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Research Centre

Future options to reduce biological GHG emissions on-farm: critical assumptions and national-scale impact

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Report to the Biological Emissions Reference Group

The Biological Emissions Reference Group (BERG) is a partnership between New Zealand's agricultural sector and the Government. BERG has been tasked with collaboratively establishing a robust and agreed evidence base on opportunities available, now and in future, to reduce biological greenhouse gas emissions (methane and nitrous oxide) on-farm. In doing so, it will consider the costs, benefits, and barriers.

This report is one of several commissioned by BERG to build this initial evidence base to inform any future actions or policies. If a policy process were to commence following this analysis, further work would be required. BERG welcomes this report and supports the analysis contained within it. However, it is out-of-scope of the BERG's Terms of Reference to express a preference for any specific options identified or recommended by the author(s).

BERG comprises the following voting members: Beef + Lamb New Zealand, Dairy NZ Limited, Deer Industry New Zealand, Federated Farmers of New Zealand, The Fertiliser Association of New Zealand, Fonterra, Horticulture New Zealand, Ministry for Primary Industries, and Ministry for the Environment.

The following organisations are observers of BERG: Climate Change Iwi Leaders Group, Meat Industry Association of New Zealand, Ministry of Business, Innovation and Employment, Ministry of Foreign Affairs & Trade, and The Treasury.

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Executive summary

This report evaluates options that may be available in future (by 2030 and 2050) to reduce biological GHG emissions on-farm. We express qualitatively our confidence that the various options would be technically available and the drivers and barriers to uptake of each option. We then quantify how much each option might reduce GHG emissions below baseline projections, considering both efficacy and potential adoption rates (taking into account potential cost/benefit as well as a range of other drivers and barriers). We also present possible packages of such mitigation options, taking into account the extent to which the various options would be additive and mutually consistent from a farm systems perspective. The quantitative assessment used the national GHG inventory tool and baseline projections provided by MPI to 2030, which we extended to 2050.

We only considered on-farm mitigation options within an existing land use. We did not include mitigation options that rely on land-use change either between different livestock systems or away from livestock entirely as that was outside the scope of this report.

Based on these criteria, our report evaluates the following individual mitigation options:

- Methane inhibitors
- Methane vaccine
- Breeding low-emissions animals
- Low-emissions feeds
- Nitrification and urease inhibitors
- Reduced N fertiliser use
- Increasing performance of individual animals
- Enhanced manure management
- De-intensification of dairy systems
- Once-A-Day milking
- Removal of breeding beef cows
- Increased tree planting (without negatively affecting production)

Assumptions about future efficacy and adoption rates of each mitigation option reflect our collective judgement and are not based on detailed economic or other modelling. Some mitigation options are well proven and already implemented today, while others are the subject of active research and have not yet reached proof of concept. Given the inherent uncertainty in our assumptions, we provide high and low estimates for many of the options.

For any option that is not commercially available at present, we assumed appropriate on-going research and development investment to bring these technologies to market, and that the necessary technological breakthroughs will be achieved. For some options, the amount of investment needed to achieve this could be substantial.

Some mitigation options could be very costly at farm level or have significant economic impacts if adopted nationally and affect New Zealand's international trade position or environmental credentials. Other options could offer strong synergies with non-climate and marketing objectives.

In our evaluation, we focused on domestic emissions only and did not consider the likely effect on global emissions from mitigation options that would alter the total amount of livestock product exported by New Zealand. The actual cost, benefits and feasibility of any mitigation option and package of options will depend heavily on domestic and international climate and non-climate policies and market responses. The inclusion of any individual mitigation option or assumption about future efficacy or adoption rate does not imply a recommendation; more detailed evaluation of their economic, social and environmental impacts will be needed before recommendations about preferred mitigation options and packages can be made.

Summary of individual mitigation options, including drivers and barriers to adoption

About 75% of biological GHG emissions from agriculture in New Zealand occurs in the form of methane (mostly from enteric fermentation), and 25% in the form of nitrous oxide (mostly from excreta deposited directly onto pastures). Our assessment indicates that a number of technologies and practices have the potential to help reduce biological GHG emissions on-farm. These options differ in their current availability, efficacy and likely adoption rates. Many mitigation options require further development to reach their potential, and some could fail to reach the market despite further development efforts due to technological, market or regulatory barriers.

