all projects' reports, identification in next user impacts and desktop analysis of mitigation effectiveness.

We provide a brief description of each source below and in Table 4. Further detail on these sources can be found in Appendices 2-6.

2.2 Information sources and methods

Analysis of agricultural mitigation science outputs

Most of the SLMACC projects resulted in a published report as the key output; and in Appendix 2 we provide a detailed analysis of most of these publications. This analysis is complemented with national trends (presented in Fleming and Preston, 2018) and was conducted to provide information regarding the scientific impact generated by the SLMACC funding.

Interviews with key stakeholders

Information was gathered from interviews with nine relevant next-user stakeholders who were directly or indirectly related to past SLMACC research projects. The stakeholders in most cases were not scientists, but managers or senior representatives of farmer industry bodies or research organisations (e.g. Beef and Lamb, DairyNZ, Ravensdown, Ballance Agri-Nutrients; see Table A3-1 in Appendix 3 for more details).

Details of the interview process (including the questions asked), results and discussion are provided in Appendix 3. The information gathered from the interviews provided important insights for the rubric evaluation, and for the discussion of gaps and enablers provided below.

The PCE questions

In order to identify the strengths and weaknesses of the different agricultural GHG mitigation options funded by the SLMACC fund, we employed a series of evaluation questions suggested by the Parliamentary Commissioner for the Environment (PCE) report (PCE, 2016).

We used this method inspired by the PCE statement "*There are no silver bullets for reducing methane and nitrous oxide emissions currently on the horizon. But the mitigation options that are the subject of research can be assessed (to some extent) against the characteristics of a silver bullet solution*." (PCE 2016, p. 37). We considered that this exercise was important to clarify the relevance of the research being funded and the potential impact that the SLMACC programme could have in the future implementation of mitigation options in New Zealand.

The information gathered with the PCE's evaluation questions supported our discussion on gaps and enablers below (Section 7), as well as for use within the evaluation rubric. The PCE's evaluation questions and all detailed results are available in Appendix 5.

Project leaders and stakeholders surveys

A survey sent to project leaders and key stakeholders elicited information that could not be obtained through an examination of project outputs (refer to Payne et al. 2018b for more information). We used the data obtained from the surveys to score projects in the rubric, and inform some of the discussion of the rubric results in Section 4. Data and analysis of the survey results are provided in Appendix 6.

Review of all projects reports, identification of impacts in next users, and desktop analysis of mitigation effectiveness

A comprehensive review of all the mitigation reports established the effectiveness of the studied research option and the implications for further research. The information was also used to identify the impact of the research on next users, when information was available. For full details see Appendix 7.

Table 4. Common rubric used by all four SLMACC review teams, with sources of information used for the agricultural GHG mitigation review.

	Sources of information for agricultural mitigation review[a]
SCIENCE CAPACITY AND CAPABILITY ENHANCEMENT	
Builds capacity for NZ to research climate change and sustainable land use, at all levels	Publication outputs (Appendix 3), stakeholder interviews (Appendix 4), and information from project reports.
Improves capability and skills amongst emerging or early career researchers	Project leader survey (Appendix 6).
INFLUENCE ON SCIENCE	
Promotes collaboration among research providers, and/or between different disciplines	Project leader survey (Appendix 6).
Generates high quality research related to climate change or sustainable land use, which is credible and legitimate (e.g. citations, impact factor) with relevant stakeholders (e.g. International Panel on Climate Change,)	Average of Scopus field weighted citation index (SFWC) (Refer to Appendix 3, Table A3-1) and Stakeholder survey (Appendix 6).
Utilises robust, best practice research methods (poor may use random or unexplainable method and excellent may use novel methods or techniques, sound results)	Assessed at project level, through reading project outputs (reports and publications).
Results in uptake and use of research within science community (excellent would result in strong uptake and use of research within science community)	Project leader survey (Appendix 6)
ENGAGEMENT AND NETWORKS	
Builds collaborative networks of key stakeholders and/or famers/industry (poor may include homogenous networks which disperse following project and excellent networks are heterogeneous (e.g. different epistemologies, type of expertise, values) and enduring)	Stakeholder survey (Appendix 6).

Uses participatory research process appropriate to level of engagement needed to achieve outcomes (based on MPI Extension Framework). e.g. where farmers/industry have opportunity to shape research approach, sources of knowledge and outcomes	Assessed at cluster level, through reading project outputs (reports and publications).
Uses structure or processes to guide stakeholder engagement (poor may have no clear processes for stakeholder engagement and excellent may use processes like a community of practice)	Assessed at cluster level, through reading project outputs (reports and publications).
Practices action learning (if applicable)	Not applicable.
LEARNING, AWARENESS AND KNOWLEDGE GAIN AMONG NEXT USERS, FARMERS AND INDUSTRY	
Generates new knowledge about climate change or sustainable land use	Stakeholder survey (Figure A6-3 in Appendix 6) and Figures 1-5 in Fleming and Preston (2018).
Promotes knowledge exchange (particularly dissemination of research findings)	Project leader survey (Appendix 6) and average of Scopus field weighted citation index (SFWC) (Refer to Appendix 3, Table A3-1).
Builds increased awareness and knowledge about climate change or sustainable land use practices	Project leader survey, focusing on different forms of extension (Appendix 6), and stakeholder survey (Appendix 6).
Promotes practice or behaviour change among intended next user groups, farmers and/or industry	Stakeholder survey, with focus on Dairy Industry's 5-point plan (Appendix 6).
USABILITY OF RESEARCH FOR END USERS	
Generates specific, usable, fit for purpose knowledge and research for policy and trade/negotiation, research, science and stakeholder communities	Stakeholders' survey (Figure A6-5 in Appendix 6).
Aligns research with the needs of next users, or farmers/industry, of the research, and is responsive to next user or farmers/industry needs and knowledge gaps (poor may lack alignment and excellent may involve iterative research to meet user needs)	Stakeholder survey (Appendix 6) and project leader survey (Appendix 6).
Acknowledges context and effects of the research knowledge or recommendations on the broader climate system or topic area	No evidence available
Creates accessible, available outputs	Stakeholder survey (Appendix 6) and project leader survey (Appendix 6).
INFLUENCE ON STAKEHOLDERS AND IMPACT FOR NZ	
[How the research is designed and delivered] maximises how wide-reaching the research influence is	Combination of sources[4].

[4] For evaluating this category, a composite index was created given by the weighted average of scores related to (weight in parenthesis): (0.25) results to question 2 of the 5-point PCE tables; (0.4) the

(inter/national, across relevant sectors and functions, e.g., policy, industry and community attitudes and behaviours)	
Results in uptake and use of research by stakeholder groups (policy, government, industry or community)	Stakeholder interviews (Appendix 4) and expert knowledge of the review team.
Influences stakeholders positively in their awareness/ consideration of decision-making, and/or action around climate change or sustainable land use (e.g. policy, government, industry or community)	Stakeholder interviews (Appendix 4).
Achieves significant direct impacts or benefits for NZ (poor would be no impact, good incremental, excellent would be wide ranging or more immediate impact)	Based on mean of 5 PCE results (Appendix 5) and expert knowledge of the review team.
Achieves significant direct spill-over impacts or benefits for NZ (poor would be no impact, good incremental, excellent would be wide ranging or immediate impact)	Stakeholder interviews (Appendix 4).

[a] The information contained in the project final reports were also used to support the Rubric evaluation.

2.3 Limitations and disclaimer

The extent to which outcomes and impacts were able to be assessed varied greatly between the projects and clusters reviewed, due to the varied availability of data. Where multiple sources of data (project outputs, survey data and interview data) were able to be triangulated, high level judgements about achievement of outcomes and impacts have been made. For the majority of projects, a lack of sufficient evidence resulted in the use of the assessment category 'insufficient evidence' for outcome and impact criteria.

Moreover, for those projects and clusters where assessments were able to be made, it remained difficult to attribute these findings definitively and purely to the relevant project and/or cluster. It is therefore noted that readers should interpret the findings of this review as indicative, as opposed to definitive findings about the SLMACC agricultural greenhouse gas mitigation programme.

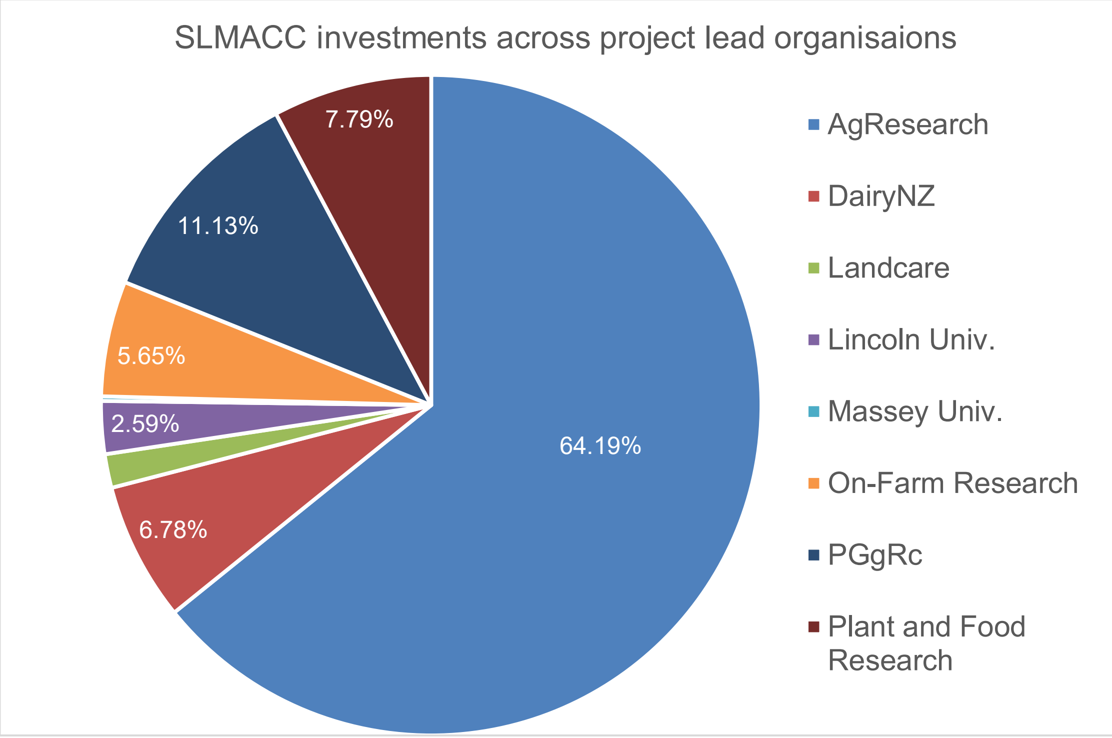
3. Summary of 31 mitigation projects

The 31 mitigation projects reviewed represent a total investment value of approximately NZ$17.2 million (in nominal value), an average of over $0.5 million per project (also see Table 3 above).

number of total publications; (0.05) the Scopus field weighted citation index; (0.15) the 'networks' results from the researchers survey and; (0.15) the 'stakeholder engagement' results from the researchers survey.

The distribution of the $17.2 million dollars across lead organisations is presented in Figure 1 below. Over half (64%) of mitigation-related funding has gone to AgResearch, and the remainder to six Crown Research Institutes or industry organisations, including Plant and Food Research and DairyNZ.

Figure 1. Distribution of the $17.2 million invested by SLMACC into agricultural GHG emission mitigation research from 2007-2017.



Most of the projects researched ways to reduce emissions by changing inputs into the farm/animal system (e.g. feeds, animal type, excreta, fertilizer, additives etc.) to reduce emissions. Some research focused on farm management interventions to improve efficiency or productivity of the farm system (e.g. improved animal efficiency or change in land use).

The different research projects were categorised into five different research clusters in this review. This was done because the nature of the research across clusters is very different and the objectives of the research are also diverse. A brief description of the five clusters is given below.

CH_4 inhibitors/vaccines

These projects aimed at discovering and developing compounds or antibodies to inhibit growth of microbes in the rumen (first stomach of ruminant), called methanogens, that are responsible for CH_4 production in farmed ruminant animals such as cattle, sheep and deer. **Eight SLMACC projects fall within this cluster.**

Low GHG animals

These projects sought options to breed animals that emit less methane emissions (e.g. low CH_4 sheep). **Three SLMACC projects fall within this cluster.**

Low GHG feeds

These projects aimed to identify diets and feeds that result in reduced animal GHG emissions when fed (e.g. forage rape). **Nine SLMACC projects fall within this cluster.**

Reduced N_2O from soil/plants

These projects aimed to identify soil management options and additives such as nitrogen process inhibitors (compounds that slow the conversion of N from one form to another) and biochar to reduce N_2O emissions from plants and soil. **Eleven SLMACC projects fall within this cluster.**

Management interventions

These projects aimed to identify farm practices that improve utilisation of carbon and nitrogen into animal products (e.g. milk, meat, wool) in the farm system and consequently reduce carbon and nitrogen losses as CH_4 and N_2O, respectively. **Seven SLMACC projects fall within this cluster.**

Details of the 31 projects (name, title, duration, value and lead organisation) are listed in Appendix 1. MPI provided the majority of final reports and several published papers that resulted from the SLMACC projects. Any missing reports were obtained through contact with lead researchers, while published papers were obtained directly from scientific journals. An existing spreadsheet of SLMACC projects was used to confirm all relevant projects were included in the review.

Appendix 2 provides a more detailed technical description of each cluster, with Figures A2-1 to A2-5 summarising the mapping of the SLMACC projects to each cluster and their contribution to the New Zealand agricultural mitigation research pipeline.

4. Outcomes: To what extent have the desired outcomes been achieved from SLMACC mitigation projects to date?

4.1 Rubric Performance Ratings

Ratings for how each cluster performed against the rubric of evaluative criteria are presented in this section. Ratings are presented by cluster and a total final average is also presented (Table 5). Criteria could be rated from 1 (low) to 3 (high); insufficient evidence (IE); emergent (E); or not applicable N/A).

Key:

Rubric ratings					
1 Low degree (Never or seldom with clear weakness)	**2** Moderate degree (Mostly, or sometimes with a few exceptions)	**3** High degree (Always to almost always)	**IE** Insufficient evidence	**E** Emergent	**N/A** Not applicable (e.g. not asked for by SLMACC)

The ratings were made by the three leading authors of this review, using the information and evidence available (see sources in Table 4 above) and making high-level observations of patterns that appeared among these mitigation clusters.

Overall, the SLMACC agricultural GHG mitigation projects, aggregated at the cluster-level of mitigation options, were evaluated as meeting four of the six evaluative criteria to a **moderate** extent; except for Influence on Science, which scored **high**, and 'Engagement and networks', which scored **low**. This low score may have been partly a reflection of the fact that GHG mitigation was not a 'front of mind' issue for farmers and industry between 2007 and 2016.

Table 5. Rubric evaluation rating. Average rubric scores shown in right hand column are based on following ranges: Low: 1.0 – 1.7; Moderate: 1.7-2.3; High: 2.3-3.0.

	CH_4 inhibitors/ vaccines	**Low GHG animals**	**Low GHG feed**	**Reduced N_2O from soil/ plants**	**Manage-ment**	***Mean***	**Overall rating**
SCIENCE CAPACITY AND CAPABILITY ENHANCEMENT							**MODERATE**
Builds **capacity** for NZ to research climate change and sustainable land use, at all levels	1	2	3	2	2	2.0	
Improves **capability** and skills amongst emerging or early career researchers	2	2	3	2	2	2.2	
INFLUENCE ON SCIENCE							**HIGH**
Promotes **collaboration** among research providers, and/or between different disciplines	3	2	2	3	3	2.6	
Generates **high quality research** related to climate change or sustainable land use, which is credible and legitimate (e.g. citations, impact factor) with relevant stakeholders (e.g. International Panel on Climate Change,)	2	3	2	2	2	2.2	
Utilises robust, **best practice research methods** (poor may use random or unexplainable method and excellent may use novel methods or techniques, sound results)	3	3	3	3	3	3.0	
Result in **uptake and use of research** within science community (excellent would result in strong **uptake and use of research** within science community)	2	3	2	2	2	2.4	
ENGAGEMENT AND NETWORKS (if applicable)							**LOW**
Builds **collaborative networks** of key stakeholders and/or next users and/or farmers/industry (poor may include homogenous networks which disperse following project and excellent networks are heterogeneous (e.g. different epistemologies, type of expertise, values) and enduring)	3	3	3	2	3	2.8	

Uses **participatory research process** appropriate to level of engagement needed to achieve outcomes (based on MPI Extension Framework). e.g. where farmers and/or industry bodies have opportunity to shape research approach, sources of knowledge and outcomes	1	1	1	1	2	1.2	
Uses **structure or processes to guide stakeholder engagement** (poor may have no clear processes for stakeholder engagement and excellent may use processes like a community of practice)	1	1	1	1	1	1	
Practices **action learning** (if applicable)	N/A	N/A	N/A	N/A	N/A	N/A	
LEARNING, AWARENESS AND KNOWLEDGE GAIN AMONG NEXT USERS, FARMERS AND INDUSTRY							**MODERATE**
Generates **new knowledge** about climate change or sustainable land use	3	3	3	3	3	3.0	
Promotes **knowledge exchange** (particularly dissemination of research findings)	3	2	1	2	3	2.2	
Builds increased **awareness and knowledge** about climate change or sustainable land use practices	1	2	1	1	2	1.4	
Promotes **practice or behaviour change** among intended end or next user groups	N/A	N/A	N/A	N/A	2	2.0	
USABILITY OF RESEARCH FOR NEXT USERS, FARMERS AND INDUSTRY							**MODERATE**
Generates specific, usable, fit for purpose **knowledge and research** for policy and trade/negotiation, research, science and stakeholder communities	2	2	2	3	3	2.2	
Aligns **research with the needs of next users, farmers or industry** of the research, and is responsive to their needs and knowledge gaps (poor may lack alignment and excellent may involve iterative research to meet user needs)	3	2	2	2	2	2.2	
Acknowledges context and **effects of the research knowledge** or recommendations on the broader climate system or topic area	IE	IE	IE	IE	IE	IE	
Creates **accessible, available outputs**	1	2	3	2	2	2.0	
INFLUENCE ON STAKEHOLDERS AND IMPACT FOR NZ							**MODERATE**

[How the research is designed and delivered] maximises how wide-reaching the **research influence** is (inter/national, across relevant sectors and functions, e.g., policy, industry and community attitudes and behaviours)	2	2	2	2	2	2.0	
Results in **uptake and use of research** by stakeholder groups (policy, government, industry or community)	2	2	2	2	2	2.0	
Influences **stakeholders positively** in their awareness/ consideration of decision-making, and/or action around climate change or sustainable land use (e.g. policy, government, industry or community)	1	2	1	3	2	1.8	
Achieves significant direct impacts or benefits for NZ (poor would be no impact, good incremental, excellent would be wide ranging or more immediate impact)	2	3	2	2	3	2.4	
Achieves significant direct **spill-over** impacts or benefits for NZ (poor would be no impact, good incremental, excellent would be wide ranging or immediate impact)	2	2	3	3	2	2.4	

Discussion of outcomes findings

Build science capacity and capability enhancement: Moderate

SLMACC is one of New Zealand's major funds for agricultural GHG mitigation research, therefore there is an expectation that science capacity and capability would increase. We found SLMACC-funded scientific publications (shown in Appendix 3) made up approximately 10 percent of the total New Zealand scientific publications on the same topic/s (refer to Fleming and Preston (2018) for an aggregated analysis of New Zealand-based agricultural mitigation scientific publications). This includes 11 publications on low GHG feeds, which represents approx. 25% of the New Zealand publications on this topic. Here we assume that as capacity is enhanced, more scientific publications are produced. Capacity is also enhanced through the size of project teams, which, according to the Project Leader survey, included between five and ten researchers for 50% of the projects. It can be argued that capacity building is also achieved through collaboration between institutes. The Project Leader survey showed that 50% of the projects included three or more research institutes, thereby encouraging the cross pollination of ideas and concepts for future scientific investigation.

The fund has also contributed to building capability through the development of [number of] early career scientists, particularly in the area of low GHG feeds, as determined through the survey of project leaders (see Appendix 6). As noted too by one of the interviewed stakeholders, "*SLMACC funding has enabled key capabilities to be maintained in New Zealand*". Given these points, we conclude that the fund has had a moderate impact on capacity and capability.

Influence on science: High

Overall SLMACC has had a high influence on science, albeit individual projects were mostly moderate in terms of influencing uptake. Across all mitigation clusters, there was evidence of robust, best practice research methods, and most clusters scored high in their promotion of collaboration among research providers. For example, stakeholder comments included, inter alia: "*The best scientists for sheep genetics are in NZ… NZ has been a world leader in science of agriculture … The science itself appears to be very good. I guess the question comes - it's not so much the science - it's 'are they focusing on the right things?'* ". Another stakeholder commented: "*All of our programs have been ranked as world-leading, and SLMACC has supported them. But for now there are no products on the market*."

The science impact of SLMACC-funded research has supported the international positioning of New Zealand organisations on research into GHG mitigation (see Fleming and Preston, 2018). For example, one researcher was invited to be part of a project team conducting similar research in Chile. An interviewed stakeholder involved in mitigation research which has been supported in part by the SLMACC programme also commented that “*all of our programmes have been ranked internationally world-leading*”.

The fund has been a strong advocate of collaboration across research providers and between different disciplines, as evidenced by the number of organisations and mix of disciplines involved in the majority of projects. As noted above, the Project Leader survey showed that 50% of the projects included three or more research institutes, thereby encouraging scientific progress. Several projects included diverse mixes of disciplines such as animal science, soil science, plant science, and farm systems. These collaborations are likely to have had an impact beyond the specific SLMACC projects, with an average of five out of seven projects indicating that the networks established endured beyond the SLMACC project (see Table A6-1 in Appendix 6). It is also important to highlight that SLMACC-funded research is at the forefront of several mitigation strategies being investigated, as evidenced by the number of citations. Out of 26 articles published directly from SLMACC mitigation research, 46 percent were cited more than 10 times and 27 percent were cited more than 30 times (in no more than a seven year period). The fund has played a critical role in funding some of the discovery research at an international scale, for example CH_4 inhibitors. One stakeholder noted the hurdle facing this research area, but could see the benefits if successful: "…*the inhibitor is the ‘least’ practical for our free range grazing systems but overall they are logical projects to deliver some options to the livestock sectors*." This work is on-going, with part of the focus on developing new technologies for delivery of inhibitors in grazing systems. Another example of the high influence on science is the international impact of the low CH_4 animal research, with 29 different countries citing the main scientific paper generated by the SLMACC project and international news praising the work that has continued in the area after the project concluded (see Fleming and Preston, 2018). A strong sense was gained from stakeholders that research funded by SLMACC has contributed to knowledge, which has been adopted by next users (scientists and research organisations) who have then continued to further expand the scientific knowledge.

While most stakeholder interviewees claimed that the SLMACC programme has made good investments into mitigation research, most of this investment occurred in the early years of the programme. As noted by one of the interviewed stakeholders, in the early days "*SLMACC really filled an important gap when more funding was needed*". This has decreased in recent years as SLMACC started to focus on other research areas beyond agricultural mitigation, and PGgRc and NZAGRC developed their own comprehensive research programmes.

Engagement and networks: Low

We rated SLMACC engagement and networks overall as ‘low’. On one hand, results from the researchers’ survey suggested there was good engagement with stakeholders in SLMACC-funded projects (Table A6-2 in Appendix 6) and this was rated highly.

However, the projects were generally not *designed* to use participatory processes, because the focus was to research a particular knowledge gap. Overall we found there was a low use of structure or processes to engage with or encourage participation of stakeholders in the mitigation projects.

Factors influencing this limited use of structure may have included the fact that GHG mitigation was not a ‘front of mind’ issue for farmers and industry between 2007 and 2016; and the mitigation research activities have ranged from mainly discovery to applied research (see Appendix 2), and have not focused on knowledge exchange beyond the applied research, testing options within farm systems.

Learning, awareness and knowledge exchange among next users, farmers and industry: Moderate

Overall, next user and end user learning, awareness and knowledge exchange was rated moderate. SLMACC often initiated research activities in specific areas, leading to knowledge exchange and next user research funded by other organisations (e.g. NZAGRC/PGgRc), as evidenced by the number of citations (see Appendix 3). Examples of such research activities include CH_4 inhibitors and farm systems research into stacked mitigation options.

SLMACC projects were moderately successful at promoting knowledge exchange within the scientific community but were generally poor at communication and extension with the general public, farmers and industry bodies. For example, there was no use of social media or similar outlets (as outlined in appendix 6). The focus was more on the traditional scientific outlets (journal publications and conference presentations), which are generally not consulted by industry, farmers, or even the public in general.

Since 2017, the results of GHG mitigation research have been increasingly used to raise awareness of the issues and potential solutions at industry-led GHG roadshows, dairy leaders' training events and GHG courses. This was instigated by the project 'Managing GHG emissions', which was part of DairyNZ's Primary Growth Partnership programme 'Train the trainer'.

Usability of research for next users, farmers and industry: Moderate

All aspects of performance within this category were rated moderate. The SLMACC Programme has aligned well with next users (researchers and stakeholders) in terms of providing sources for research investment in new areas or by supporting the development of 'proof of concept' projects. It has supported new insights and findings for the development of new research areas and provided evidence, or not, on the usefulness of different mitigation options. One stakeholder noted that anything that helps farmers to adjust on-farm management is "..*good value to us*". Another stakeholder noted "*We recognise the solutions as having a practical application*". In addition, the SLMACC fund was noted by stakeholders from the PGgRc and NZAGRC for enabling complementary work that they could not carry out under their contracts the particular mandates of their business models. The flexibility of the fund allowed for both exploratory work that has informed subsequent science, and the extension of existing work that were of interest to key research groups in mitigation.

In terms of accessibility of research outputs (see Table A3-1 in Appendix 3) a total of 26 papers have been published in peer-reviewed journals from SLMACC-funded projects on agricultural GHG mitigation. Of these, 23 papers have been published in international journals, and, as of July-August 2017, 22 had been cited (based on records in Google Scholar). It is worth noting that of the four publications that had zero citations, three of them were published in 2017 and therefore had had little time to accrue any citations. Almost three quarters (73%) of the published articles had been cited more times than the average of those articles published in the same field and year (see Table A3-1 in Appendix 3).

In terms of practical answers to real problems for farmers, most of the SLMACC agricultural mitigation funded research has not aligned well with farmers' current issues/concerns/demands. As noted by one stakeholder: "*The science in NZ is very good, but the options are not actually being used*." Another stakeholder noted "*A lot of our farmers have been concentrating on water quality…because there are rules going to be in place [for water]… so climate change has been seen as something a little bit further down the track*". This misalignment should not be seen as a flaw in the SLMACC program itself, but rather as a reflection of the lack of incentives on farmers to uptake mitigation technologies and innovations. Because projects were aligned with governmental objectives at the time of procurement, SLMACC has primarily focused on identifying options to reduce the emissions of GHG from agricultural systems – objectives that are still far from farmers, because regulation or incentives to *apply* any options and reduce on-farm GHG are not in place. As noted by one stakeholder: *"There hasn't been an incentive or a penalty to take up these mitigation options for the sake of GHG".*

However, industry are increasingly seeing the need for practical information for farmers: farmers have not been prioritizing climate change, but (as stated by one industry representative) *"..we have been working to change that in the materials we produce."* This is a key barrier to adoption, which is discussed further in Section 6 below. As interest in reducing emissions among farmers grows, there remains a need to translate the potential impact of different mitigation options into useable information for farmers: "*If we want farmers to adopt mitigation technologies or practices then being able to estimate it is one thing, we need something farmers can actually go 'well if I do this then that's going to have this impact here and that impact there'.*"

The SLMACC investment has also helped to filter out mitigation options that would not have an on-farm use: "*What they have done is added to the development of a number of practices and actually shown that some practices that we thought might be promising weren't promising*." This comment demonstrates the advantages of following a process similar to the PCE's evaluation questions (see Appendix 5), thereby ensuring mitigation options are thoroughly evaluated prior to wider extension to the rural sector. Two of the questions posed by the PCE were 'is the mitigation option effective?' and 'can the mitigation option be integrated into existing systems?' Ventures that have not resulted in successful mitigation products have still provided insights that are seen as useful by innovators in the field: "*You actually sometimes learn more from failures than you do from successes."*

Influence on stakeholders and impact for NZ: Moderate

All aspects of performance in this category received on average moderate to high ratings. Although practical uptake is limited at this stage, it is important to note that some of the research efforts have improved our knowledge of co-benefits of developing mitigation strategies, for example, the potential for improved water quality. This type of information provides the necessary data for potential overseas branding of New Zealand's low carbon footprint products.

According to one of the stakeholders interviewed, the SLMACC fund has ensured the government could take the lead on some of the mitigation research areas and stay ahead in the field globally, which has been "*strategically very important for New Zealand.*". The benefits in terms of water quality and GHG improvements, they said, are significant to our national brand. This thought was backed by another industry stakeholder with regards to the impact of reducing the country's emissions profile and improving water quality: "*…the flow on effects for the country is huge because we are selling an international product as well on international markets.*"

One of the few mitigation options that have so far come out of work co-funded by SLMACC, PGgRc and NZAGRC is the discovery of the low CH_4 per unit of dry matter intake trait in sheep, with 10% difference in emissions between low and high selection line animals. The transition of this outcome to market is expected to take place in a matter of years.

5. Mitigation knowledge and knowledge gaps

The SLMACC programme to date has resulted in many desired outcomes for New Zealand and internationally, including creating valuable new knowledge. It has funded research that is at the forefront of several mitigation strategies being investigated (e.g. CH_4 inhibitors, low GHG animals), and has strongly aligned with other programmes such as the PGgRc and NZAGRC in New Zealand and Global Partnerships in Livestock Emissions Research (GPLER) and Global Research Alliance (GRA) internationally.

However, there are also possible knowledge gaps, some of which have been identified by stakeholders and are summarised in Table 6. Examples include more focus on methane rather than nitrogen; energy needs to keep two new-born lambs alive; and current versus future management interventions.

Table 6. Some relevant research gaps identified by stakeholder interviewees within the five GHG mitigation clusters.

CH_4 Vaccines/ Inhibitors	Low GHG Animals	Low GHG Feed	Reduced N_2O from soil/plants	Management Interventions
• A pathway for inhibitors to be used in grazing • Promoting *"what can be done now rather than what necessarily could be available in the future…There used to be a climate-change tech-transfer fund of some description, that seemed to disappear*."	• The next step is to extend from research flocks to the whole national flock, to get better data. We also need to understand how the low emission trait impacts on other traits. • Support is needed to transition research to farmers, and to encourage them to select the particular trait. • More research needs to be taken about rumen size and energy needed for ewes to keep two lambs alive.	• Extension is key. We need to provide the incentives for uptake. We need an ETS integrated with the agricultural system with obligation at the point of the farm. • It would be good to have freely available life-cycle models with guidance on how to use them. • More public audits are needed. Then people can adapt their business models. The government and local government role is to create that transparency.	• More help is needed for applied research that could be commercialised and used by farmers. • More farmer or grower-specific knowledge is needed to complement traditional science. • "*What is the next high-value land use the primary sector will migrate to?*" We need to think about what the future land uses will be like under these constrained environments.	• We need to look into the correlation between nitrate loss and reduction in GHG emissions. • The focus has been on nitrogen, we need more investment in methane, and not so much on farm system change. • We need to understand how the mitigation options will work in the farm system, how they might interact with each other, and how they will fit in with other environmental concerns.

5.1 Extension is a key knowledge gap

While some stakeholders discussed specific gaps relevant to their field, a common theme was that more effort on extension of mitigation options to farmers is needed. Several respondents mentioned that there is a need for government to support the transition of scientific research to market, as well as providing an incentive for the uptake of mitigation options by farmers through regulation, audits, or economic drivers. As one stakeholder put it, there is a need to focus on *"what can be done now rather than what necessarily could be available in the future…There used to be a climate-change tech-transfer fund of some description, that seemed to disappear* [possibly referring to the SLMACC-Tech Transfer fund: see related Technology Transfer Review Report]."

Two respondents wanted to see a tool that could be used by farmers to understand the environmental footprint of their farm, and a third emphasised that information is not sufficiently shared with farmers.

There was a sense that not enough is known about the actual application of mitigation options in a real farm environment in which many other issues need to be managed. In addition, there is a desire to understand how the various mitigation options will interact, positively or negatively, with each other. It is important that mitigation options are not tested on-farm in isolation of other farming challenges. One stakeholder stated the following, which we have identified as a knowledge gap: "*A lot of it* (of the research being done so far) *is probably a little bit academic in that it tends to look at single issues, and farm systems don't run on single issues.*" Integration of mitigation options within existing farm systems needs to be developed with the input of the end-user, to aid ease of adoption and affordability. More details and discussions from these stakeholders' identified gaps are available in Appendix 4.

Technical gaps related to agricultural mitigation science across the five clusters were identified by the review team and backed up by input from other researchers and stakeholders (see also Appendix 2, Figures A2-1 to A2-5, where gaps are presented in red text).

5.2 Research gaps in the 'CH_4 inhibitors/vaccines' cluster

- Several compounds/extracts that reduce CH_4 production (e.g. hydrogen sinks and inhibitors) by ruminants have been identified and methods to deliver them to pasture-based animals are being developed. However, it is likely that different delivery methods and different recommendations relating to their use will be required. Therefore, development of a range of practical methods to deliver these methanogen-inhibiting compounds with different activities and hydrogens sinks is required to enable their use in pastoral farming systems.
- A lot of knowledge has been generated to develop compounds to inhibit the growth of rumen methanogens, such as microbial rumen sequencing data. Further scope exists for extending and utilising the sequencing data to identify microbial targets other than methanogens to indirectly lower CH_4 production and increase N utilisation, thereby decreasing N excretion.
- Identify specific bio-active compounds that are naturally present in forages or food industry by-products that lead to reduced CH_4 production in the rumen.

5.3 Research gaps in the 'low GHG animals' cluster

- Sheep selected for producing less CH_4 were found to have smaller rumens. The effect of long-term selection for animals with low CH_4 production over many generations on animal health and production is being investigated. However, the direct effect/mechanism of smaller rumens on digestive function and animal metabolism is not known. Therefore, greater understanding of the direct effect of smaller rumens on the ability of the animal to eat and digest feed is needed.
- Breeding values to select sheep for low CH_4 production will be available to farmers in the short term. Therefore, providing information and education on breeding for low CH_4 traits to farmers will need to be developed.
- Further research is required to develop a suitable low cost direct or indirect method to identify cattle with lower emissions. Once identified, a screening programme can be initiated for identifying low CH_4 cattle in New Zealand.
- The genetic relationship between CH_4 emissions and feed efficiency (similar to a measure of feed conversion into product) is only partially understood, as there have been only a few experiments where both have been measured. This work is needed for cattle to advance our understanding of feed utilisation and CH_4 production.

5.4 Research gaps in the 'low GHG feed' cluster

- It was repeatedly found that animals that consume forage rape (a vegetable-like forage) produce less CH_4, however, the mechanism(s) behind this reduction have not been identified. Identification of this mechanism of reduced CH_4 when feeding forage rape will possibly enable the transfer of this mechanism to other forages/diets.
- There is some evidence that grazing animals on particular plant cultivars within a forage species or particular forage species can reduce either CH_4 and/or N_2O emissions. However, there is currently no classification system available for identifying forage cultivars or species that can result in reduced GHG emissions when used. Therefore, development of a ranking system such as the forage value index, used for comparing ryegrass cost and performance, but in terms of GHG emissions, is required.

5.5 Research gaps in the 'reduced N_2O from soil/plants' cluster

- Earlier research on nitrification inhibitors mainly focused on dicyandiamide (DCD), a chemical that was applied either directly to agricultural land as a suspension or in combination with N fertilisers. While this product was effective a reducing N_2O emissions and N leaching, it was removed from the market due to concerns relating to traces being detected in milk. Alternative compounds are being investigated with funding from MPI through the Global Research Alliance. Promising alternatives could be fast-tracked with SLMACC funding.

- Ingestion of forages plants such as brassicas and plantain have been found to result in reduced N_2O emissions from urine deposited by the grazing animal. This has been termed ‘biological nitrification inhibition’ (BNI). It would be beneficial to understand the mechanism(s) responsible for BNI in such plants, to enable the transfer of this mechanism to other plant species.
- Nitrous oxide production and emission from soils is regulated by, among other factors, the soil oxygen concentration, where low concentrations lead to increased emissions. An improved understanding of the role of soil structure on oxygen concentrations and diffusion through soils may lead to new mitigation options for N_2O emissions from soils.

5.6 Research gaps in the ‘management interventions’ cluster

- Farmers require information on the costs and benefits of concurrent use of several GHG mitigation options on their farms. To date, this type of study has focused on evaluating the GHG footprint of strategies aimed at reducing nutrient losses to waterways. However, there have been no on-farm studies evaluating multiple GHG mitigation options. A further gap is evaluation of mitigation options and farm practices that integrate environmental mitigation of losses to water and air. This type of ‘farm system’ research is needed to develop information for farm advisors and farmers on the net GHG benefits from the use of multiple options, and how to successfully integrate these into farm systems across the country. As one industry stakeholder told us, in order to enable farmers to reduce emissions or even reach a carbon-neutral level, “*..there’s a significant need for a tool for farmers to be able to assess what their footprint essentially is at the gate and what they can do to change it, particularly one that would incorporate multiple activities across a farm and across farm management*.”
- An increasing proportion of animal manure is being collected, stored and applied to agricultural land, rather than being directly excreted onto paddocks by livestock. This is due to the increasing use of animal shelters and non-pasture animal standing and/or feeding areas called ’stand-off pads’ and ‘feedpads’. While a reduction in excretion onto soils helps to reduce both nitrate leaching from paddocks as well as N_2O emissions from soils, there is a risk of greater total GHG emissions due to enhanced emissions during the management of the manure. This substitution of sources and emissions is termed ‘pollution swapping’. It is recommended, in the

first instance, to conduct a review of the most effective GHG mitigating manure management systems, followed by experimentation to quantify the extent of selected mitigation systems.

- Irrigation of land under generally warm conditions could exacerbate N_2O emissions, therefore guidelines are required for irrigators to minimise emissions whilst maintaining production. Several studies have been conducted to date. We recommend a review of irrigation management practices to reduce GHG emissions to determine if/where further research is warranted.

5.7 Other GHG mitigation options not included across the five clusters

- Future-proof on-farm mitigation strategies: agricultural GHG mitigation research to date has been performed under current climate conditions. More research is required to assess mitigation options under changing climate conditions, through controlled experimental research e.g. using New Zealand’s free-air CO_2 enrichment (FACE) facility near Palmerston North combined with farm-scale modelling.
- Land use diversity: Changing from livestock production-dominated agriculture to more diverse land uses that have smaller total GHG footprints while adhering to water quality regulations, community values and providing financial security. As noted by one stakeholder: "*What is the next high-value land use the primary sector will migrate to?*"
- Capturing or reducing CH_4 emissions by ruminants: It may be possible to develop technology to capture, filter or oxidise CH_4 from ruminant breath prior to it being exhaled into the atmosphere.
- Multi-targeted inhibitors: identification and development of inhibitors that can reduce both CH_4 and N_2O production.
- Agricultural GHG mitigation research focusses on biological emissions, however, agriculture also produces GHGs from energy use. Therefore, cross sector (agriculture and energy) investigation into mitigation options to reduce biological and fossil fuel GHG emissions simultaneously.
- Most GHG mitigation research to date has aimed only at determining the reductions of CH_4 and/or N excretion from animals, while the effect on animal health, productivity and quality of animal products have not been determined. This has to be known before a mitigation option can be promoted into industry.

6. Enablers of and barriers to adoption

Despite public investment in the science behind agricultural mitigation options, it is important to consider the barriers that farmers might face when deciding whether or not to adopt a particular option. The barriers to adoption become even more important under current conditions, as, across the world, the agricultural industry has still not received strong signals in terms of regulation or incentives to reduce its GHG emission footprint. And New Zealand is no exception. A common theme throughout our stakeholder interviews was that despite the scientific excellence pervading the SLMACC programme, it hasn't led to significant uptake of mitigation products: "*We've used SLMACC more for a science investment than for uptake*".

Enablers of adoption can be defined as particular conditions that lead to an increase in the number of farmers using one or more mitigation options. Enablers can range from national/regional policies through to individual incentives within particular regions. We expand on this below, after which we consider the barriers to adoption.

6.1 Enablers: facilitating the adoption of on-farm mitigation

We identified ***three key strengths and enablers*** from SLMACC agricultural mitigation projects funded over the period from 2007 to 2017. In particular, these enablers minimised some of the barriers identified in the following section. Building on these strengths can provide support for future mitigation research and adoption efforts.

Diversity on funded research

There are no 'silver bullet' GHG mitigation options, and farmers may have to adopt a variety of options to meet potential future targets. Given this, SLMACC has funded a *diverse* range of scientific research, e.g. across the five mitigation research clusters discussed in this review. This breadth has been an important strength of the programme because it has allowed the development of a wide range of mitigation options, some of which have not proven viable, and others that have.

Supported collaboration across research institutes

The majority of SLMACC mitigation projects included more than one institute, facilitating cross-collaboration between institutes and research teams. This has been a critical enabler for the exchange of ideas and advancing scientific investigation. This particular enabler of the SLMACC programme has also been a positive outcome for these projects, as evidenced by five out of seven projects indicating the scientific networks established endured beyond the SLMACC project.

Developing quality science for next-users (researchers) to extend science further
The outstanding quality of the science and research endeavours funded by the SLMACC programme has enabled SLMACC to have significant impact on next-users for continued scientific progress. This was achieved through the SLMACC procurement process, whereby research contracts were typically awarded to research teams that could demonstrate how their research would meet the goals of the SLMACC programme and whether their research was of high science quality and built science capability. A further requirement was the ability to deliver results, evidenced by existing track records. This robust evaluation process contributed to the development of good quality science for next-users.

6.2 What has limited farmer adoption of mitigation technologies or practices?

The first important direct barrier to the adoption of mitigation options ***has been the limited number of GHG mitigation options currently available*** for stakeholders or farmers to use in New Zealand.

Most scientific research into mitigation options have been carried out overseas; especially the USA, UK and Australia (see Figure 1-5 in Fleming and Preston (2018). More importantly, the majority of discovered mitigation technologies and practices are not suitable for New Zealand farming conditions. For instance, the Dutch consortium DSM released a CH_4 inhibitor this year (2018) that can reportedly reduce emissions by 20 percent in farming cattle. However, this inhibitor is mainly intended to be provided with feed in on-barn feedpads. Efforts are being made by the PGgRc to adapt this option to New Zealand conditions.

Secondly, the number of options available for on-farm use is limited. Specifically, products such as CH_4 vaccines and inhibitors, low emission animals and feed supplements require further research before being made available to the market. While some options may require only a few more months' research (e.g. low CH_4 sheep), some may take several years of further research before farmers can implement them on farm (e.g. CH_4 vaccines, if the breakthrough is realised).

"*A lot of it* (of the research being done so far) *is probably a little bit academic in that it tends to look at single issues, and farm systems don't run on single issues.*" This point, raised by a stakeholder, relates to the limited number of options noted above. Applied research is a key component of the research pipeline, to ensure mitigation options are practical and can either fit within existing farm systems or systems can be easily adapted to accommodate the new technology or practice.

The second key barrier to adoption relates to the lack of understanding on the impacts of potential policy mechanisms (e.g. incentives or taxes) to encourage farmers to adopt low GHG mitigation options. This includes not knowing whether the point of obligation for GHG emissions would fall on farmers or on industry. Furthermore, farmers are unsure if they will be facing a tax or will be recognised for their efforts through incentives or other such mechanisms. This is mainly due to the fact that the government is still developing the policy mechanisms, with input provided by the Interim Climate Change Committee (ICCC). Although on-farm decisions will still be required to reduce GHG emissions regardless of the point of obligation, it can impact the *type* of mitigation a farmer, or the industry as a whole, may adopt.

However, even if mitigation options would become readily available to farmers and the policy was in place, there would still be ***other potential barriers to adoption*** of mitigation strategies in the future, such as the cost exceeding the benefit or non-financial barriers. On the latter group, Jaffe (2017) provides a typology of 29 different non-financial barriers that could affect farmers' decisions when adopting a new practice, option or technology. These 29 barriers are categorised into seven groups, which are shown in Figure 2. Studies looking at the relevance of these barriers in New Zealand agriculture are still limited, although evidence exists on the occurrence of several of them.[5]

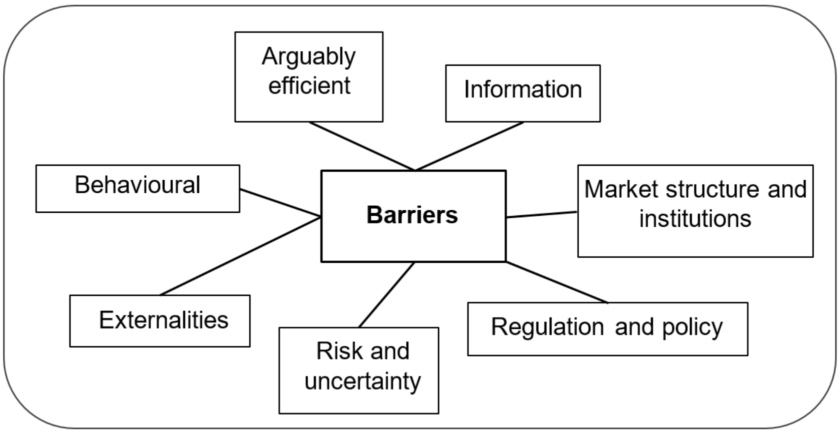


Figure 2. *Barriers to efficient decision making in farming contexts.*[6]

[5] However this evidence is not related to the adoption of GHG mitigation options. For a list of studies providing evidence on barriers in New Zealand agriculture see https://motu.nz/our-work/environment-and-resources/agricultural-economics/no-cost-barriers/database-of-evidence-on-barriers-to-adoption-in-agriculture-in-new-zealand-and-overseas

[6] Adapted from Jaffe (2017).