Table I presents a summary of our assessment for individual options for 2030, using a traffic-light evaluation of barriers and risks to adoption for each option. The options have been ordered by the confidence that each option will be available in principle (although this confidence can be modified depending on the assumed efficacy and the scale at which a mitigation option is assumed to be used). Emission reductions indicated in this table are relative to projected baseline emissions in 2030, reflecting the assumptions about efficacy and adoption rates developed in our report.

While assessing the potential efficacy of mitigation options is primarily a scientific and technical problem, their ability to reduce emissions in practice depends on their actual adoption by farmers. This will be influenced by practical, economic, social and environmental considerations.

For several mitigation approaches that address N_2O, issues related to water quality and nutrient discharges will be strong and even primary drivers for their adoption; this includes reduced nitrogen fertiliser use and application of nitrification and urease inhibitors but potentially also dairy de-intensification, low-emissions feeds and animal breeding. The extent to which water quality acts as driver for uptake of GHG mitigation options will vary strongly between catchments meaning their impact on national emissions may be more limited.

The ability to adopt mitigation options is also highly variable among farmers and farm types. Important factors include the level of management intensity, with dairy systems generally having more mitigation options available (but also important differences between high- and low-input dairy systems). Important differences also arise from farmer skills, access to skilled labour, relevant information and skilled advisors, finance, ability and willingness to take risks, and the extent to which markets dictate farm practices. This makes any assumption about adoption rates a challenging task, with a wide range of likely outcomes. Individual farms may find some options impossible to adopt even though they are considered possible in general for this farm type, and vice versa.

Packages of mitigation options

When these individual options are combined into different mitigation 'packages', biological GHG emissions from New Zealand's pastoral sector could about 12-24% below 2005 levels by 2030, and 9-40% below 1990 levels by 2050. The wide range in potential outcomes results from different assumptions that can be made about both efficacy and adoption rates of various mitigation options.

Given the significant technical and commercial challenges to realisation and implementation of some of the mitigation options, especially at the high end of assumptions, these figures illustrate the challenges for the pastoral sector to contribute to New Zealand's overall mitigation targets under the Paris Agreement. All the modelled mitigation packages rely heavily on new technologies.

Note that the absolute reductions that can be achieved in 2030 and 2050 relative to a historical base year (1990 or 2005) depend heavily on future changes in animal numbers and total production that would occur under projected 'business as usual'. Forecasting future animal numbers and total production is subject to high uncertainty and official government projections have changed markedly in recent years. The official government projections underlying this report differ in some cases from the expectations of industry. We therefore consider the results from our report to be more robust with regard to the relative reductions of on-farm GHG emissions below a given baseline than as a projection of future absolute emissions.

Table I: Summary of confidence that mitigation options will exist in-principle, risks and barriers to their uptake, and potential range of annual emission reductions under low and high efficacy and adoption rates by 2030, relative to total agricultural GHG emissions. Significant co-benefits with non-climate policy are flagged where they occur.

Mitigation option	confidence	mitigation (low)	mitigation (high)	cost/benefit	market	environmental	system-fit	universality	monitoring
Breeding low-CH_4 sheep	VH	0.0%	0.3%						
Urease inhibitors	VH	< 0.2% *							
Performance: Dairy	VH	1.1%							
Performance: Beef	VH	approx. 0.7% *							
Performance: Sheep	VH	0.3%							
Manure: bio-digesters	VH	0.1%							
Once-A-Day milking	VH	0.3%	1.0%				Co-benefit		
Individual trees: dairy farms	VH	3.5%				Co-benefits			
Small-scale plantings on sheep & beef farms	VH	3.3%				Co-benefits			
CH_4 inhibitor: twice-a-day in-shed feeding (dairy)	H	0.3%	2.4%						
Low-emission feeds (dairy): existing forages	H	1.5%	2.3%						
Low-emission feeds (S & B): existing forages	H	0.5%	0.7%						
Reduced N fertiliser use	H	0.2%	0.2%			Co-benefit			
Breeding low-CH_4 cattle	H	0.0%	0.2%						
Dairy de-intensification	H	1.3%							
Nitrification inhibitors: DCD	H	0.2% **	1.0% **			Co-benefit			
Nitrification inhibitors: novel	H	0.2% **	1.0% **			Co-benefit			
Manure: spreading	H	< 0.2% *				Co-benefits			
Manure: restricted grazing	H	< 0.4% *				Co-benefits			
CH_4 inhibitor: slow-release (all systems)	M-H	0.7%	4.7%						
Breeding low-MUN cattle	L-M	***				Co-benefit			
CH_4 vaccine	L	2.1%	6.4%						
Low-emission feeds (dairy): GM ryegrass	L	0.0%	0.0%						