7. Recommendations

We recommend the following actions to maximise the future value and usefulness of SLMACC-funded research:-

- Ensure any future SLMACC-funded programmes on agricultural GHG mitigation include engagement with targeted next and end users, at an early stage and throughout the project. It is important that mitigation options are not tested on-farm in isolation of other farming challenges. Integration of mitigation options within existing farm systems needs to be developed with the input of the end-user, to aid ease of adoption and affordability. This will ensure the research topic, design and resulting knowledge is relevant, creates feasible options for uptake, is packaged appropriately, and has a pathway for extension to farmers and industry. This may be particularly relevant to specific mitigation projects with a strong applied research component. This may need to be co-developed and co-funded by industry organisations such as DairyNZ and Beef + Lamb NZ.
- Commission a project with researchers, policy agents, change agents and involved practitioners to identify existing practical mitigation knowledge that could be disseminated. Funding should then be prioritised for extension activities that support uptake of existing available options.
- Ensure that a future SLMACC-funded programme includes resources for a coordinated communication plan to report key findings of future research projects to future users and the wider public. To ensure consistent messaging and to facilitate delivery of the information, such a plan should be developed in collaboration with the NZAGRC/PGgRc, relevant industry organisations (e.g. DairyNZ and Beef and Lamb NZ) and existing industry initiatives (e.g. Dairy Industry Action for Climate Change), and also utilise existing communication and extension mechanisms such as the Climate Cloud (www.climatecloud.co.nz). We note the similarity of these recommendations with those in the companion Technology Transfer Review report.
- In the event that agricultural GHG mitigation research is no longer funded by the SLMACC programme, that the recommendations outlined above are considered by an alternative funding vehicle e.g. NZAGRC, PGgRc.

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Appendix 1: SLMACC projects included in the current review of agricultural greenhouse gas mitigation research, clustered by five mitigation research areas.

	Project				
#	MPI ID	First year	# yrs	Title	Lead organisation
1. CH_4 inhibitors/vaccines cluster					
1	AGR30689	2012/13	1	Enteric methane mitigation through nanoparticles	AgResearch
2	AGR30783	2012/13	3	Hydrogen management in the rumen	AgResearch
3	C10X1105*	2011/12	1	Hydrogen management for methane mitigation	AgResearch
4	METH0801	2008/09	2.5	Protozoa, Low Methane rumen, Mitigas	PGgRc
5	METH0802	2008/09	2.5	Accelerated ruminant methane mitigation	PGgRc
11	C10X0829*	2008/09	1	Forage/fungal associations for reducing methanogenesis	AgResearch
12	C10X0901*	2009/10	3	Identifying non-agricultural and agricultural plant species with anti-methanogenic properties	AgResearch
16	LINX0901*	2013/14	2	Biochar in grazed pasture systems	Lincoln University
2. Low GHG animals cluster					
6	DRCX0803	2008/09	2.5	GHG mitigation using efficient cows	DairyNZ
7	METH0901	2009/10	3	Sheep, cattle and methane predictors	PGgRc
17	MAF POL_ 2008/42*	2013/14	2	To improve the sheep component of the CH_4 model and provide management strategies for farmers to reduce CH_4 production	On-farm Research

	3. Low GHG feeds cluster				
3	C10X1105*	2011/12	1	Hydrogen management for methane mitigation	AgResearch
8	AGR30624*	2012/13	3	Total GHG emissions from supplementary feeds in farm systems	AgResearch
9	AGR30737	2012/13	3	Brassicas - a win-win option for GHG mitigation and animal productivity	AgResearch
10	AGR30887	2012/13	3	High sugar ryegrasses and methane emissions	AgResearch
11	C10X0829*	2008/09	1	Forage/fungal associations for reducing methanogenesis	AgResearch
12	C10X0901*	2009/10	3	Identifying non-agricultural and agricultural plant species with anti-methanogenic properties	AgResearch
13	C10X1102	2011/12	1	Brassicas, methane and nitrous oxide	AgResearch
14	MAF POL_ 2008/30	2007/08	0.4	Assessing the role of dietary carbohydrate to protein ratios on GHG emissions from pastoral agriculture	AgResearch
15	MAF POL_ 2008/36*	2007/08	0.25	Nitrous oxide - novel mitigation methodologies	Lincoln University
	4. Reduced N_2O from soil/plants cluster				
15	MAF POL_ 2008/36*	2007/08	0.25	Nitrous oxide - novel mitigation methodologies	Lincoln University
16	LINX0901*	2013/14	2	Biochar in grazed pasture systems	Lincoln University
22	AGR30649	2012/13	0.3	National impacts of temperature and moisture on DCD effectiveness	AgResearch
23	C10X1101	2011/12	1	DCD effects on N fixation	AgResearch
24	MAF POL_ 2008/32	2007/08	1.4	Quantifying the variability of the effectiveness of nitrification inhibitors on N_2O emissions	AgResearch
25	16110	2012/15	2.3	Direct nitrous oxide (EF_1)	AgResearch
26	11063	2008/09	1	Desktop study of emission factors for urease inhibitors for nitrogen fertiliser	Landcare NZ
27	12207	2010/11	1	Reductions in FracGASM and FracGASF in the GHG inventory when urease inhibitor has been applied to the soil and with N fertiliser	Landcare NZ

28	C10X0827	2008/09	1	Plant canopy nitrous oxide emissions	AgResearch
29	LIN30678	2012/13	1	Biochar effects on urea-derived N_2O and ammonia	Lincoln University
30	MAUX0903	2009/10	1	Can cattle do it?	Massey University
5. Management interventions cluster					
8	AGR30624*	2012/13	3	Total GHG emissions from supplementary feeds in farm systems	AgResearch
17	MAF POL_ 2008/42*	2013/14	2	To improve the sheep component of the methane model and provide management strategies for farmers to reduce methane production	On-farm Research
18	ONF30870	2013/14	2	Grazing management systems to reduce nitrous oxide emissions	On-farm Research
19	AGR131402	2009/10	1	Assessment of the GHG footprints of the low and high input dairy systems of the Canterbury P21 farmlet trial	AgResearch
20	AGR131405	2013/14	2	Identification of problem areas within farms and farming systems and approaches to mitigate nitrous oxide hot spots.	AgResearch
21	PFR30735	2012/13	2.3	Irrigation and nitrous oxide	Plant & Food Res
31	C10X0902	2009/12	3	System analysis to quantify the role of farm management in GHG emissions and sinks for the pastoral sector	AgResearch

Source: Collated by current project team with data on SLMACC projects received from MPI. *Note*: * Project that aligns with more than one mitigation cluster.

Appendix 2: Technical description of mitigation options and knowledge gaps within the five clusters of SLMACC projects

Research projects focusing on the mitigation of agricultural GHG emissions can be undertaken at a range of spatial and temporal scales, depending on the hypotheses being tested, experimental design and the available budget. Furthermore, research activity typically aligns with a research pipeline, from discovery research, moving through to development and applied research. Discovery research is often (but not always) laboratory-based, while development research focuses on proof-of-concept research trials. In contrast, applied research operates at a larger scale, allowing researchers to focus on proof of practice of a mitigation option, sometimes within a farm system context to allow observations of interactions, potential synergies and unintended consequences.

It was important to evaluate the SLMACC-funded research in the context of other government investment into agricultural mitigation in order to better understand the contribution of SLMACC funding into the research investment efforts at national scale. The subsections below therefore include a description of all the government-funded research activities relating to each mitigation cluster. The SLMACC-funded projects, as detailed in Table 2, are referred to with numerical values (from 1 to 31) in brackets within the text below and in Figures A2-1 to A2-5.

Key knowledge gaps, identified in Section 6, are illustrated in red text in Figures A2-1 to A2-5.

CH_4 inhibitors/vaccines cluster

Inhibition of CH_4 emissions can be achieved by directly inhibiting the growth and activity of methanogens that produce CH_4 or make rumen conditions less favourable for their growth and activity. These approaches are referred to as ‘direct inhibition’ and involve disruption of their metabolic function (activity) and growth (numbers). The success of a mitigation technology requires an understanding of the diversity of methanogens in the rumen and discovery of metabolic steps that are common across the diverse methanogens. To that effect, a large body of research has involved determining the diversity in methanogen species present in the different ruminant species on different diets around the world (Henderson et al., 2015) and genome sequencing of the individual methanogen species (Seshardi et al., 2018) to identify common metabolic properties to target with inhibitors or vaccines. Inhibitor discovery has involved screening feeds and feed extracts containing bioactive compounds (e.g. essential oils, tannins, medicinal compounds) (e.g. 11, 12) small molecule chemicals (5), small biological particles (“nanobeads”) carrying enzymes to disrupt methanogens (1) and vaccines to produce antibodies in the ruminant animal against methanogens. Part of this research has involved developing new and more effective methods to screen inhibitory compounds, development of delivery methods of inhibitors in grazing systems and determining positive or negative side effects on animal function and production (2).

Work on vaccines, nanobeads and small-molecule inhibitors is still in progress in New Zealand; however, there are currently no products close to release to the open market. One commercial company (DSM Nutrition Products, Basel, Switzerland) has developed a small-molecule inhibitor called 3-nitrooxypropanol (3-NOP) which has been successfully fed as part of the total mixed ration (TMR) of dairy and beef cattle, reducing CH_4 emissions by about 30% without affecting dry matter intake (DMI) and animal production (Vyas et al., 2016; Hristov et al., 2015). Pulse dosing 3-NOP in the rumen was, however, not as effective in reducing CH_4 emissions (Reynolds et al., 2014) and therefore its usefulness for inclusion in supplements fed during milking, which would be practical in grazing systems, still needs to be proven. One potential option is the development of slow release boluses with 3-NOP.

Hydrogen produced during fermentation of feed in the rumen is utilized by methanogens to form CH_4 (Janssen, 2010). Therefore, making rumen conditions less favourable for methanogens has involved reducing hydrogen formation in the rumen or redirecting hydrogen produced away from methanogens by providing alternative “sinks” for the hydrogen. Reducing hydrogen formation has been attempted through defaunation (4) of protozoa from the rumen, dietary changes to depress acetate and butyrate formation (which are associated with hydrogen formation) and feeding rumen modifiers such as ionophores [e.g. monensin; (Waghorn et al., 2008)]. Alternative hydrogen sinks to methanogenesis that have been studied include nitrate (3) and sulphate [which might be present at higher concentrations in some forages such as brassicas (9,13)], malic acid, furmaric acid (Molano et al., 2008) and unsaturated lipids (3).

Defaunation has been successful in decreasing CH_4 emissions in some studies, but is hard to achieve, even under experimental conditions (Guyader et al., 2014). Ionophores and other propionate promotors have been successful in reducing CH_4 emissions, but with very variable results. Increasing the lipid content of the diet has been found to reduce CH_4 emissions (e.g. Patra et al., 2013, 2014; Grainger and Beachemin et al., 2011); the magnitude of the role of unsaturated lipids as a hydrogen acceptor appears a minor mechanism, however. Nitrate supplementation consistently reduces CH_4 emissions (Lee and Beauchemin, 2014) and development of nitrate lick blocks is in progress, which could be used under grazing conditions (Hegarty, 2011). Added biochar to the diet might absorb gases in the rumen and thereby reduce emissions. Two studies in New Zealand found no clear mitigating effect of biochar on CH_4 emissions *in vitro* (16, 30), however.

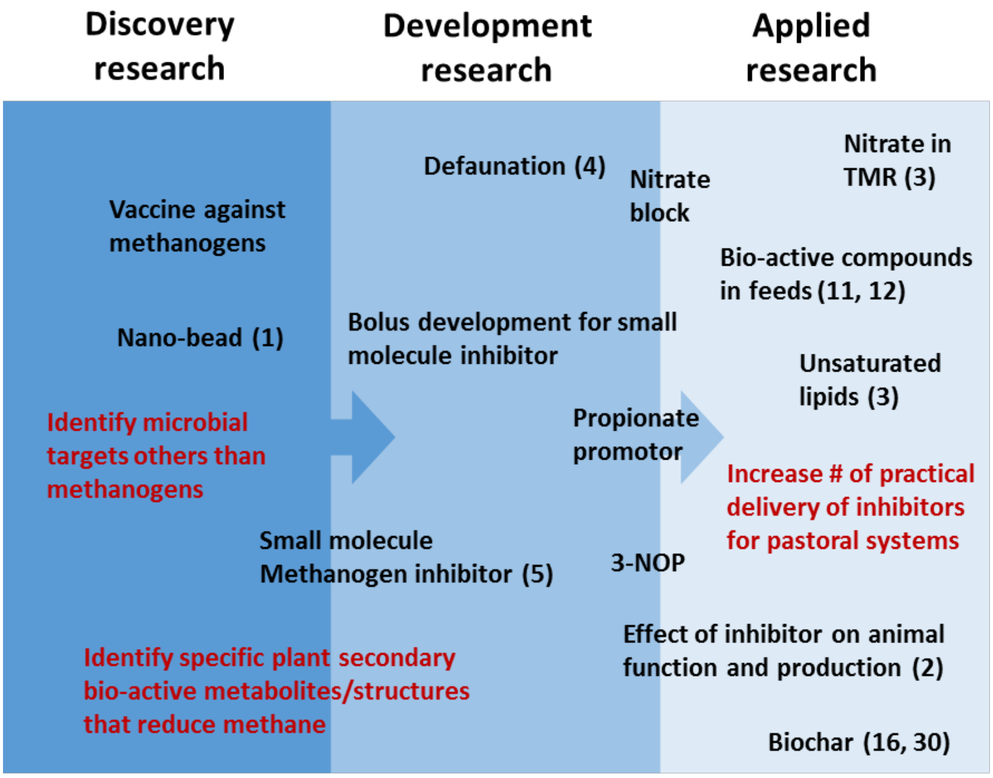

Figure A2-1. Methane inhibitor/vaccine research projects with research gaps identified in red text. TMR, total mixed ration; 3-NOP, 3-Nitrooxypropanol.

Low GHG animals cluster

Reducing CH_4 emissions from animals through breeding can be achieved by improving life-time animal production, reducing DMI per head (through improved feed conversion efficiency (6)) or direct selection for reduced CH_4 emissions (7). Methane intensity (emissions per unit of product) has decreased since 1990 according to the New Zealand GHG inventory (Ministry for the Environment, 2018) due to improvements in genetic merit for milk production in dairy cows, increased lambing percentage in sheep, and management factors such as improved nutrition. Reducing the total farm maintenance energy requirements of livestock due to reduced animal mature weight and increasing longevity (reduced need for replacement animals) were found to be effective strategies to reduce life-time CH_4 emissions (6, 17).

Reducing DMI per unit of animal product (improved residual feed intake; RFI) will likely reduce CH_4 emissions. Breeding values for DMI and RFI are available in some countries for beef and dairy cattle. It has also been found that there is a genetic basis for reduced CH_4 emissions (both g/d and g/kg DMI) in sheep (7; Pinares-Patino et al., 2013) and cattle (Hayes et al., 2016), with the trait being heritable. Part of the research into low CH_4 animals has focused on finding correlated proxies for the CH_4 yield trait (7) to increase genetic progress and provide cost-effective methods for maintaining breeding values in future and development of genomic breeding values. Another stream of research has focused on making sure the selection for reduced CH_4 yield does not result in negative correlated production traits.

Milk urea N (MUN) is a heritable trait in dairy cows (Mucha et al., 2011) and MUN was previously related to urinary N excretion by the animal (Spek et al., 2013). Urine N excretion in turn is the main source of N_2O in New Zealand pastoral systems (de Klein and Ledgard, 2005). However, the genetic correlation between MUN and urinary N excretion has not been determined to date. Currently, a research programme is funded by MBIE to address this question and investigate the reductions in urinary N that can be achieved by the dairy industry by using sires selected for low MUN concentrations.

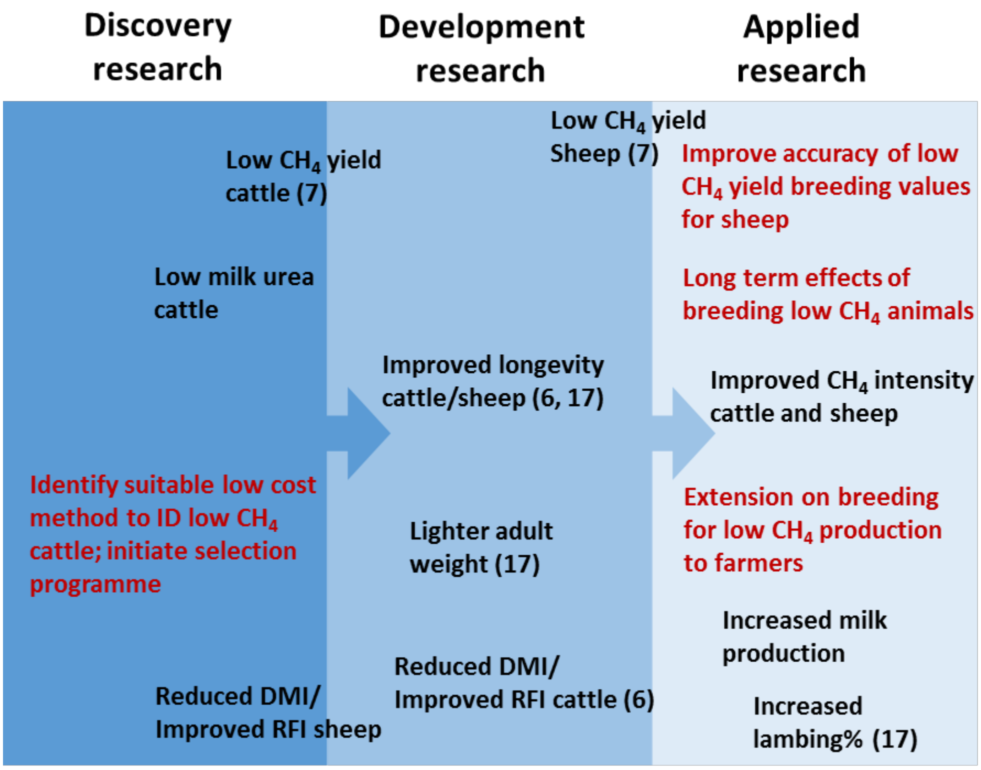

Figure A2-2. Low greenhouse gas animal research projects with research gaps identified in red text. DMI, dry matter intake; RFI, residual feed intake.

Low GHG feed cluster

Feeds (diets) can alter enteric CH_4 emissions through digestive availability (digestibility, rumen retention time etc.), changing rumen conditions (e.g. rumen pH, acetate/butyrate/ propionate ratio), promoting microbial growth (hydrogen incorporation in microbial bodies), and the amount of DM intake. Methane yield is generally reduced with increasing feeding level, reduced retention time of feed in the rumen, very high concentrate inclusion in the diet (>70% of diet DM), and increased lipid and tannin content in the diet (8). In New Zealand, grazing forage rape has been found to reduce enteric CH_4 emissions (9, 13), while there is limited evidence of similar results from grazing of turnips and fodder beet (19). Fodder beet has also been found to result in a lower N_2O emission factor from urine (EF_3; percentage of N deposited lost as N_2O-N) compared to kale (19). In ryegrass-based pasture-fed animals, the chemical composition of the pasture eaten explained very little of the variations in CH_4 emissions (Muetzel and Clark, 2015). In a recent study comparing three ryegrass cultivars (conventional diploid, high sugar diploid and tetraploid), however, one cultivar repeatedly resulted in higher CH_4 emissions (10), suggesting that there is scope for identifying low CH_4 ryegrass properties/cultivars. High lipid grasses are in development via conventional breeding and via genetic modification, and these grasses will likely be CH_4 mitigation options for future grazing systems. In general, diets with increasing digestibility (energy content) promote greater DMI, which will lead to reduced CH_4 emission intensity because more nutrients are available for animal production.

Many other forages, feeds and food industry by-products have been screened for their ability to reduce CH_4 emissions. In New Zealand, *in vitro* screening identified garlic, horopito, osage, orange, oregano, cauliflower (12) and the fungus *Mortierella wolfii* as reducing CH_4 gas concentration, but not grass endophytes (11). However, *in vitro* results do not necessarily translate to a response *in vivo* and *vice versa* (Flachowsky and Lebzien, 2009; Sun et al., 2011) and therefore those results should be confirmed *in vivo*. Plants containing condensed tannins have been found to reduce CH_4 emissions *in vitro* and *in vivo*. But uptake by farmers of condensed tannin-containing forages is hindered by their inferior agronomic performance compared with perennial ryegrass and white clover. However, progress has been made internationally in breeding improved *Lotus corniculatus* and sainfoin cultivars (e.g. Grant, 2004; Acharya et al., 2013), providing potential future opportunities for condensed tannins as a mitigation option. These forages are also more drought tolerant than ryegrass and white clover.

In terms of N_2O emissions, feed can affect the total amount of urinary N excreted by animals, the proportion of feed N excreted as urine, and reduce the N_2O emission factor from excreta-N deposited onto soil. The main driver of N excretion by animals is the N content of the diet. Improving energy availability in the rumen (e.g. through increased water soluble carbohydrates (WSC; 10, 14), soluble fibre etc.) can improve N capture in the animal. Reducing the N: WSC ratio in pasture improved N use efficiency in dairy cows (Edwards et al., 2007). Supplementing lactating dairy cows with maize silage or fodder beet bulbs (low N feeds) and grazing diverse pastures (pasture containing ryegrass, clover, chicory, plantain etc.) reduced N excretion and lowered the N_2O EF_3 (8, 19). Using brought-in supplements with lower N content than pasture, rather than growing pasture DM on-farm allows farmers to reduce the amount of N eaten by animals. This reduces the need for N fertiliser to produce feed, thereby reducing GHG emissions associated with N fertiliser and urine and dung depositions (de Klein and Ledgard, 2005). The proportion of N in urine relative to faeces is also mainly driven by the N concentration of the diet, with lower N diets partitioning more of the excreta N into faeces. Other factors that might increase the N partitioning towards faeces include increasing diet fibre content, inclusion of condensed tannins in the feed and feeding forages with compounds that affect ammonia-producing rumen microorganisms. An example of such a compound is polyphenol oxidase that is found in red clover.

Feed type may reduce N_2O emissions from deposited excreta via mechanisms other than reducing the urine N concentration or partitioning more N into faeces. Laboratory studies have shown that increased concentrations of hippuric acid in urine can have a marked effect on nitrification and denitrification rates and on subsequent N_2O emissions (Kool et al. 2006; Bertram et al. 2009). However, when tested under field conditions, no reduction in N_2O emissions was observed (15).

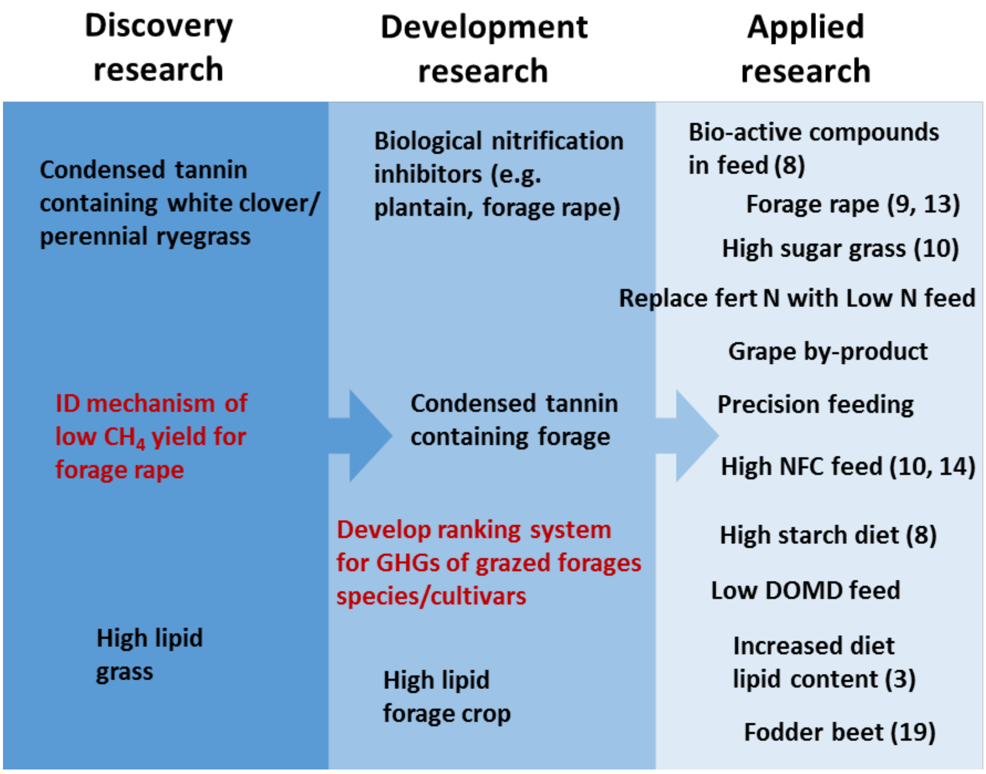

Figure A2-3. Low greenhouse gas feeds research projects, with research gaps identified in red text. NFC, non-fibre carbohydrates; DOMD, digestible organic matter on a dry matter basis.

Reduced N_2O from soil/plants cluster

Soil additives such as nitrogen process inhibitors [urease inhibitors (26, 27) and nitrification inhibitors (22-25)] and, more recently, biochar, have the potential to mitigate NH_3 and/or N_2O emissions (15, 16, 29). Nitrification inhibitors and urease inhibitors provide a technology for reducing gaseous losses of N_2O and NH_3, respectively. Direct application of the nitrification inhibitor dicyandiamide (DCD) to New Zealand pastoral soils was found to slow the conversion of ammonium (NH_4^+) to nitrate (NO_3^-), thereby reducing N leaching and N_2O emissions from deposited urine (Di and Cameron, 2002). Since that early discovery, a large number of research projects have focused on improving the understanding of the effectiveness of DCD and investigating potential unintended consequences. This includes quantifying the half-life of DCD in soils under contrasting temperatures and soil moisture contents (22), assessing the potential impacts of DCD on white clover growth and N fixation (23), and testing DCD on a wide range of key soil types used for dairy farming (24). Another known application of nitrification inhibitors is as an amendment to N fertiliser products to reduce N losses including N_2O emissions. However, the DCD load on granules impacts on the efficacy of such products: when trialled in New Zealand at loads deemed commercially viable, N_2O emissions were not reduced (25). DCD was also applied with farm dairy effluent (FDE) and again no reduction in N_2O emissions was observed (25). It is important to note that there is currently a voluntary suspension of sales and application of DCD to farmland in response to the detection of DCD residues in milk. Future options to meet international trade requirements are being considered.

Urease inhibitors such as N-(n-butyl) thiophosphoric triamide (nBTPT), coated onto the surface of urea granules, inhibit the hydrolysis of urea fertiliser in soil, slowing the conversion of urea to NH_4^+, thereby decreasing the rate of ammonia (NH_3) volatilisation. Emissions have been reduced by, on average, approximately 80% in the UK (Watson, 2000). New Zealand studies where nBTPT was applied at 250 mg nBTPT/kg urea reduced NH_3 emissions, on average, by 43% from urea and 48% from urine (26). This reduced loss of N as NH_3 also means urea fertiliser is potentially more effective at stimulating pasture growth, suggesting N application rates could be lowered accordingly. However, agronomic field studies examining pasture responses to urea treated with nBTPT have shown mixed results (Blennerhassett et al. 2006; Martin et al. 2008) suggesting a pasture response is not guaranteed. Following a review of this research (27) and publication of the findings (Saggar et al. 2013), the national GHG inventory now applies an adjustment of 0.55 to the fraction lost as NH_3 from urea fertiliser (FracGASF) that has been treated with nBTPT. This is currently the only available mitigation option included in the national GHG inventory.

Biochar (organic matter carbonised under controlled conditions) is a very stable form of carbon, and thus has been suggested as a method for sequestering carbon in soil. In addition to promoting C sequestration, there may be other synergies such as reduced N_2O emissions from urine patches. While application of biochar to the soil surface has not been successful at reducing N_2O emissions (29), incorporating biochar into soil does reduce N_2O emissions (15, 16). This research also showed that there was no unintended consequence in terms of increased NH_3 emissions. Furthermore, lower soil nitrate concentrations were observed, suggesting potential for reducing both N leaching and N_2O emissions. Cost and coverage remain the main challenges with biochar: while cost is market-driven, one possible solution for applying biochar to large areas of pasture is to add biochar to feed and use the animal to distribute the product through its faeces (30).

Soil pH management provides an opportunity to minimise N_2O and N_2 emissions where an increase in soil pH can reduce N_2O emissions and the ratio of $N_2O:(N_2O+N_2)$ via denitrification (Stevens and Laughlin, 1998; Samad et al, 2016). For New Zealand soils, van der Weerden et al. (1999) proposed that managing soil pH at approximately 6.5 may act as an effective N_2O mitigation option; the current recommended optimum soil pH for pasture production is 5.8-6.0 (Morton and Roberts, 2009). A new (2017) European/New Zealand research programme funded by MPI and overseas organisations will investigate the potential for managing soil pH to reduce N_2O emissions, with a focus on understanding the role of soil functions and biodiversity and the cost: benefit of improved soil pH management. Research is also underway in New Zealand and overseas on accelerating N_2O reduction via denitrification, by improving understanding of the role and presence of the N_2O reductase gene (nosZ); this work is funded by MPI via the Global Partnerships in Livestock Emissions Research (GPLER).

Plant leaves are also a source of N_2O emissions (28), suggesting new mitigation strategies that target the leaf rather than just the soil may be worthy of investigation.

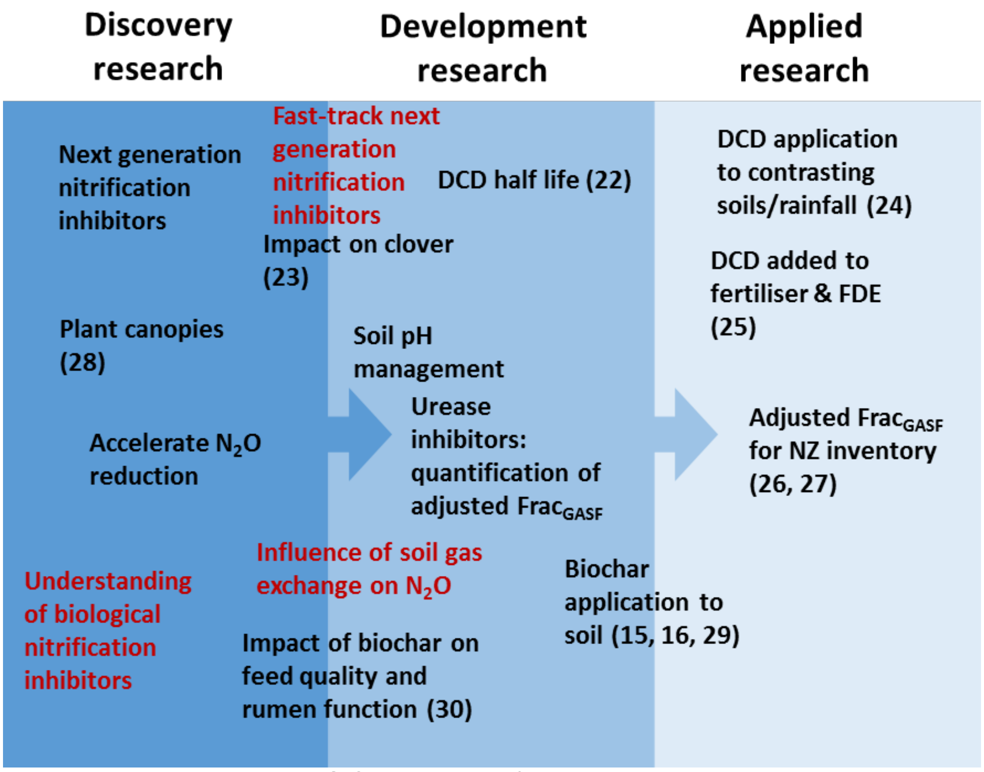

Figure A2-4. Reduced N_2O from soil and/or plants research projects, with research gaps identified in red text. BNI, biological nitrification inhibition; NUE, nitrogen use efficiency; DCD, dicyandiamide; FDE, farm dairy effluent; $Frac_{GASF}$, fraction lost as NH_3 from urea fertiliser.

Management interventions cluster

Farm management interventions cover a broad range of activities, including on-farm management of livestock, feed and manure, and external inputs such as supplements, fertiliser and irrigation. Because these interventions do not target the rumen or soil processes directly, they are often referred to as indirect mitigation approaches. These approaches seek improvements in efficiency of utilisation of feed resources or productivity. Therefore, their effects are particularly relevant for reducing emissions per unit of animal product and gross emission, not necessarily emission factors. Due to the cost associated with farm systems research, many of these interventions are evaluated through modelling, with some targeted component research providing data for model development and scenario testing. While this is an accepted approach for evaluating management practices, an implication of this is the possibility that the modelled outcomes will not accurately mimic outcomes in real-life commercial situations.

Farm inputs such as brought-in feed (8), fertiliser and irrigation will increase feed supply, thereby increasing intensification through stocking rate and/or production per animal (e.g. milk solids per cow). Intensification will typically lead to increased GHG emissions per on-farm hectare (8, 19), while emissions intensity (emissions per unit product) can either increase (19), remain unchanged or decrease (8). Reduced fertiliser inputs directly impact on the amount of feed produced, and have an associated reduction in carbon footprint (estimated via a life cycle assessment; LCA) due to CO_2 emissions from fertiliser manufacturing and transportation. Irrigation management reduced N_2O emissions when irrigation frequency was reduced, and when grazing on poorly drained soils was delayed by 6 days following irrigation (21). N leaching did not appear to be influenced by irrigation intensity (21).

On-farm livestock management can influence emissions intensity, as suggested by a modelling study on CH_4 emissions per lamb produced (17). This work showed that CH_4 emissions per lamb sold could be reduced by 14% due to more lambs produced without the maintenance cost of running more ewes, while increasing ewe scanning percentage from 160 to 180% (1.6 to 1.8 foetuses/ewe) could reduce CH_4 output by 8%. Increasing ewe longevity was another option that reduced CH_4 output by 6% by maintaining fewer replacements within the flock (17). These combined effects would result in a CH_4 reduction of 21% per lamb sold.

A combination of lower stocking rates together with improved breeding worth or animal health have been shown to reduce total GHG emissions, while maintaining or increasing production (31; Vibart et al. 2015; Beukes et al. 2011). Low stocking rates are associated with a lower feed supply, due to a reduction in N inputs, including direct N fertiliser use for on-farm pasture production and off-farm supplement production. While reduced N inputs will lead to fewer cows (because there is less feed), having top genetic merit cows and milking these for longer should increase feed conversion efficiency, with less feed required for maintenance and more feed converted into animal product. Improving livestock fertility levels and breeding management in dairy cows would subsequently allow a reduction in heifer replacement rates. Modelling has indicated that reducing replacement rates from approx. 22% to 18% could reduce GHG emissions (enteric CH_4 and N_2O from excreta and N fertiliser) at a herd level by between 3 and 11% (31, Garnsworthy, 2004; van der Weerden et al. in prep.).

Diurnal variation in urinary N concentration may be correlated with diurnal grazing behaviour (Betteridge et al. 2013; Clark et al. 2010), therefore changing the feeding time may reduce N_2O emissions (18). While measurements were combined with data from other studies, there was insufficient data to be able to predict diurnal patterns of N excretion based on feeding time or feed composition (18). A similar study on sheep found that about 60% of urine and faecal N is deposited within 12 hours of feeding, suggesting that delaying feeding to the afternoon may reduce NH_3 and N_2O emissions due to the cooler night temperatures (18).

Avoiding grazing when soils are wet reduces the amount of excreta deposited when soil conditions favour enhanced N_2O emissions (de Klein and Ledgard, 2005). Several studies have shown that reducing grazing hours during wet conditions by placing stock onto off-paddock facilities (e.g. stand-off pads) can reduce direct and indirect (via N leaching) N_2O emissions from paddocks (de Klein et al., 2006; Luo et al., 2013). However, an unintended consequence of this practice is increased GHG emissions from manure management; these can be greater than the reduction in emissions from wet paddocks, depending on soil drainage (van der Weerden et al. 2017).

Adoption of a low rate of FDE application, and application to a larger area, has recently been suggested as a strategy for reducing GHG emissions (Watkins et al. 2016). Modelling results indicated that emissions were slightly reduced due to shorter periods of effluent storage and lower rates of N fertiliser use.

Identifying potential on-farm N_2O hot-spots provides an opportunity to effectively target mitigation options in key areas of the farm landscape (Matthews et al. 2010). This requires an assessment of where such hotspots may exist, quantifying the degree of increased N_2O activity, and presenting recommendations on how to mitigate this increased activity. A study focused on all these key aspects for dairy farms (20), and the paddock gateways were found to represent the most important hot-spots. These areas had increased N_2O emission factors, but similar excreta inputs, compared with the rest of the paddock. Mitigation options offered included avoiding application of N fertiliser and manure to these areas, applying gravel or carbon-rich materials to the soil surface near gateways, improving drainage or locating gates on free draining soils where possible.

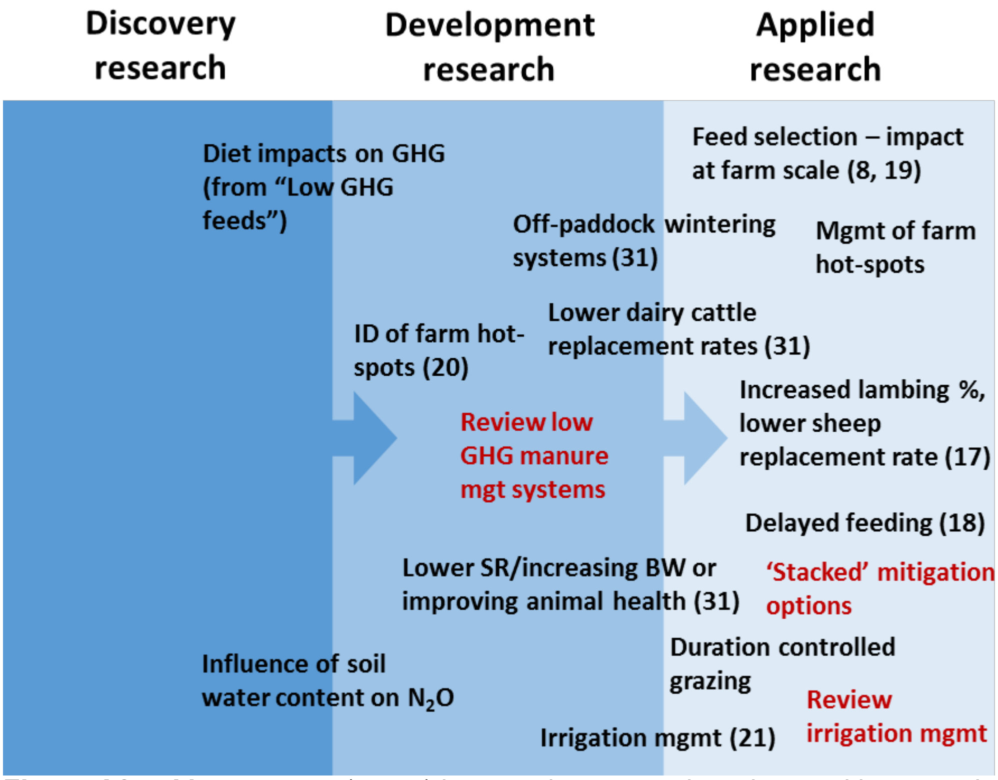

Figure A2-5. Management (mgmt) intervention research projects, with research gaps identified in red text. SR, stocking rate; BW, body weight; LCA, life cycle analysis.

Appendix 3: Analysis of publication outputs

Scientific scrutiny is a key feature of high quality research. One of the most agreed ways to assess scientific scrutiny across fields is provided by publication outputs. In this section publication outputs were assessed across the five mitigation clusters defined in this review.

Publications from SLMACC funded Agricultural GHG Mitigation Research

There were 26 journal publications produced from the final list of 31 projects used in this review (Table A3-1). Research papers were categorised into their respective clusters and relevant information was documented for each case (Table A3-1). Although this list is as comprehensive as possible (to August 2017), there are three caveats to consider when evaluating its contents:

- There are some projects that, due to intellectual property (IP), have not produced any publication outputs. An example of a SLMACC project with no publication is "Accelerated Ruminant Methane Mitigation" (SLMACC code METH0802).
- Some projects have several publications not listed here because they were produced as consequence of follow-up research funded by other organisations, following an original

SLMACC grant. These papers were defined as ‘indirect outputs’ of a particular SLMACC project, because they were produced during or following completion of projects funded by a different funding body (such as the PGgRc or NZAGRC). These indirect papers are neither listed nor discussed in this report.

- Even though all leading scientists from all SLMACC projects were contacted for this evaluation, not all responded. Given this, some relevant publications may be missing from the list.

The far-right column of Table A3-1 lists the specific SLMACC project that the paper relates to. Some SLMACC projects, such as project AGR30887, have several associated publications, while others have just one. Projects not listed may be due to the points discussed above. A specific column was devoted to highlighting the journal or proceedings in which the paper was published. Twenty-three of the 26 publications appeared in international peer-reviewed journals. Of these, two were published in multidisciplinary journals – both in Plos ONE (Sun et al., 2015, and Veneman et al., 2015). This is important to highlight as papers in multidisciplinary journals can have a higher impact in terms of citations, but not necessarily in terms of specific new technical or scientific knowledge. This last point should be considered when evaluating citation metrics, as in some cases papers that are sound and relevant for a particular technical field (like the chemistry behind inhibitors) may result in a lower citation impact than a paper that discusses, for example, a global agricultural emission model and is published in a multidisciplinary journal (e.g. Havlík et al., 2014). To address this, the ‘Scopus field-weighted citation’ (SFWC) metric is provided in Table A3-1. This index, directly extracted from Scopus, aims to capture how relevant a paper is within its field. The index is normalised: a value over 1 means that the paper is more impactful than other similar papers (considering field and year of publication), while under 1 means that the paper on average has received fewer citations than similar papers in the field. The average SFWC of the papers is 2.83, suggesting that papers published based on SLMACC projects provided an above-average relevant impact to international agricultural GHG mitigation research. The paper of de Klein et al. (2011) had the highest impact among the published papers, followed by the paper of Pinares-Patino et al. (2013).

For completeness, we also list the number of citations in Google Scholar at July–August 2017. Although Google Scholar is not as reliable as Scopus or the ISI Web of Knowledge for citation impacts, its main advantage is that it incorporates new citations relatively quickly and that it also incorporates citations from materials not published in scientific journals or book chapters, such as Masters or PhD theses and conference papers. This last point is relevant, as a paper could be producing important impacts in education (with a growing citation tendency in Master theses, for example), which would not be reflected in citation metrics derived from Scopus or ISI Web of Knowledge. According to Google Scholar metrics, Beukes et al. (2010) had the highest citation impact, being the only paper with more than 100 citations. However, important to mention here is that differently from the SFWC, recent papers will have a disadvantage in terms of their total number of citations, compared to papers published several years ago.

Table A3-1. Journal Publications Directly Derived from SLMACC Agricultural GHG Mitigation Projects.

Paper	Journal	Citations[a]	SFWC[b]	Avg Journal Impact Factor 2014-2016			Funding acknowledged	# Institutions in authorship (international)	MPI ID
				Cite-Score[c]	JIF[d]	SNIP[e]			
1. CH_4 inhibitors/vaccines cluster									
Veneman et al. (2015)*	Plos ONE	12	2.71	3.32	3.03	1.14	EC's 7th Framework Program. PGgRc is listed as "competing interests"	3 (2)	C10X1105
2. Low CH_4 animals cluster									
Beukes et al. (2010)	Agriculture, Ecosystems & Env.	101	5.43	4.10	n/a	1.80	PGgRc	1	DRCX0803
Pinares-Patino et al. (2013)*	Animal	75	7.51	1.90	1.94	1.16	PGgRc, SLMACC & NZAGRC	1	METH901
Rius et al. (2012)	Journal of Dairy Science	46	3.24	2.69	2.49	1.49	NZ dairy farmers & SLMACC	3 (1)	DRCX0803
3. Low GHG feed cluster									
Cosgrove et al. (2012)*	New Zealand Journal of Agricultural Research	2	0	1.06	1.09	0.76	SLMACC	1	C10X0829
Cosgrove et al. (2015)*	Journal of New Zealand Grasslands	0	n/a	n/a	n/a	n/a	SLMACC	1	AGR30887
Hoogendoorn et al. (2016)	Agriculture, Ecosystems & Env.	1	1.13	4.10	n/a	1.79	SLMACC & Taishan Scholars Program	2 (1)	AGR30737
Jonker et al. (2016a)*	Journal of Animal Science	3	1.8	1.78	2.00	1.28	SLMACC & PGgRc	1	AGR30624
Jonker et al. (2016b)	Animal Production Science	1	n/a	1.17	1.19	0.87	SLMACC & Livestock Emissions & Abatement Research Network (LEARN)	4 (2)	AGR30887
Kittelman et al. (2015)*	Applied and Environmental Microbiology	5	1,13	4.08	3.77	1.33	NZAGGRC/PGgRc, SLMACC, NZ Genomics Ltda.	1	AG30624
Luo et al. (2015)*	Animal	8	2.47	1.90	1.94	1.16	SLMACC & PGgRc	1	C10X1102

Pacheco et al. (2014)	Animal Production Science	21	1.54	1.17	1.19	0.87	PGgRc, MPI & New Zealand dairy farmers	2	AGR30737
Sun et al. (2015)*	Plos ONE	10	1.77	3.32	3.03	1.12	SLMACC & PGgRc	2 (1)	C10X1102
Sun et al. (2017)*	Animal Nutrition	0	0	n/a - CiteScoreTracker 2017 = 1.06 as at 15 Nov 2017			SLMACC & PGgRc	2	AGR30737 & C10X1102
Sun et al. (2016)	Animal Production Science	1	1.6	1.17	1.19	0.87	PGgRc & SLMACC	1	AGR30737 & C10X1102
Taghizadeh-Toosi et al. (2012)**	Plant and Soil	72	3.69	3.22	2.99	1.42	Not mentioned	1	LINX0901
4. Reduced N_2O from soil/plants cluster									
Bowatte et al. (2014)**	Plant and Soil	10	1.26	1.17	2.99	1.42	NZAGRC	1	C10X0827
De Klein et al. (2011)	Animal Feed Science and Technology	62	7.83	2.16	1.82	1.54	MAF, Ballance Agri-Nutrients, Ravensdown Fertiliser & the P21	3	MAF POL_2008/32
Kelliher et al. (2014)	Agriculture, Ecosystems & Env.	16	3.41	4.10	n/a	1.80	MPI, DairyNZ, Fonterra & the Fertiliser Association of NZ	3	AGR30649
Pereira et al. (2014)**	Animal Feed Science and Technology	8	0.93	2.16	3.07	1.54	MAF (CONT-20453-SLMACC-MAU)	3 (1)	MAUX0903
Saggar et al. (2013)	Science of the Total Environment	36	1.91	4.54	4.33	1.78	Not mentioned	4	12207
Van der Weerden et al. (2016a)**	Agriculture, Ecosystems & Env.	2	1.13	4.10	n/a	1.80	MPI & Ballance Agri-Nutrients	4	16110
Van der Weerden et al. (2016b)**	Agriculture, Ecosystems & Env.	4	4.53	4.10	n/a	1.80	MPI & Ballance Agri-Nutrients	4	16110
Luo et al. (2017)	Advances in Agronomy	0	0	4.57	4.36	2.68	MPI, MBIE & Taishan Scholars Program	9 (6)	AGR131405
5. Management interventions cluster									

Jonker et al. (2017)	Animal Production Science	0	0	1.17	1.19	0.87	NZAGRC & SLMACC	3	AGR131402
Beukes et al. (2011)	Animal Feed Science and Technology	39	4.16	2.16	1.82	1.54	FRST/SLMACC	1	C10X0902

Notes: # indicates project number as given in Table 2; a) Number of citations recorded in Google Scholar (July–August 2017). b) *Scopus* field-weighted citation (SFWC, values to August 2017 – see footnote 4 for more references). c) *Scopus* CiteScore: The average number of citations in the present year to publications from the previous three years. d) *Web of Science* Journal Impact Factor: Average citations in the present year to publications from the previous two years. e) *Scopus* Source Normalised Impact per Paper: journal impact factor adjusted for differences in citation practices using the length of the reference list, see http://www.journalindicators.com/methodology for an explanation. * indicates that the paper is available open source. ** indicates papers that are not in open source journals but available on *ResearchGate* or *Academia*.

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Appendix 4: Stakeholder interviews

Stakeholder interview process and results

A series of targeted interviews related to the GHG mitigation review were conducted by David A. Fleming and Kate Preston (both from Motu) with various key industry-related representatives regarding the SLMACC programme and its investment in agricultural GHG mitigation research. The aim was to interview two individuals for each of the five mitigation clusters. Nine individuals were interviewed, with one individual responding for two different clusters. The individuals interviewed were selected after performing a stakeholder analysis/identification. To do this, relevant next-users (stakeholders) across projects in the review were identified and among the identified next-users key representatives were interviewed.

Interviews were conducted either by phone or in person, as outlined in Table A4-1, and lasted around 30 minutes to one hour with each person. A set of interview questions was followed loosely, allowing for adaptation to each interviewee's knowledge. The used schedule is presented at the end of this appendix.

Across the questions, respondents were asked to evaluate various issues, on a 1 to 10 scale, and to answer open-ended questions. Stakeholder impressions, by mitigation cluster, are presented in Figure A4-1. Within each cluster there are two respondents, labelled A and B in the chart. The missing bar in the figure under "animal genetics" corresponds to an interviewee who was unsure about a particular scoring for this case as they could not recall the details of the SLMACC projects in the area. Key arguments provided by the various stakeholders are summarised in Table A4-2 below.

Table A4-1: Affiliation of stakeholders interviewed.

Affiliation of interviewees	Interview method
Ballance Agri-Nutrients	Phone
Beef + Lamb New Zealand	Phone
Beef + Lamb New Zealand (B+LNZ) Genetics	Phone
Dairy NZ	Phone
Irrigation New Zealand	Phone
New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC)	Phone
Pastoral Greenhouse Gas Research Consortium (PGgRc)	In person
PGG Wrightson	Phone
Ravensdown	In person

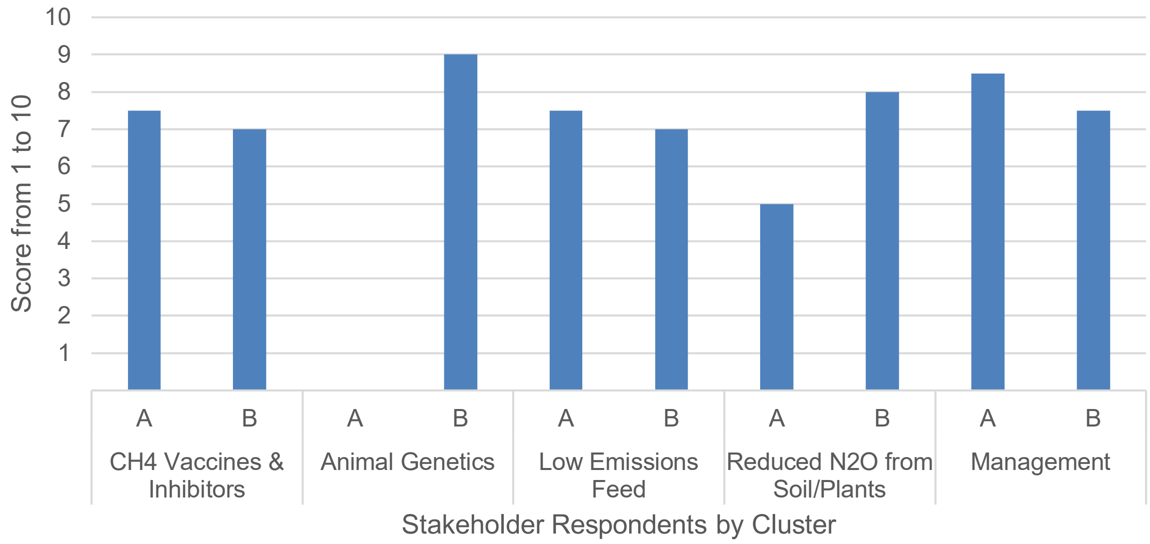


Figure A4-1. Stakeholder Impressions of the **relevance** of the SLMACC programme for New Zealand research or policy (or overall agricultural mitigation research if not familiar). Within each cluster there are two respondents, labelled A and B.

Table A4-2. Responses supporting stakeholder impressions of the relevance of the SLMACC programme (or overall agricultural mitigation research if not familiar) to New Zealand

CH_4 Vaccines/ Inhibitors	Low GHG Animals	Low GHG Feed	Reduced N_2O from Soil/Plants	Management Interventions
• SLMACC gave the PGgRc flexibility to add to their projects	• A partnership with SLMACC helped the PGgRc get a piece of work done on animal genetics • In the early days, "*SLMACC really filled an important gap when more funding was needed*". Then when the PGgRc increased its funding and the NZAGRC was launched, SLMACC funded exploratory work that was outside the core focus of the two main funding organisations.	• SLMACC research has been very relevant, but also frustrating • The SLMACC programme has provided a more hollistic approach in recent years, with GHG now being looked at alongside water quality. Things are now coming through to the commercial stage	• Research by SLMACC has added to work by Lincoln University and Ravensdown. • It has been important for the government to take the lead on this work, and is "*strategically very important for New Zealand*"	• SLMACC funds a critical area. It improves knowledge which is in turn needed to shape policy • Anything that will help farmers to adapt is "*good value to us*".

Research and Policy

The view that SLMACC has been relevant to New Zealand research and policy was widespread. Some stakeholders emphasised that SLMACC had been a flexible funder that enabled the extension of work outside of their own scope of work or interest. It was emphasised too that the SLMACC Programme provided important exploratory research that was important for the PGgRc and NZAGRC, particularly allowing some early investigation into new mitigation research concepts. It was noted that an important feature of SLMACC is that it is more flexible than the NZAGRC and PGgRc, which follow strict business plans.

Stakeholders were also asked about the alignment and generation of 'fit-for-purpose' knowledge of the SLMACC programme. While most interviewees claimed that the SLMACC programme has aligned very well its investments with the need for research development in the country, most alignment occurred in early years of the programme, as a key funder of mitigation research work. This has decreased in recent years as SLMACC started focusing on other research areas beyond agricultural mitigation, and PGgRc and NZAGRC developed their own comprehensive research programmes.

Stakeholders were asked to rank the extent to which the SLMACC funding resulted in uptake of research by stakeholders (Figure A4-2), which mainly consisted of the uptake of research outputs or advanced mitigation options by research groups or farmers and industry, depending on the cluster and the relevant projects discussed. These scores support the responses in Table A4-3. While scores are relatively high, there was an overarching sense from discussion with the respondents that while there has been great scientific progress and use of scientific outputs by different research groups, the uptake of advanced mitigation options remains low.

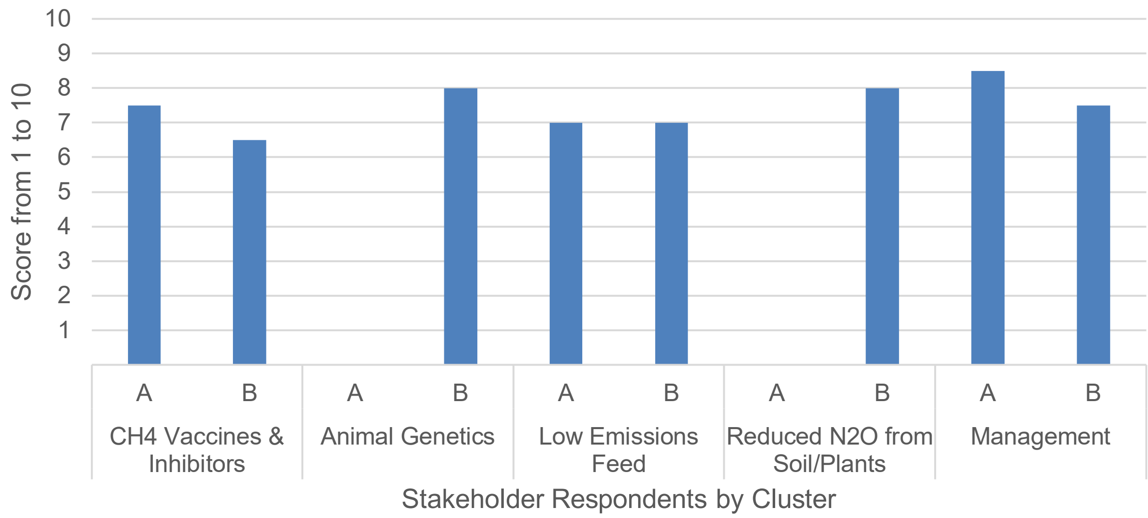


Figure A4-2. Stakeholder views that SLMACC fund resulted in uptake (1 being low uptake, 10 being high uptake)

Table A4-3. Responses supporting stakeholder views on whether SLMACC funding resulted in uptake

CH_4 Vaccines/ Inhibitors	Low GHG Animals	Low GHG Feed	Reduced N_2O from soil/plants	Management Interventions
• "*We've used SLMACC more for a science investment than for uptake*". • It is still not known whether a vaccine will work. On the other hand, there is still a lot of work needed to make inhibitors suitable for animals that graze. • "*What they have done is added to the development of a number of practices and actually shown that some practices that we thought might be promising weren't promising.*"	• A low GHG genetic trait in sheep has been selected for, but it is not ready for industry yet. • For breeders a low GHG trait will just be one more trait to consider. • SLMACC has assisted the progress of the PGgRc	• Farmers will only adopt mitigation options if there is an economic incentive. • More work is needed to link the scientific findings to commercial avenues.	• More help in commercialising ideas would be good. The economic incentives aren't there for some mitigation options to be taken up. • There has definitely been uptake in urease inhibitors and DCD, as well as animal feed strategies. • Even when things don't result in a product, the insights are still valuable.	• Many options are there, but the extension is lacking. Farmers are not told enough and many options are not practical for them. • The uptake by farmers has been low, but the research has been useful for policy. • "*A lot of our farmers have been concentrating on water quality…because there are rules going to be in place, so climate change has been seen as something a little bit further down the track. But we have been working to change that in the materials we produce...* "

A strong sense was gained that research funded by SLMACC has contributed to knowledge, which had been adopted by next users (scientists and research organisations) who have then continued to further expand the scientific knowledge. However, stakeholder interviewees tended to focus a significant part of their argument about the uptake of SLMACC to that of farmers and industry bodies: this is therefore the focus of the discussion below.

Uptake by farmers and industry bodies still faces many challenges; in particular, respondents argued that there are only a limited number GHG mitigation options available on the market, that they are not practical, and that the incentives to use them do not exist.

Respondents indicated that work to find a vaccine continues, but it is not known what the chance of success is. Meanwhile, there has been success with inhibitors internationally, however, a suitable mode of delivery for animals that graze remains a challenge. The low GHG trait, specifically low CH_4 yield (g/kg DMI), has been successfully genetically selected for in sheep, which in research flocks shows 10% gains compared to high selection line animals. There has been little progress in selecting for a low GHG trait in cattle; this has partly been due to challenges in accurate measurements of CH_4 emissions. But, as one respondent emphasised, the lack of progress on these fronts is not to be blamed on SLMACC, it is the nature of science.

Within the cluster of low GHG feed, interviewees pointed to barriers to the commercialisation of products and lack of incentives to implement them. The same comments came through among interviewees for 'reduced N_2O from soil/plants', but their responses were more variable. A particular success was DCD, but that mitigation option is currently banned from use in New Zealand due to residues found in milk. Urease inhibitors were also mentioned as an outcome that has had successful uptake in this realm. Respondents on management interventions said there was a lack of practical and cost-effective mitigation options available to farmers along with limited incentives for them to use them.

The next section of the survey was concerned with research gaps that exist within the five GHG mitigation clusters, with key points summarised in Table A4-4.

Table A4-4. Some research gaps identified by stakeholder interviewees within the five GHG mitigation clusters.

CH_4 Vaccines/ Inhibitors	Low GHG Animals	Low GHG Feed	Reduced N_2O from soil/plants	Management Interventions
• A pathway for inhibitors to be used in grazing • Promoting *"what can be done now rather than what necessarily could be available in the future…There used to be a climate-change tech-transfer fund of some description, that seemed to disappear*."	• The next step is to extend from research flocks to the whole national flock to get better data. We also need to understand how the low emission trait impacts on other traits. • Support is needed to transition research to farmers, and to encourage them to select the particular trait. • Care needs to be taken about rumen size and energy needed for ewes to keep two lambs alive	• Extension is key. We need to provide the incentives for uptake. We need an ETS integrated with the agricultural system with obligation at the point of the farm. • It would be good to have freely available life-cycle models with guidance on how to use them • More public audits are needed. Then people can adapt their business models. The government and local government role is to create that transparency.	• More help is needed for applied research that could be commercialised and used by farmers • More farmer or grower-specific knowledge is needed • "*What is the next high-value land use the primary sector will migrate to?*" We need to think about what the future land uses will be like under these constrained environments.	• We need to look into the correlation between nitrate loss and reduction in GHG emissions • The focus has been on nitrogen, we need more investment in methane, and not so much on farm system change. • We need to understand how the mitigation options will work in the farm system, how they might interact with each other, and how they will fit in with other environmental concerns.

Stakeholders were also asked to rank the impact of the SLMACC fund, regarding the cluster they were familiar with, both in terms of science and in terms of practical options for farmers and industry bodies (for agriculture, in general) (Figure A4-3). The low ranking of the impact on practical options relative to the impact on science is obvious, especially for the 'low GHG feed' and the 'reduced N_2O from soil/plants' clusters. The key responses surrounding these rankings are provided in Table A4-5.

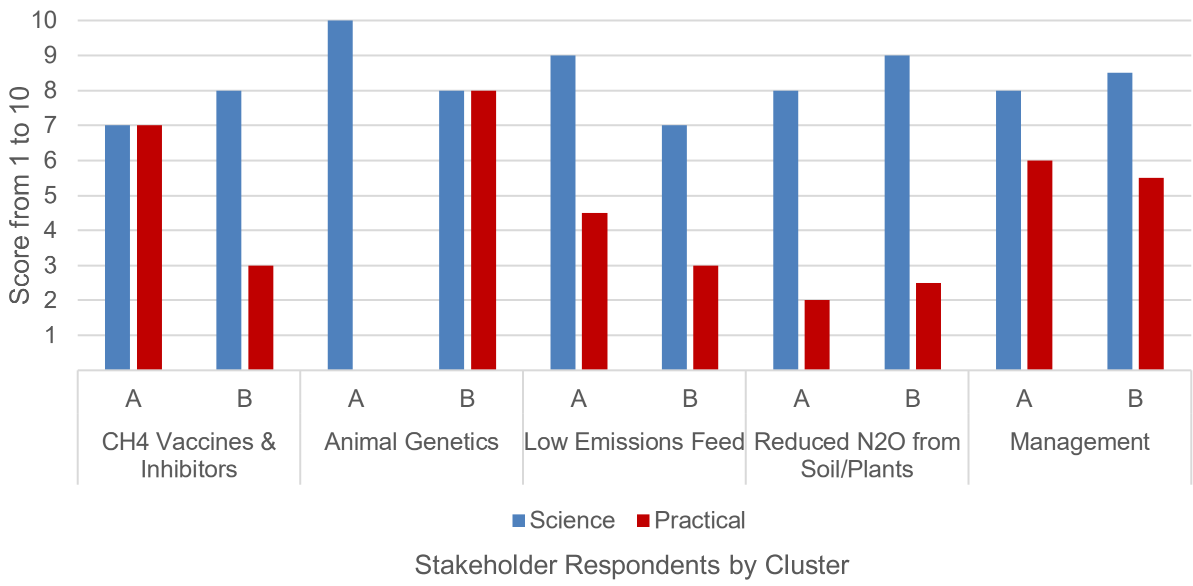


Figure A4-3. Rankings by stakeholders of the Impact of SLMACC funded research for New Zealand in terms of science and in terms of practical options for agriculture.

Table A4-5. Stakeholder views of the Impact of SLMACC funded research for New Zealand in terms of science and in terms of practical options

CH4 Vaccines/ Inhibitors	Low GHG Animals	Low GHG Feed	Reduced N_2O from soil/plants	Management Interventions
• All of our programmes have been ranked as world-leading, and SLMACC has supported them. But for now there are no products on the market. • "*…the inhibitor is the "least" practical for our free range grazing systems but overall they are logical projects to deliver some options to the livestock sectors.*"	• The best scientists for sheep genetics are in NZ. Practical uptake is low but has potential and will be worked on this year. • We recognise the solutions as having a practical application.	• NZ has been a world leader in science of agriculture, but there are still not many options and adoption of them has been low because of lack of incentives. • The science in NZ is very good, but the options are not actually being used.	• The science providers do good science, but a lot of technologies are not reaching the market. • The science is very important. The means to lead to a discovery is there, but the practical outcomes are not available yet. • DCD was very successful but unfortunately can no longer be used.	• The science has been good but it has focused on nitrogen rather than methane. We still don't have many options, at most they can only achieve a 5-15% reduction in emissions, and they are not practical. • "*The science itself appears to be very very good. I guess the question comes - it's not so much the science - it's are they focusing on the right things?*" • "*A lot of it is probably a little bit academic in that it tends to look at single issues, and farm systems don't run on single issues.*"

The views of respondents with respect to these questions were consistent: New Zealand's scientific capacity in agricultural mitigation is strong and SLMACC had an important role in supporting the research, but the availability of practical GHG mitigation options to reduce emissions is still low. However, there were various views on the reasons for the lack of practical solutions. Some respondents felt that there were still few options available, while one interviewee suggested that many technologies had not made it to the market because of the huge investment required. One respondent from the management interventions cluster suggested that the limited number of mitigation options available are barely practical for farmers to take up, and lead to only a small reduction in emissions anyway. The cost and risk for the uptake of mitigation options, to already financially indebted farmers, was highlighted. On the other hand, some respondents were optimistic that the science is on track to achieve practical GHG mitigation options for the future.

Interview schedule used in the interviews to stakeholders

<u>Introduction of the topic/interview objectives:</u> *3-5 mins*

<u>Questions:</u> *25-30 mins*

Are you familiar with the SLMACC programme? (Y/N questions)

a. With its funding to agricultural mitigation research?
b. With the PGgRc?
c. With NZAGRC?

What is your overall impression of the SLAMCC programme? Scale 1 to 10 (not relevant, very relevant for NZ research and policy)

Are you familiar with agricultural mitigation research?

Can you list some mitigation options/practices currently available to reduce GHG?

Have past SLMACC funded research resulted in uptake and use of research by you or other stakeholder groups that you are aware of (policy, government, industry or community)

a) In other words: Have you uptake/used in any way the research produced by SLAMCC projects across the five clusters?
   If so, can you score them from 1 (negligible uptake) to 10 (high uptake)

b) Do you think the research aligns with the needs of next or end users of the research, and is responsive to next or end user needs and knowledge gaps
   If so, can you score them from 1 (lack alignment) to 10 (iterative research to meet user needs)

c) Do you think the research has generated specific, usable, fit for purpose knowledge and research for policy and/or trade negotiation

What research gaps do you think mainly exist still across the five clusters and what the SLMACC programme could do to fill these?

Have any projects, across mitigation clusters, influenced your awareness/consideration on the mitigation area?

How would you rate the impacts that these research projects (across clusters) have produced in NZ?

a. In terms of science: 1 to 10
b. In terms of practical responses for Ag: 1 to 10

Any spillovers/indirect benefits or costs that you can think on?

Appendix 5: Evaluation of agricultural mitigation options using the PCE framework

The Parliamentary Commissioner for the Environment (PCE) report (PCE, 2016) stated, "*There are no silver bullets for reducing methane and nitrous oxide emissions currently on the horizon. But the mitigation options that are the subject of research can be assessed (to some extent) against the characteristics of a silver bullet solution.*" (PCE 2016, p. 37). Following this statement, the PCE proposed five main questions that mitigation options should be assessed on (PCE 2016):

1. Is the mitigation option effective?
2. Does the mitigation option have other impacts?
3. Is the mitigation option likely to be cost-effective?
4. Can the mitigation option be integrated into existing systems?
5. Does the mitigation option make sense from a national perspective?

A scoring system was linked to these questions in the current evaluation (Table A5-1) with the aim to provide quantifiable answers that could be compared across the five mitigation clusters. Most of the GHG mitigation options were included in the PCE questionnaire framework (Table A5-2).

Methods

To obtain data for these evaluation criteria, the questions provided by the PCE report (2016) were followed as closely as possible. The only changes made to the original PCE questions in the current evaluation were; in question 2, '(positive or negative)' was added at the end; and in question 4 'existing systems' was replaced by 'existing pastoral systems'.

The questions were put together in a table format and emailed to a selection of researchers. These researchers were identified as those that in the past were directly and actively involved in agricultural GHG mitigation research projects funded by the SLMACC programme. The tables with questions were shared via email with 29 researchers in total, with survey responses received from 15. This data collection process was carried out in November/December 2017. The five PCE evaluation questions were asked for mitigation options identified across the five agricultural mitigation clusters (Table A5-2). Researchers were asked to answer the questions using a Likert scale from 1 (low) to 5 (high). A 'guideline' document was provided to the researchers. The guideline instructions were designed by the AgResearch team and are provided in Table A5-1. The objective of the guideline instructions was to provide the researchers a ‘road map’ of how to score the five questions. No inquiries were received about this guideline table from the researchers, so it can be assumed that they were followed by all respondents.[7] All data received was managed confidentially by the Motu team.

[7] One respondent, however, answered using comments, so it was not possible to process these answers using scores. Therefore, all results presented here consider 14 responses

Table A5-1: Scoring of the 5 PCE questions. Scoring guidance for each question to provide a 'mental framework' rather than a set of questions to be answered. **1** = low to **5** = high

Is the mitigation option effective? Effective per animal or per unit of N (e.g. reduction in CH_4 per unit of DM intake or N_2O per unit of N applied/deposited)? - Will it reduce emissions? - Will effectiveness be maintained over time?	**Does the mitigation option have other impacts (positive or negative)?** - Will emissions of another GHG gas or farm system gas increase? - Will there be greater impacts on water quality?	**Is the mitigation option likely to be cost effective?** - Will it be costly to farmers to adopt, or is there a financial benefit to the farm? Values are guidance only.	**Can the mitigation option be integrated into pastoral systems?** - Is adoption easy and practicable, or complex? - Is the adoption reversible? - Are there regulation issues or barriers to adoption e.g. animal welfare or residues in food	**Does the mitigation option make sense from a national perspective?** - Is there national coverage? - Can it be accounted for in the GHG inventory?
1: Increase in emissions: CH_4 per unit of DM intake or N_2O per unit of N applied **2:** ≥ 0% to < 10% reduction in emissions: CH_4 per unit of DM intake or N_2O per unit of N applied **3:** ≥ 10% to < 20% reduction in emissions: CH_4 per unit of DM intake or N_2O per unit of N applied **4:** ≥ 20% to < 30% reduction in emissions: CH_4 per unit of DM intake or N_2O per unit of N applied **5:** ≥ 30% reduction in emissions: CH_4 per unit of DM intake or N_2O per unit of N applied	**1:** Another GHG increases / marked degradation of water quality **2:** Other GHGs do not change/ minor degradation of water quality **3:** Other GHGs also reduce slightly / no impact on water quality **4:** Other GHGs reduce moderately / minor improvement to water quality **5:** Other GHGs also reduce markedly / marked improvement to water quality.	**1:** Large cost to farmer (e.g. >$2/kg CO_2e saved per ha) **2:** Medium cost to farmer (e.g. $0.20 - $2/kg CO_2e saved per ha) **3:** Small cost to farmer (e.g. < $0.20/kg CO_2e saved per ha) **4:** Zero to small benefit to farmer (e.g. $0-0.5 /kg CO_2e saved per ha) **5:** Significant benefit to farmer (e.g. > $0.5/kg CO_2eq saved)	**1:** Requires complex new techniques and processes to be developed before considering farm adoption / It is a permanent change / potential for regulations to be breached and animal welfare or residues in food may happen **2:** Implemented with major alteration involving current knowledge & technologies to farm system / It is likely to be a permanent change / Major barriers to adoption **3:** Implemented with moderate alteration to farm system / Reversing back to before adoption is possible at a cost / moderate barriers to adoption **4:** Can be implemented with minor alteration to farm system / Reversing back to before adoption is relatively easy / minor barriers to adoption **5:** Fits readily into existing pastoral farming systems / Reversing the system back to before adoption is easy and has no further consequences / no barriers to adoption.	**1:** Limited to <5% of pastoral farms / major accountability challenges: currently considered too difficult to resolve. **2:** Limited to ≥ 5% to < 10% of pastoral farms / major accountability challenges, but achievable. **3:** Limited to ≥ 10% to < 25% of pastoral farms / moderate accountability challenges, but achievable **4:** Limited to ≥ 25% to < 50% of pastoral farms / minor accountability challenges, but achievable **5:** Applicable to >50% of pastoral farms / accountable in inventory

Table A5-2. Mitigation options per cluster included in the PCE framework.

Methane inhibitor	Low GHG animals	Low GHG feed	Reduced N_2O from soil/plants	Management
-Nanobeat* -Small molecule methanogen inhibitor -Defaunation -Nitrate in TMR -Bio-active compound in feed -Biochar -Early life intervention with CH_4 inhibitor	-Low CH_4 yield sheep -Low CH_4 yield cattle -Improved longevity cattle/sheep -Lighter adult weight -Reduced DMI/ RFI -Increased lambing %	-Bioactive compounds in feed -Increased diet lipid -Forage rape -High sugar grass/feed -High starch feed -Fodder beet -Fungus Mortierella wolfii bioactive compounds to reduce enteric CH_4 -Diet interventions to increase urine hippuric acid	-Chemical nitrification inhibitors -Urease inhibitors -Biochar -Plant-targeted interventions to mitigate N_2O emitted via plant canopies	-Low N feeds replacing N fertiliser -Sheep performance improvement (lambing hoggets, increasing ewe scanning %, reduced sheep replacement rates) to reduce CH_4 -Feeding time and feed composition to reduce N_2O -Dairy system herd improvement – higher breeding worth/genetic merit + lower stocking rate to reduce total farm GHG -Dairy system lower N input - reduced N fertiliser inputs + low N diet to reduce total farm GHG -Dairy system reduced replacement rate to reduce total farm GHG -Management of on-farm urine hot-spots to reduce N_2O -Irrigation management (return rate, irrigation scheduling, delayed grazing following irrigation)

Results

The average scores of each cluster across the five PCE questions are presented in Figure A5-1 to Figure A5-5. Full detailed results (including the number of respondents) for all the mitigation options, by clusters, are provided in Table A5-3.

Figure A5-1. Average score for question 1

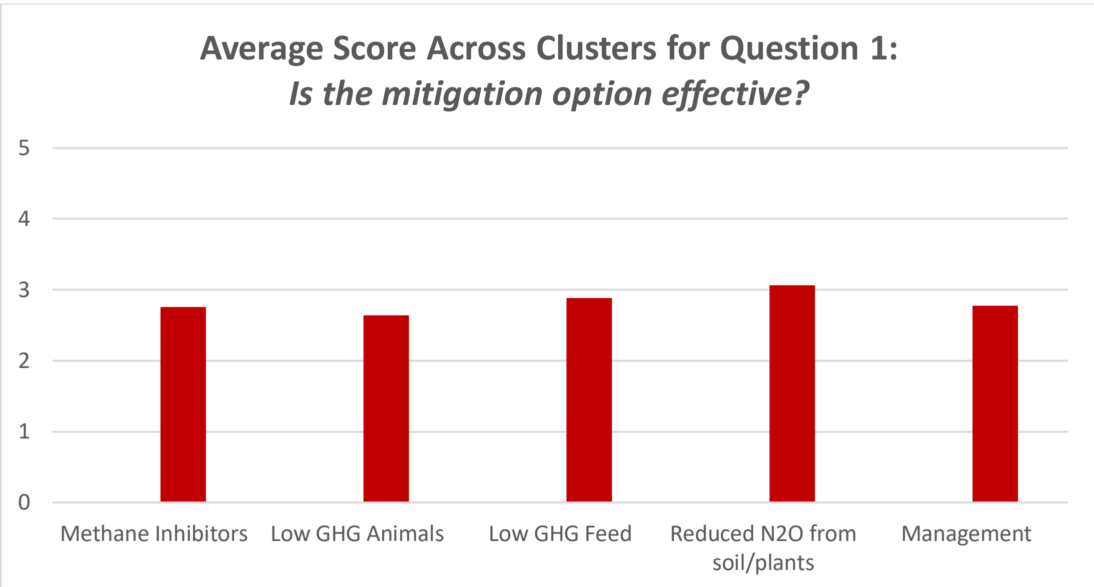


Figure A5-2. Average score for question 2

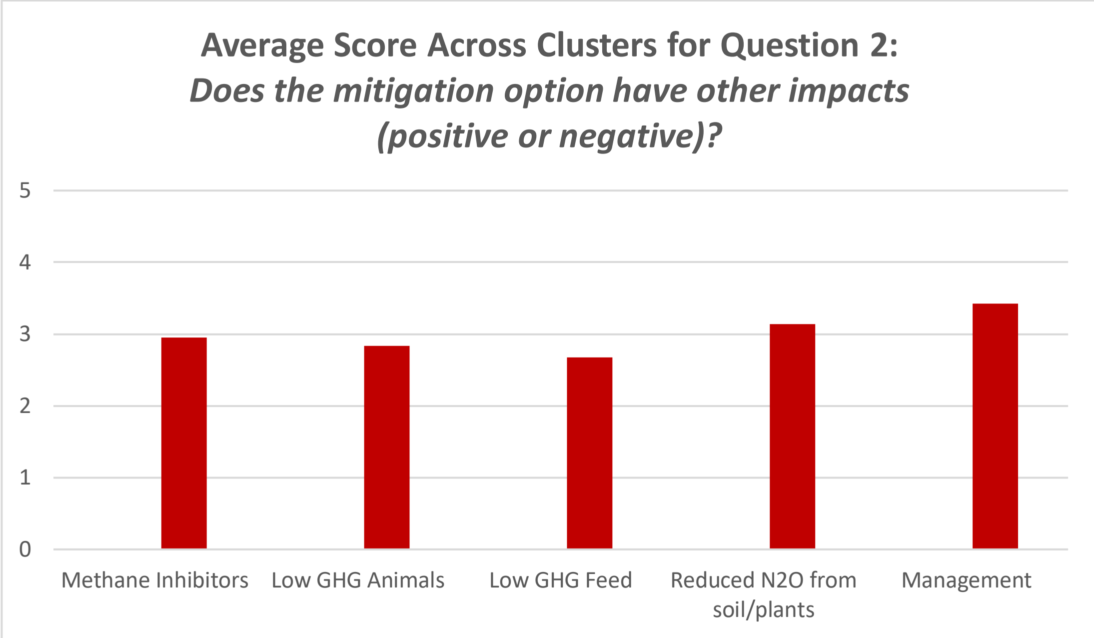


Figure A5-3. Average score for question 3

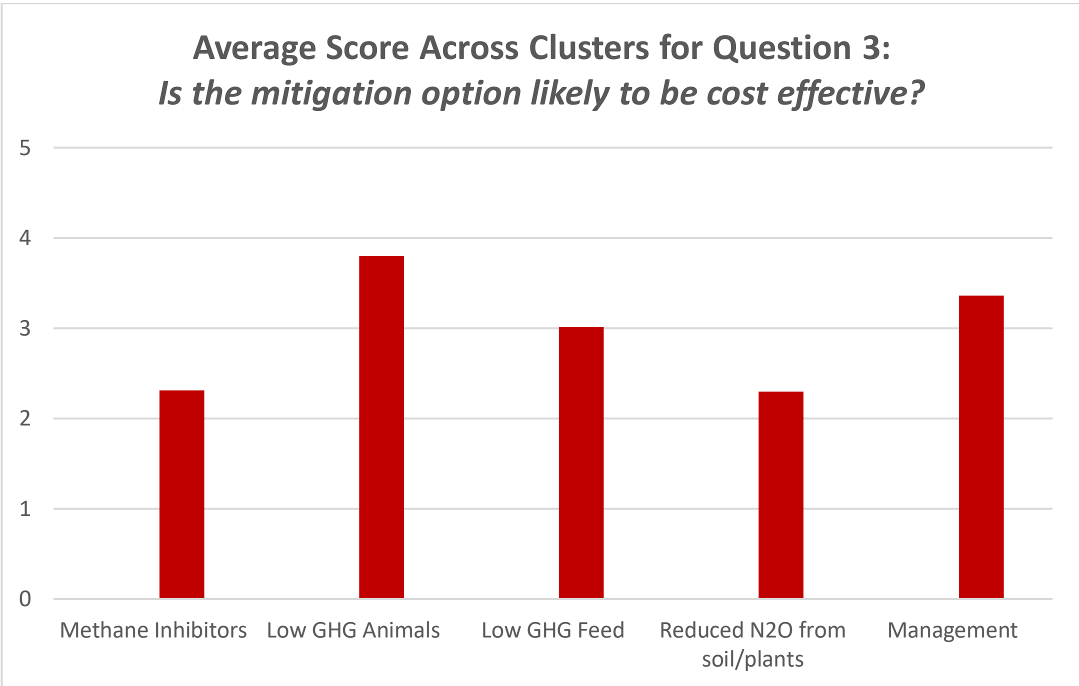


Figure A5-4. Average score for question 4

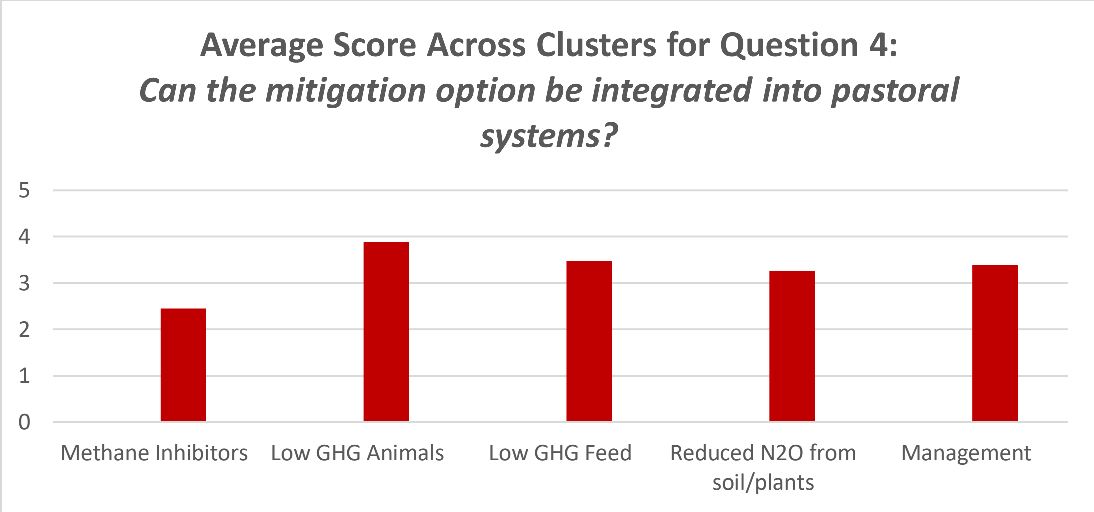
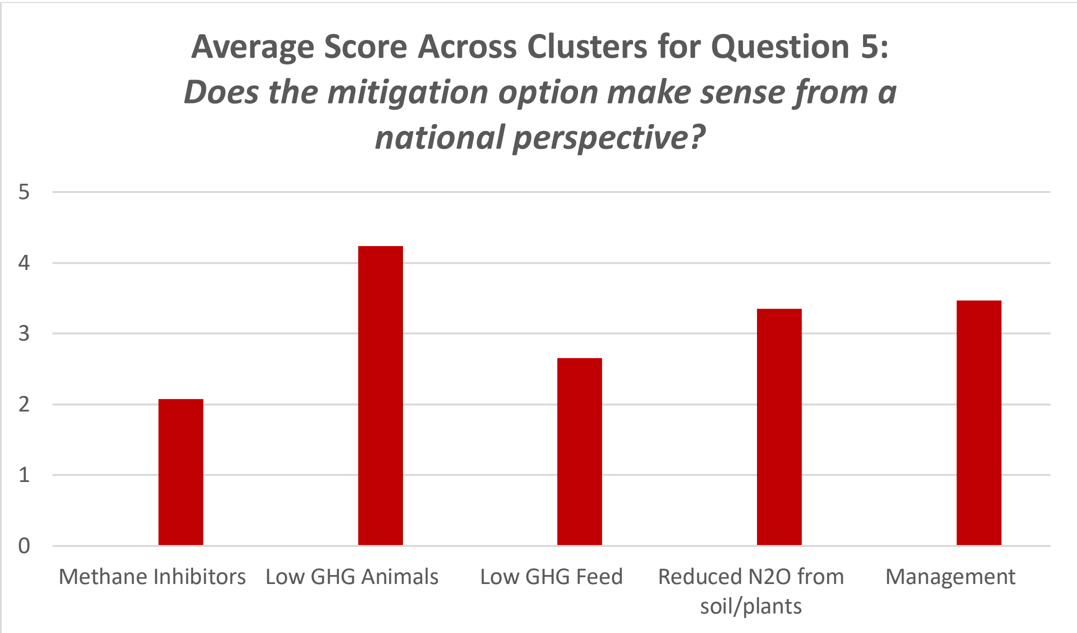


Figure A5-5. Average score for question 5



Discussion of findings

The main aim of this questionnaire was to provide an overview of the potential effectiveness of the options available across the five clusters for reducing emissions, by considering the expected impact on agricultural emissions, side-effects, and the cost and feasibility of implementation. Results provided here are not intended to produce ranking of priorities, but rather to provide information for a discussion on the pros and cons of different mitigation options. A consideration regarding this exercise is that a scoring system of this type could lead to misinterpretations if it is intended to create a ranking system. This is because some components of a particular object being evaluated (a mitigation option in the current case) can be interpreted differently by different people, and respondents will have differing levels of understanding of the various options. For instance, some researchers could be more familiar with the costs of a mitigation option than others and consequently score them differently – even though they might have assumed similar costs.

Although 15 is not a large number of responses, it is important to reinforce that they include some of the most influential scientists looking at agricultural GHG mitigation options in New Zealand. However, it is important to note that several of these scientists were themselves conducting some of the SLMACC research. On one hand this means they were very conversant with the options they were involved with, whereas on the other hand potential exists for subconscious bias. Therefore, these results should be treated with caution. Below, results are aggregated at the cluster level; however, in many cases there was considerable variation in responses across mitigations within clusters (Table A5-3). Regardless, an overall assessment of the results considering the average responses across clusters is provided. It should be emphasised that the number of responses to individual questions within clusters is very low (1 to 7), as shown in Table A5-3 above.

Methane inhibitor/vaccines cluster

The 'methane inhibitors/vaccines' cluster had an average score between 2 and 3 for the five PCE questions. The response scores regarding the question "is mitigation option effective" ranged from the lowest score of 1 to the highest score of 5 across various mitigation options and researchers, with an average score of 2.76. The general view was that the options pose little to no harm on other aspects of the environment (question 2). However, the feasibility of implementing these mitigation options, according to the average scores, appears relatively low (question 4), but this could be due to the stage of development of these mitigations options (i.e. largely proof-of-concept). In terms of cost effectiveness (question 3), some options within the cluster were thought to have a medium or large cost to farmers, but for others the cost was expected to be zero of even offer a small benefit to farmers. There was a large range in scores (1 to 5) among the mitigation options in the methane inhibitors/vaccines' cluster for question 4 "ease of implementation in pastoral systems" and question 5 "does the mitigation option make sense from a national perspective".

Low GHG animals cluster

The results for 'low GHG animals' are particularly interesting in that the cluster received the lowest average scores for effectiveness of the mitigation option (question 1), but the highest average scores in terms of cost effectiveness (question 3), ability to be integrated into pastoral systems (question 4), and sensibility from a national perspective (question 5). Scores for effectiveness of the mitigation option in this cluster indicated a potential reduction in emissions by up to 30%, with most scores suggesting reductions would be between 10% and 20%. This could come at little to no harm to other aspects of the environment, or possibly small reductions in other GHGs (question 2). Most scores for cost effectiveness suggest that the mitigation options in the 'low GHG animals' cluster would come at little to no cost to farmers, or even benefit farmers financially. Barriers to adoption were generally thought to be no more than moderate, and national coverage could reach at least 10% of farms, with many responses stating that this could be greater than 50%.

Low GHG feed cluster

In general, the 'low GHG feed' cluster had moderate scores across the PCE questions, although it did receive the lowest average score for impacts on other GHG gases/water quality. There was a wide range of responses on all questions, with individual scores from different researchers and across different mitigation options in the cluster ranging from 1 to 4 (and up to 5 for cost effectiveness and integration). Considering the average responses, mitigation options in 'low GHG feed' can be expected to offer a small reduction in emissions, with little to low impact on other GHGs/water quality. The options within the cluster would come at a small cost to farmers, face moderate barriers to adoption, and would be limited to 5% to 10% of pastoral farms. However, this is a significant oversimplification given that individual responses ranged from high (5) to low (1) on all questions.

Reduced N_2O from soil/plants cluster

Average scores for 'reduced N_2O from soil/plants' were above 3 for all five PCE questions except for cost effectiveness (2.30). As for the low GHG feed cluster, large variation in responses was provided on all five PCE questions among mitigation options in the cluster, with scores ranging from 1 to 4. Considering the average scores, the mitigation cluster has the potential to reduce emissions by 10% to 20% with additional benefits for other GHGs/no impact on water quality. The options come at a medium cost to the farmer, have moderate barriers to adoption, and could be viable on 10% to 25% of pastoral farms. However, this is a significant oversimplification given that individual responses ranged from high (5) to low (1) on all measures. It is worth noting that the ‘reduced N_2O from soil/plants’ cluster had the highest average score for mitigation effectiveness.

Management interventions cluster

Average scores in the mitigation options in ‘management interventions’ cluster were above 3 for all PCE questions, except for mitigation effectiveness (average score of 2.78). There was variation in the responses to question 1, but the majority implied mitigation potential of up to 20% of emissions. ‘Management interventions’ had the highest average score for impacts on other GHGs and water quality (question 2) relative to the other 4 mitigation clusters, and was second behind low GHG animals in terms of its score for cost effectiveness (question 3). It also had the second highest score in terms of sensibility from a national perspective (question 5).

Table A5-3. Detailed summary of responses [mean and number of observations (obs)] across each mitigation option, by cluster, as summarised in Figures A5-1 to A5-5. Scoring: 1 (low) to 5 (high). For 'other impacts' scaling is 1= high negative impact to 5= high positive impact

		Effective	Other Impacts	Cost Effectiveness	Integration	National Perspective
1. Methane inhibitors/vaccines cluster						
General	mean	4.00	.	.	5.00	5.00
	obs	1	0	0	1	1
Nanobeat	mean	3.00	2.00	1.00	1.00	1.00
	obs	1	1	1	1	1
Small molecule methanogen inhibitor	mean	4.33	2.67	2.67	2.67	3.00
	obs	3	3	3	3	3
Defaunation	mean	2.00	4.00	1.00	1.00	1.00
	obs	1	1	1	1	1
Nitrate in TMR	mean	3.00	2.00	2.00	2.00	2.00
	obs	1	1	1	1	1
Bio-active compound in feed	mean	3.00	4.00	4.00	4.00	3.00
	obs	2	2	2	2	2
Biochar	mean	2.00	4.00	2.00	2.50	2.00
	obs	2	2	2	2	2
Early life intervention with CH_4 inhibitor	mean	2.00	2.00	3.50	4.00	2.50
	obs	2	2	2	2	2
2. Low GHG animals cluster						
General	mean	2.00	3.00	3.00	4.00	5.00
	obs	2	1	1	1	2
Low CH_4 yield sheep	mean	2.75	2.50	3.75	4.00	3.75
	obs	4	4	4	4	4
Low CH_4 yield cattle	mean	2.75	2.50	3.75	4.00	4.00

	obs	4	4	4	4	4
Improved longevity cattle/sheep	mean	2.67	3.00	4.33	4.00	4.67
	obs	3	3	3	3	3
Lighter adult weight	mean	2.33	3.00	3.33	3.33	4.33
	obs	3	3	3	3	3
Reduced DMI/ RFI cattle	mean	2.67	2.67	3.33	3.67	4.33
	obs	3	3	3	3	3
Increased lambing %	mean	2.67	3.33	4.33	4.33	4.33
	obs	3	3	3	3	3
3. Low GHG feed cluster						
General	mean	3.00	2.50	3.00	2.50	2.50
	obs	2	2	2	2	2
Bioactive compounds in feed	mean	3.00	3.00	3.50	3.50	3.50
	obs	2	2	2	2	2
Increased diet lipid	mean	3.00	2.00	2.50	2.50	2.50
	obs	2	2	2	2	2
Forage rape	mean	3.67	2.33	3.67	4.00	2.67
	obs	3	3	3	3	3
High sugar grass/feed	mean	2.75	3.25	3.75	4.50	3.25
	obs	4	4	4	4	4
High starch feed	mean	3.00	3.33	2.33	3.33	2.67
	obs	3	3	3	3	3
Fodder beet	mean	2.67	3.00	3.33	4.00	2.67
	obs	3	3	3	3	3
Fungus *Mortierella wolfii* bioactive compounds to reduce enteric CH_4	mean	2.50	2.00	2.50	3.00	2.00
	obs	2	1	2	2	2

Diet interventions to increase urine hippuric acid	mean	2.50	2.50	2.50	3.00	2.00
	obs	2	2	2	2	2
4. Reduced N_2O from soil/plants cluster						
Chemical nitrification inhibitors	mean	4.83	3.43	2.43	4.00	4.00
	obs	6	7	7	7	7
Urease inhibitors	mean	2.38	3.08	2.86	4.29	4.00
	obs	7	6	7	7	7
Biochar	mean	1.8	2.90	1.40	1.80	1.40
	obs	5	5	5	5	5
Plant-targeted interventions to mitigate N_2O emitted via plant canopies	mean	3.25	3.13	2.50	3.00	4.00
	obs	4	4	4	4	4
5. Management interventions cluster						
General	mean	4.00	5.00	4.00	4.00	4.00
	obs	1	1	1	1	1
Low N feeds replacing N fertiliser	mean	2.67	3.42	3.00	3.50	3.33
	obs	6	6	6	6	6
Sheep performance improvement to reduce CH_4	mean	3.25	3.38	3.50	3.50	3.75
	obs	4	4	4	4	4
Feeding time and feed composition to reduce N_2O	mean	2.83	2.83	3.50	3.33	3.33
	obs	3	3	2	3	3
Dairy system herd improvement – higher breeding worth/genetic merit + lower stocking rate to reduce total farm GHG	mean	2.83	4.25	3.50	3.50	4.00
	obs	6	6	6	6	6
Dairy system lower N input - reduced N fertiliser inputs + low N diet to reduce total farm GHG	mean	3.00	3.58	2.80	3.33	3.83
	obs	6	6	5	6	6
Dairy system reduced replacement rate to reduce total farm GHG	mean	2.57	3.79	3.71	3.29	3.86
	obs	7	7	7	7	7

Management of on-farm urine hot-spots to reduce N_2O	mean	2.67	3.08	3.50	3.75	3.67
	obs	6	6	6	6	6
Irrigation management	mean	2.40	3.10	3.40	2.90	2.00
	obs	5	5	5	5	5

Appendix 6: Project leaders and stakeholders survey

In order to collect more information about projects, a survey of 13 researchers/past SLMACC project leaders was conducted in collaboration with the 'SLMACC Technology Transfer Review' project, targeting past SLMACC research project leaders, to gather additional information regarding the SLMACC projects under evaluation. The collection of data was mainly conducted via an online survey using the software Survey Monkey, in the second half of 2017. In addition some data was also collected from meetings between past SLMACC project leaders and Motu researchers. Table A6-1 summarises the number of responses obtained, with the number of researchers classified across the five GHG mitigation clusters in the current review.

Table A6-1. Number of respondents (to survey and interviews) across clusters

Cluster	Number of individual respondents	Total number of project leaders across all projects*	Percentage of respondents
CH_4 inhibitors / vaccines	2	3	66%
Low GHG animals	1	2	50%
Low GHG feeds	3	5	60%
Reduced N_2O from soil/plants	5	9	56%
Management interventions	2	4	50%
Total	13	23 of 31 total projects	56%

* Some project leaders led two or more projects (given there were 31 projects analysed in the current review). A few projects (and therefore research leaders) fell into more than one mitigation cluster, see Table 3.

The questions used were designed with the main aim of providing data for the evaluation framework. For more references please see Penny (2018b).

Survey results and discussion

In this section a summary is provided of the main results obtained from the survey/interviews. Highlighted between quotation marks are the main data captured and reported.

Most projects had relatively small core teams, with half of the respondents reporting research teams of less than five people and the other half reporting research teams with five to ten researchers. However, in relation to the 'wider project team' (including for example stakeholders or partners on advisory or reference groups), most projects reported having more than one organisation involved, signalling collaboration across organisations.

In terms of cross-disciplinary collaboration within teams, in most cases researchers were in a similar technical field to that of the project focus, with just two projects having scientists outside the technical scope of the project. These scientists included a statistician (one project) and an economist and a social scientist (one project).

Results in relation to stakeholder engagement of the different research projects, based on a Likert scale from 1 (low) to 7 (high) are presented in Table A6-2. The scores suggest that stakeholder and end-user engagement was generally implemented at all stages of the research[8]. Across the mitigation clusters, 'reduced N_2O from soil/plants' received the lowest score on average, indicating a lower stakeholder involvement than in the other four clusters.

Table A6-2. Average score across mitigation clusters in response to the question "to what extent did the project team engage with stakeholders and end-users in the following… (as shown in columns' heads)". Scores from 1 (low) to 7 (high)

Custer	The question framing and design	During the course of the research	In the design of outputs or activities	Average
Vaccine and Inhibitors	5.5	3.5	6	5
Low GHG animals	4	7	5	5.3
Low GHG feed	5.3	5	5.7	5.3
Reduced N_2O from soil/plants	4.6	3	4.6	4.1
Management interventions	5	5		5

For the question "to what extent do you consider that the network of individuals or organisations involved in this SLMACC project has endured beyond the life of the project?" results show that in general, the "management intervention" cluster had been more successful in maintaining established networks than the other four clusters (Figure A6-1). In contrast the cluster "low GHG feed" had a smaller network endurance.

[8] As this survey was framed for all review projects evaluating the SLMACC programme, the more broad concept of 'end-users', instead of farmers/industry, was used.

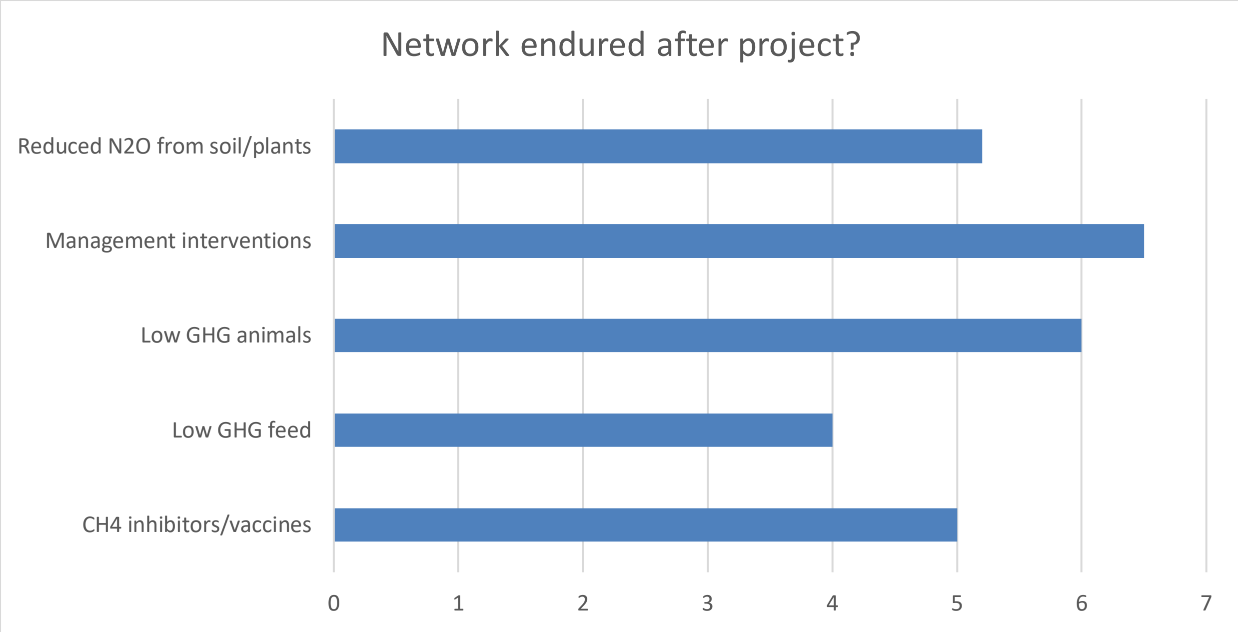


Figure A6-1. Results from the question "to what extent do you consider that the network of individuals or organisations involved in this SLMACC project has endured beyond the life of the project?"

In relation to early career researchers, only three out of the 13 research project leaders stated that they worked with postgraduate students. Five each stated they had worked with interns, and with post-doctorate students. Across those research projects, which included post-docs, most rated the extent of their involvement in the project with a high score of 6 or 7 (high engagement), except in one case with a low score (of 2). In relation to recent graduates, six projects reported "graduated early career researchers" (ECR, neither students nor interns) in their teams, but scores of the extent of their involvement were quite heterogeneous, with an average of 4.5 (standard deviation of 1.26) across the six projects. These findings suggest that although some participation of students or young scholars has occurred across projects, their involvement has not been active and SLMACC mitigation projects have not necessarily supported the formation of new talent in New Zealand.

After the question "did you use monitoring and evaluation during the project to adjust your milestones, activities or outcomes?" most project leaders stated that they employed some sort of monitoring and evaluation, with the exception of projects in the reduced N_2O from soil/plants cluster, where only two out of five projects used monitoring and evaluation. Of projects that did not use monitoring and evaluation, some reasons were because the project was short and so there was no opportunity, and because a clear experimental plan was followed.

Regarding the question about knowledge exchange within the scientific community, two project leaders stated that their projects had used 'newsletters or webpages for a scientific audience'; one project in the low GHG animals cluster and one project in the low GHG feeds cluster. In this category the most common method to disseminate knowledge were journals (nine cases) and conference presentations (eight cases) (Table A6-3).

Table A6-3. Responses across clusters after the questions "what were the methods of knowledge exchange of the research generated through the project, within the scientific community?"

Cluster	**(1) Journal publications (number)**	**(2) Presentation of research at a conference or workshop within New Zealand (Yes/No)**	**(3) Presentation of research at a conference or workshop internationally (Yes/No)**	**(4) Newsletters or webpages for a scientific audience (Yes/No)**
Vaccine and Inhibitors	1	Y	N	N
Low GHG animals	3	Y	Y	Y
Low GHG feed	12	Y	Y	Y
Reduced N_2O from soil/plants	8	Y	Y	N
Management interventions	2	Y	Y	N

Notes: Column (1) shows total number of journal publications across the whole cluster as detailed in Table A3-1 in Appendix 3. Column (2) to (3) report yes if at least one project used this method. All clusters also have projects with MPI technical reports as part of their exchange of knowledge.

The survey showed that none of the projects engaged in the use of social media to "broadcast the research beyond the scientific community", while two projects used the general media to share information about the project. However, a high number of studies did report 'sharing knowledge with advisory group or community of practice', while some also reported 'meeting or exchange with end users' (four cases). The latter of these two forms of communication received the higher impact score from researchers in terms of increasing awareness of the project – average of 6.3 and 5.7, respectively, in a scale from 1 (low) to 7 (high).

In terms of evidence of "uptake and use of the research by the scientific community", many researchers stated readings and citations of the project outcomes. One study had been recognised by local and international organisations. Two researchers suggested that uptake of their findings had been limited because of non-positive results. One successful case has led to designs being purchased internationally. Quotes from researchers with respect to impacts achieved across different SLMACC funded projects are provided in Table A6-4.

Table A6-4. Quotes from researcher with regard to impacts of SLMACC funded projects.

The Board of the Intergovernmental Panel on Climate Change (IPCC) has recognised the findings of this research in its Emissions Factor Database not only endorsing the research but also acknowledging that it has potential to be applied globally.
This research is used by the New Zealand Ministry for Primary Industries to account for the effect of the mitigation option on emissions reductions in the National Greenhouse Gas Emissions inventory for UNFCCC and Kyoto Protocol (future Paris Agreement) International reporting.
This research has been cited in 39 peer reviewed papers including in Nature Scientific Reports
Results of the study were not positive with respect to the mitigation option, so it was not communicated - if they had been then greater knowledge transfer would have occurred through various avenues (journals, international conferences etc.)
The mitigation component of this study did not evolve into any follow-up research, partly because of the results obtained, and also partly because of imposed regulation. However, results obtained were used for a meta-analysis resulting in a second journal publication.
Research outputs was taken up by PGGRC-NZAGRC
Citations, request for reprints, request for models
The work developed rapid measures of methane emissions in sheep and designs developed are currently being purchased by organisations in other countries and in another case a large scale GRA project is underway
Project leader was invited to be part of the project team conducting similar research for the case of Chilean agriculture.
Within a couple of weeks since publication on line, there have been more than 50 readings

Note: Statements have been slightly modified from original quotes for sake of clarity and to preserve anonymity.

Stakeholders survey

The 'SLMACC Technology Transfer Review' project also conducted a survey that targeted stakeholders related to primary industries in New Zealand with the aim to assess their knowledge and perceptions about the overall SLMACC programme. The survey was conducted in October 2017 using the software Survey Monkey. There were in total 148 respondents to the survey. The number of respondents classified by the organisation or sector of their work is provided in Figure A6-2.

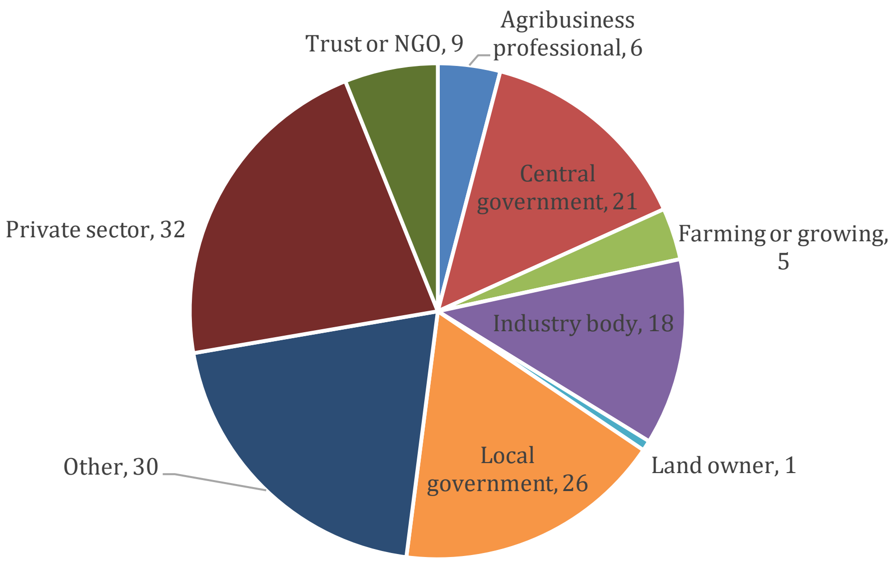


Figure A6-2. Number of respondents to stakeholders survey by sector (n=148)

The survey asked respondents about a number of resources, as provided in Figure A6-3, generated through the SLMACC programme over the last decade.

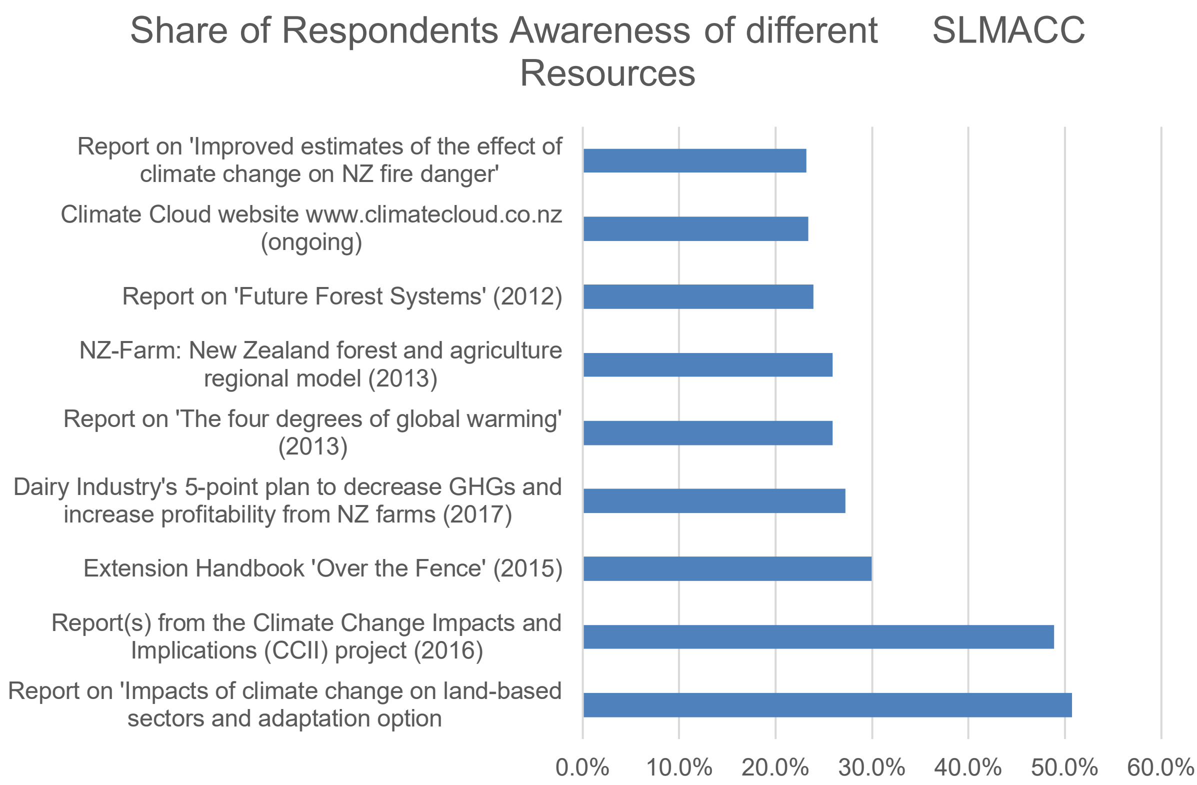


Figure A6-3. Share of respondents' awareness to different resources derived from specific SLMACC projects in the last decade.

Two of the nine projects in the survey related to agricultural mitigation research projects, one of which was evaluated in this report: the "Dairy Industry's 5-point plan to decrease GHGs" (project 31). The second mitigation research project was not evaluated in this report: "increase profitability from NZ-FARM (2017) and NZ-FARM: New Zealand forest and agriculture regional model" (2013; NZ-FARM). Research relating to the NZ-FARM model was not part of this review because it was not designed to develop a mitigation option for agricultural emissions. It was however included in the survey because it developed a concrete tool as part of a SLMACC project that has been used lately to assess agricultural GHG emissions and mitigation (e.g., Daigneault et al, 2016).
The levels of awareness of these two agricultural GHG mitigation-related projects were in the middle range of responses, with an approximate rate of awareness of 35%.[9]

From those respondents who were aware of the "dairy industry's 5-point plan" or those who were aware of "NZ-FARM", 77% (of 26) and 80% (of 25), respectively, were aware of the SLMACC

[7] Not all respondents answered the question shown in Figure A6-2. 136 out of 148 total respondents responded to the question on awareness of "Dairy Industry's 5-point plan" and 135 to awareness of "NZ-FARM". These lower response rates were a common feature across different questions of the survey.

programme. This means that around one out of every five respondent did not know about SLMACC.

The main uses of the “5-point plan” and “NZ-FARM” among all categories were to access information on climate change mitigations or adaptation to climate change (Table A6-5). Compared to users of the “5-point plan”, users of “NZ-FARM” were more likely to have been part of an applicant group for SLMACC funding or part of a SLMACC team or advisory group, and relatively less likely to use SLMACC for a specific purpose.

Table A6-5. Please choose the category which best describes how you have been involved with the SLMACC fund: (please tick all that apply)

	All	**Users of 5-point plan**	**Users of NZ Farm**
Part of an applicant group for SLMACC funding	31.6%	20.0%	50.0%
Part of a SLMACC project team or advisory group	28.1%	10.0%	30.0%
Accessed information on climate change mitigations (this could include attending presentations or workshops, reading written or electronic information)	71.9%	90.0%	85.0%
Accessed information on adaptation to climate change (this could include attending presentations or workshops, reading written or electronic information)	77.2%	80.0%	85.0%
Used SLMACC information for a specific purpose (e.g. policy development)	36.8%	45.0%	25.0%
Number of Responses	57	20	20

SLMACC-funded products, specifically the “5-point plan” and “NZ Farm”, were mainly accessed as “read information” (100% of respondents) (Table A6-6)’ and used to “increase knowledge” (53 – 75%) (Table A6-7). For a third to a half of respondents, other uses were to develop policy or strategy, support a decision, plan for the future, or use indirectly (Table A6-7).

Table A6-6. How have you accessed SLMACC research? (please tick all that apply)

	All	**Users of 5-point plan**	**Users of NZ Farm**
Attended conferences, presentations or workshops	29.0%	20.0%	37.5%
Read information (including electronic)	96.8%	100.0%	100.0%
Unsure	0.0%	0.0%	0.0%
Other (please specify)	3.2%	6.7%	25.0%
Number of Responses	31	15	8

Table A6-7. How have you used SLMACC research? (please tick all that apply)

	All	Users of 5-point plan	Users of NZ Farm
To increase knowledge	61.3%	53.3%	75.0%
To support a decision or action	35.5%	33.3%	50.0%
To plan for the future	25.8%	33.3%	37.5%
To develop policy or strategy	35.5%	53.3%	50.0%
Indirectly (e.g. to inform research, policy or advice)	45.2%	53.3%	37.5%
Other (please specify)	0.0%	0.0%	0.0%
Number of Responses	31	15	8

The survey asked respondents about their impressions of how SLMACC has contributed to expanding the research in New Zealand on different topics including GHG mitigation. The impact of SLMACC on science in GHG mitigation research compared to other research areas was assessed using a Likert scale from 1 (low) to 7 (high impact) (Figure A6-4). There were 65 or 66 respondents to each topic.

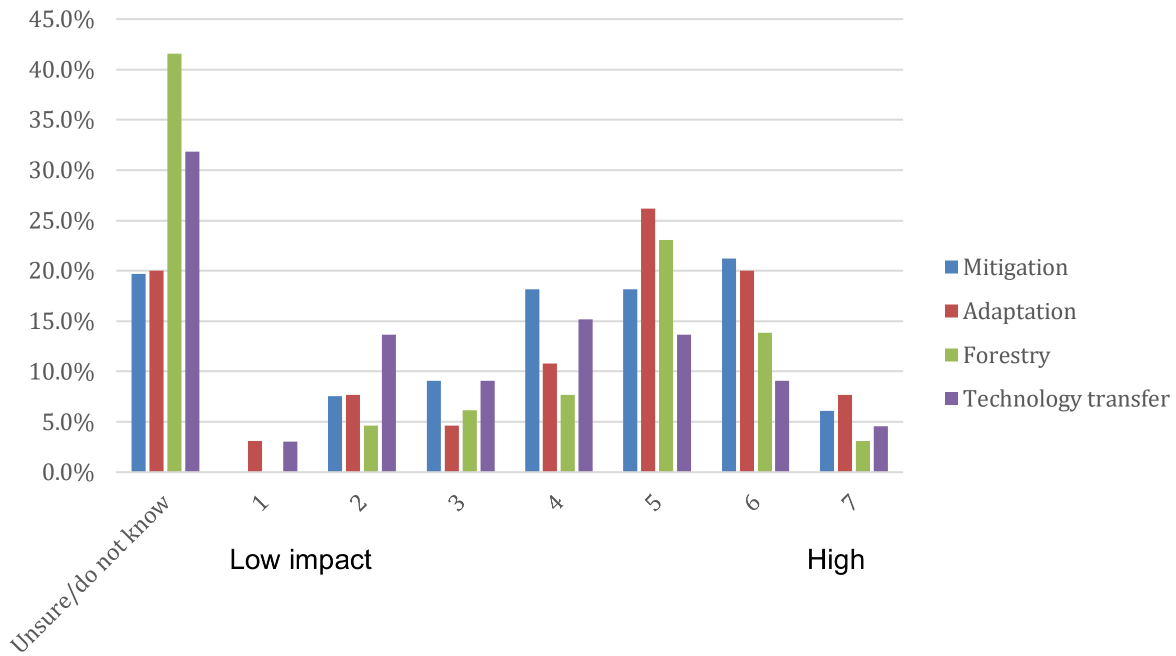


Figure A6-4. Respondent ratings of the extent to which the SLMACC programme has contributed to expanding the science in New Zealand related to GHG mitigation, climate change adaptation, forestry and technology transfer

There were no strong differences in opinions across the different topics as indicated in Figure A5-4. Excluding respondents who said they were unsure/did not know, the average ranking was between 4.00 and 4.75 for all SLMACC topic areas. The agricultural mitigation topic area, and also the climate change adaptation topic area, received the largest number of high impact scores (6 and 7), in contrast to forestry and technology transfer topic areas.

Appendix 7: Technical summary of mitigation effectiveness

In this section, we have collated a summary of the quantifiable mitigation effectiveness reported at the individual project level and provide an assessment of whether research in this particular stream has continued or ceased (Table A7-1).

Table A7-1: Summary of mitigation effectiveness observed within individual SLMACC projects. Note: several projects align with more than 1 category.

#	Project title	Mitigation effectiveness	Status of research into mitigation option (On-going/Ceased)
1.	**CH_4 inhibitors/vaccines cluster**		
1	Enteric methane mitigation through nanoparticles	• *In vitro* pure culture, 21-100% inhibition of CH_4 by nanoparticles.	Research in this area is still ongoing (GPLER funding) with development of nanoparticles and testing *in vitro* in batch and continuous culture.
2	Hydrogen management in the rumen	• Anthraquinone/chloroform supplementation in the diet inhibited CH_4 yield by 60-70% in sheep (Exp. 1), approximately 50% when fed to growing sheep (Exp. 2), approximately 60% in lactating dairy cows (Exp. 3) and by 50-90% and 80% when fed to newly born calves (Exp. 4 and 5, respectively). • Feeding these methanogen inhibitors did not affect total tract diet digestion in sheep or performance in newly born calves. In growing sheep and lactating dairy cows, intake drastically decreased and consequently animal performance, however, this is likely inherent to the particular compounds used rather than due to CH_4 inhibition. When the inhibitors were removed from the diet of the newly born calves, CH_4 yield increased to similar levels as in control animals suggesting that there was no imprinting of the low CH_4 yield imposed in early life.	Research in this programme has provided additional information for the chemical methanogen inhibitor programme including SLMACC project 5 to show that digestion and production of the animal are not impaired when methanogen inhibitors are fed. Early life intervention work has contributed to the international FACCE-JPI programme including funding from MPI.
3	Hydrogen management for methane mitigation	• Exp. 1, adding nitrate to the diet of lactating dairy cows reduced CH_4 yield by 20% without affecting DMI, or milk production, while adding linseed oil to the diet did not affect CH_4 emissions. • Exp. 2, a new methanogen inhibitor (acetylene) was tested *in vitro* and *in vivo*. The inhibitor was found to eliminate CH_4 emissions almost completely in sheep, however, emissions rose to pre-inhibition levels after 5 days, while dosing the inhibitor daily.	To our knowledge, there has not been any follow up of these programme findings. However, many studies abroad have tested the effect of nitrate and lipids in the diet on CH_4 emissions. A meta-analysis indicated a dose response in CH_4 yield (g/kg DMI) to nitrate as: [-8.3 × nitrate (g/kg BW) + 15.2; R^2 =0.8.] [1](Lee and Beauchemin, 2014). Effect of increasing dietary lipids on reducing CH_4 yield (g/kg DMI) has been determined in many meta-analysis evaluations and ranged from -0.093 to -1.07 decrease in CH_4 yield per unit of fat (g/kg DMI) increase. However, there are also many individual experiments with no effect of dietary fat increase on CH_4 yield (Patra et al., 2013, 2014; Grainger and Beauchemin, 2011).
4	Protozoa, Low Methane rumen, Mitigas	• The aim was to develop a defaunation protocol, find selective inhibitors for studying rumen function and develop protocols for screening inhibitors. Developing a defaunation protocol failed and its mitigation potential could therefore not be tested. • Several methanogen inhibitors were identified but their mitigation potential not tested.	The inhibitors identified were used in for example SLMACC project 2 and the *in vitro* system was used in SLMACC project 11 and 12 and many other research programmes including follow on projects from SLMACC project 1 and 5. Research abroad has continued to determine effects of defaunation on CH_4 emissions. A meta-analysis by Guyader et al. (2014)[2] found a negative relationship between CH_4 yield and rumen protozoa concentration [8.14 ×

			protozoa concentration (log10 cells/mL) -30.7]. However, as for lipids, there are also many individual experiments with no effect of rumen protozoa concentration on CH_4 yield.
5	Accelerated ruminant methane mitigation	• Methanogen enzyme targets for inhibitors discovered, inhibitors screened using modelling to target identified methanogen enzymes and to select a number of inhibitors successfully tested in pure culture. Direct mitigation potential was not tested.	The PGgRc/NZAGRC funded work is still continuing to date since this SLMACC project in 2009-2011 with several compounds now tested *in vitro* and *in vivo* in sheep and cattle for effects on CH_4 emissions in short and longer term trials. Also several related GPLER projects have contributed to this topic area.
11	Forage/fungal associations for reducing methanogenesis	• *In vitro*, forage endophytes had no effect on CH_4 production, while some fungi did reduce CH_4.	To our knowledge, there has not been any follow up of these programme findings.
12	Identifying non-agricultural and agricultural plant species with anti-methanogenic properties	• *In vitro* screening of 220 plant species, 10 decreased CH_4 by more than 50%, and 4 of these had no negative effect on overall fermentation.	To our knowledge, there has not been any follow up of these programme findings.
16	Biochar in grazed pasture systems	• Biochar did not mitigate CH_4 production in a dual flow continuous culture fermenter system, but instead enhanced emissions.	To our knowledge, there has not been any follow up of these programme findings.
2. Low GHG animals cluster			
6	GHG Mitigation using Efficient cows	• Dairy cattle with lower RFI (residual feed intake/feed efficiency) had low dry matter intake, but numerically higher CH_4 yield and urinary N excretion.	Dairy cattle RFI funded project has continued after this programme, but to our knowledge no further GHG measurements were performed in NZ. International work in this research area has been inconsistent with more efficient animals having lower, similar or higher CH_4 yield depending on the trial.
7	Sheep, cattle, and methane predictors	• Research mainly focused on finding metabolic, metabolomic, genomic markers to indirectly select for low CH_4 yield cattle and sheep. • It was reported that heritability of CH_4 production and CH_4 yield were 0.29 and 0.13, respectively, in 1255 sheep.	The PGgRc/NZAGRC funded work is still continuing to date since this SLMACC project in 2009-2012 with breeding of low CH_4 yield sheep and finding correlated proxies to indirectly select for animals with low CH_4. Research breeding values can be released to farmers in the short term. Further work is continuing to determine the effect of breeding for CH_4 yield in sheep on N excretion and feed efficiency (RFI). Also, some cattle work has been funded recently through NZAGRC.
17	To Improve the Sheep Component of the Methane Model and Provide Management Strategies for Farmers to Reduce Methane Production	• CH_4 per lamb reduced by 21% if implementing 3 management changes: lambing hoggets, increasing ewe scanning % and reducing replacement rate.	To our knowledge, there has not been any follow up of these programme findings.
3. Low GHG feed cluster			
3	Hydrogen management for methane mitigation	• *See under CH_4 inhibitors/vaccines*	*See under CH_4 inhibitors/vaccines*

8	Total GHG emissions from supplementary feeds in farm systems	• Increased CH_4 yield factor, determined with sheep in respiration chambers, when 25-50 % of lucerne silage was substituted with either maize silage or maize grain. • Carbon footprint of various supplements was modelled using an LCA approach with PKE having high CO2-eq/kg DM > barley grain, concentrate > forage rape, bulb turnips > pasture silage, forage kale, maize silage, cereal silage and hay > molasses > brewers grains > food industry by-products	To our knowledge, there has not been any follow up of these programme findings, however, carbon footprint values of supplementary feeds are used for modelling carbon footprints of farm systems. In addition, research has been conducted on the effect of other plant species (e.g. plantain, lucerne, Italian ryegrass, forage crops) on N_2O emissions. This work suggested that plantain has the greatest potential to reduce emissions and further work is now being conducted to assess the effect of plantain on GHG emissions (including CH_4, N_2O and soil C effects)
9	Brassicas - a win-win option for GHG mitigation and animal productivity	• Rape diet reduced CH_4 yield by 32-34% when measured using the SF_6 method in grazing sheep and 32-37% for sheep fed in respiration chambers. • Total N excretion with urine and faeces and EF_3 were similar for sheep fed forage rape and ryegrass pasture in indoor trials. • In heifers, CH_4 yield was 40% lower for cattle fed forage rape than in cattle fed pasture and • EF_3% was similar for urine of animals fed either forage. • Meta-analysis of the EF_3 data indicated increased EF_3 of 1.54% vs 1.20% for urine of animals fed forage rape vs ryegrass based pasture.	Results of this project have been used in the LCA modelling of sheep and beef farms in SLMACC project 8. Also, research has continued to determine the effect of glucosinolates, secondary metabolites of brassicas, on N_2O emissions.
10	High sugar ryegrasses and methane emissions	• In a ryegrass cultivar comparison, CH_4 yield was overall 7-12% lower for sheep fed a high sugar or a tetraploid ryegrass cultivar compared with sheep fed a conventional diploid cultivar. • In grazing trials with CH_4 measured using the SF_6 method, CH_4 yield was lower for sheep grazing a tetraploid ryegrass cultivar (15.4 g/kg DMI), intermediate for sheep grazing a high sugar grass cultivar (17.6 g/kg DMI) and highest for sheep grazing a conventional diploid ryegrass cultivar (20.5 g/kg DMI).	To our knowledge, there has not been any follow up of these programme findings. But, commercial improvement of tetraploid ryegrass cultivars and cultivars with high sugar continue and data from these trials have been used for marketing high sugar grass as resulting in lower CH_4 emissions.
11	Forage/fungal associations for reducing methanogenesis	• *In vitro*, forage endophytes had no effect on CH_4 production, while some fungi did reduce CH_4.	To our knowledge, there has not been any follow up of these programme findings. However, recently a request for proposal released by MPI related to identifying endophyte metabolites that could reduce CH_4.
12	Identifying non-agricultural and agricultural plant species with anti-methanogenic properties	• *See under CH_4 inhibitors/vaccines*	*See under CH_4 inhibitors/vaccines*
13	Brassicas, methane and nitrous oxide	• CH_4 yield was 30 and 20 % lower for sheep fed forage rape at 7 and 15 weeks, respectively, than for sheep fed ryegrass based pasture. • Total N excretion was similar for sheep fed forage rape and ryegrass based pasture. • The EF_3 was 59% lower for urine of sheep fed forage rape.	Results of this trial have been the basis for SLMACC project 9 (EF_3 data included in meta-analysis). Brassicas have also been studied in other GHG funded research programmes (e.g. PGgRc/NZAGRC) and their use has been reviewed for its suitability to include in the national GHG inventory of NZ.
14	Assessing the Role of Dietary Carbohydrate to Protein Ratios on GHG Emissions	• With artificial diets, increasing dietary water soluble carbohydrate (WSC) to N ratio resulted in decreased urine N relative to faecal N. • In diet with high NDF (fibre), increasing WSC:N ratio appeared to increase CH_4 yield, while in medium and low NDF diets, increasing WSC:N in the diet resulted in decreased CH_4 yield.	High sugar grass was simulated with artificial diets in this study and SLMACC project 10 tested the effect of feeding actual high sugar ryegrass cultivar on CH_4 emissions and N excretion.

	from Pastoral Agriculture		
15	Nitrous Oxide-novel mitigation methodologies	• Hippuric acid addition to urine did not reduce N_2O emissions, whereas DCD applied to soil (representing a known mitigation option) reduced emissions by more than 50%.	To our knowledge, there has not been any follow up of the hippuric acid programme findings. DCD has been removed from the market.
4. Reduced N_2O from soil/plants cluster			
15	Nitrous Oxide-novel mitigation methodologies	• *See under low GHG feed*	*See under low GHG feed*
16	Biochar in grazed pasture systems	• *See under CH_4 inhibitors/vaccines*	*See under CH_4 inhibitors/vaccines*
22	National impacts of temperature and moisture on DCD effectiveness	• No specific reduction potential investigated: but rather analysis of half-life of DCD	To our knowledge, there has not been any follow up of these programme findings. DCD has been removed from the market.
23	DCD effects on N fixation	• No specific reduction potential investigated, but rather evidence of no effect on white clover.	To our knowledge, there has not been any follow up of these programme findings. DCD has been removed from the market.
24	Quantifying the Variability of the Effectiveness of Nitrification Inhibitors on N_2O Emissions	• Average reduction of 45% in EF_3 for urine deposited in May on 6 soils	To our knowledge, there has not been any follow up of these programme findings. DCD has been removed from the market.
25	Direct nitrous oxide (EF1)	• No reduction in EF_1 with DCD added to urea or farm dairy effluent (FDE)	The results of this study (revised EF1 values for urea fertiliser and FDE) have been incorporated into the national inventory methodology. DCD has been removed from the market.
26	Desktop study of emission factors for urease inhibitors for nitrogen fertiliser	• Recommended FracGASF for urea + UI reduced by 0.4	Basis for SLMACC project 27.
27	Reductions in FracGASM and FracGASF in the GHG inventory when urease inhibitor has been applied to the soil and with N fertiliser	• Confirmed recommendation that FracGASF for urea + UI reduced by 0.4; subsequent published paper suggested 0.45.	Value generated was adopted in the national GHG inventory of NZ. To our knowledge, there has been no other follow up of these programme findings.
28	Plant canopy nitrous oxide emissions	• No specific reduction potential investigated: but rather identifying that plant leaf surfaces are a source of N_2O	Some work has been proposed to assess the effect of the plant canopy on urine interceptions and spreading, and associated N_2O emissions, with funding from NZAGRC.
29	Biochar effects on urea derived N_2O and ammonia	• No reduction in N_2O emissions with surface-applied biochar (coated onto urea prillls).	To our knowledge, there has not been any follow up of these programme findings.
30	Can cattle do it?	• Biochar did not affect silage quality or rumen function (both *in vitro*), nor CH_4 emissions.	To our knowledge, there has not been any follow up of these programme findings.
5. Management interventions cluster			

8	Total GHG emissions from supplementary feeds in farm systems	• Dairy farms: Carbon footprint per kg MS reduced by 15-17% when a range of mitigation options applied, where biggest reduction of 7-9% due to fertiliser being replaced with bought-in maize silage. • Sheep & Beef farms: adding forage rape crop to the feeding system reduced GHG by 1-2% per kg product (due to reduced CH_4 yield, but balanced by increased N_2O from crop establishment & production).	To our knowledge, there has not been any follow up of these programme findings, however, carbon footprint values of supplementary feeds are used for modelling carbon footprints of farm systems. In addition, research has been conducted on the effect of other plant species (e.g. plantain, lucerne, Italian ryegrass, forage crops) on N_2O emissions. This work suggested that plantain has greatest potential to reduce emissions and further work is now being conducted to assess the effect of plantain on GHG emissions (including CH_4, N_2O and soil C effects)
17	To Improve the Sheep Component of the Methane Model and Provide Management Strategies for Farmers to Reduce Methane Production	• *See under low GHG animals.*	*See under low GHG animals.*
18	Grazing management systems to reduce N_2O emissions	• Data analysis: Insufficient data to suggest cattle N_2O emissions could be reduced through management of feeding time or feed composition. For sheep, delayed feeding to the afternoon may reduce NH_3 and N_2O due to cooler night temperatures (unquantified).	To our knowledge, there has not been any follow up of these programme findings.
19	Assessment of the GHG footprint of the low and high input dairy systems of the Canterbury P21 farmlet trial	• CH_4 yield was 28% lower for dry cows grazing fodder beet than those grazing forage kale. • 'Low stocking efficiency' dairy system had 25% lower GHG emissions compared to 'High stocking efficiency' system, primarily due to lower stocking rate while maintaining milk production with high genetic merit cows.	As a result of this project, further work was conducted under the NZAGRC to also assess the GHG footprint of the P21 farmlets in Waikato and South Otago, which is currently being prepared for scientific publication.
20	Identification of problem areas within farms and farming systems and approaches to mitigate N_2O hot spots.	• Farm gates identified as a hotspot for N_2O, various mitigation options suggested but none quantified in terms of effectiveness.	To our knowledge, there has not been any follow up of these programme findings.
21	Irrigation and N_2O	• Less frequent irrigation reduced EF_3 by 22-50%; Delaying grazing on poorly drained soil by 6 days following irrigation reduced EF_3 by >60%	To our knowledge, there has not been any follow up of these programme findings. However, further non-related work into the effects of irrigation on N_2O emissions has been explored by other Canterbury-based researchers.
31	System analysis to quantify the role of farm management on GHG emissions and sinks for pastoral sector	• Dairy systems: combination of lower replacement rates, increased body weight + lower stocking rate, longer lactation, stand-off pad, replacing N fertiliser with low N feed reduced GHG/kg MS by 15-20% and increased MS/ha by 15-20%. Total emissions per ha reduced by 16-19% when all mitigation options combined. • Sheep & Beef: increasing breeding-ewe weaning %, decreasing breeding-ewe replacement rates, and increasing proportion of total cattle on farm investigated. Every 10% increase in weaning% reduced GHG by 1% and GHG intensity by 3%. Decreasing replacement rate had minimal impact on GHG.	The results of this study were used to inform the management practices developed for the P21 dairy farmlet studies conducted in 4 regions of NZ. Following the completion of the P21 study, a SLMACC funded project (project 19) assessed the GHG footprint of the Canterbury farmlets. This was then followed with an NZAGRC-funded GHG assessment of the Waikato and South Otago farmlets. Furthermore, this study led to development of farm optimisation model IDEA and the improvement of the Molly enteric CH_4 sub-model within DairyNZ's Whole Farm Model, which has subsequently been used in other DairyNZ GHG research projects.

		• Increasing proportion of trading and dairy-heifer grazer cattle relative to breeding cows: for every 10% increase in dairy heifer grazers, total GHG reduced by 0.5% and emissions intensity by 2.1%.	The sheep & beef results were used to inform modelling and on-farm measurements in a subsequent NZAGRC-funded programme, as well as informing several extension programmes including a SFF-funded climate change technology transfer project “Understanding GHG and climate change”.

[1]Lee, C., Beauchemin, K.A. 2014. A review of feeding supplementary nitrate to ruminant animals: nitrate toxicity, methane emissions, and production performance. Can. J. Anim. Sci. 94: 557-570.
[2]Guyader, J., Eugène, M., Nozière, P., Morgavi,D.P., Doreau, M., Martin, C. 2014. Influence of rumen protozoa on methane emission in ruminants: a meta-analysis approach. Animal 8: 1816-1825.