Legend: colour coding is used to illustrate our assessment as follows (mitigation outcome refers to the reduction of total biological GHG emissions from agriculture that would be achieved under assumptions of high efficacy/uptake and low efficacy/uptake, respectively).

Confidence rating	Mitigation outcome	Risk rating
Very high (VH)	> 4.0%	high risk
High (H)	1.0-4.0%	medium risk
Medium (M)	0.2-1.0%	low risk
Low (L)	< 0.2%	no risk identified

Notes:

* the option was not modelled but a maximum value inferred from basic assumptions (see text for details)

** the modelled value excludes application on beef farms since the inventory cannot represent this at present

*** the option was not quantified at all, given missing current evidence to estimate future impact

If future baseline emissions turn out higher than assumed in this report, then greater mitigation efforts and a wider portfolio of actions would be needed to achieve the same absolute emissions by 2030 or 2050 (and vice versa). Increasing transparency and robustness of government baseline projections and their alignment with industry forecasts would be highly desirable as different choices have a significant impact on the absolute emissions reductions that can be achieved relative to historical reference years.

Within those caveats, Table II summarises the estimated percentage reductions that the different mitigation packages considered in this report could achieve in 2030 and 2050 under different assumptions about efficacy and adoption rates.

Table II: Summary of estimated emissions reductions achieved by different mitigation packages. "High" and "low" refers to the high and low end of assumptions about efficacy and adoption rates for individual mitigation options.

Mitigation package	comment	2030 (relative to 2005)	2050 (relative to 1990)
Baseline	based on MPI projections, and extended in this report to 2050	- 4.1%	+ 15.8 %
Full package	all options except dairy de-intensification approaches	- 14% (low) - 24% (high)	- 10% (low) - 40% (high)
Sectoral packages	dairy de-intensification package	- 9% (low) - 16% (high)	- 2% (low) - 17% (high)
	sheep/beef package	- 8% (low) - 12% (high)	+ 8% (low) ± 0% (high)
Alternative full package	dairy de-intensification plus sheep/beef package	- 12% (low) - 24% (high)	- 9% (low) - 33% (high)

The role of existing versus novel technologies and practices

Figure I illustrates the contributions of different mitigation options for one comprehensive package of interventions, at the highest assumed efficacy and adoption rates. This Figure illustrates the contributions of individual options to the overall potential outcome. Note this Figure reflects highly ambitious assumptions; other packages and adoption rates are included in the full report.

Within the overall packages of mitigations, increasing the uptake of current technologies (e.g. optimising productivity, reducing nitrogen fertiliser, improved manure management) bring about only small incremental gains. Even if our assumptions about adoption rates for those approaches underestimate their full potential, they are unlikely to achieve a large shift in overall emissions. Other currently available mitigation approaches such as dairy de-intensification combined with once-a-day milking could reduce emissions more significantly, but carry market challenges and potentially large economic and social risks for the country associated with such a transition.

The other current technology available, planting more trees on farms in ways that don't reduce overall production, is possible and if deployed at scale could make a difference. Such options exist for both dairy and sheep/beef farms and were included in our mitigation packages, but they face different types of challenges. Trees are unlikely to be planted in contiguous blocks on dairy land, meaning that policy changes would be required to enable carbon accounting for individual/sparse trees. Such a change in accounting rules would also imply a liability in cases where any land-owner (regardless of whether dairy, sheep or beef) wishes to remove individual trees or other woody vegetation not currently regarded as forest. On sheep and beef land, trees are more likely to be planted in contiguous and dense enough blocks to meet the current definition of forest land and thus don't face the same accounting challenges.

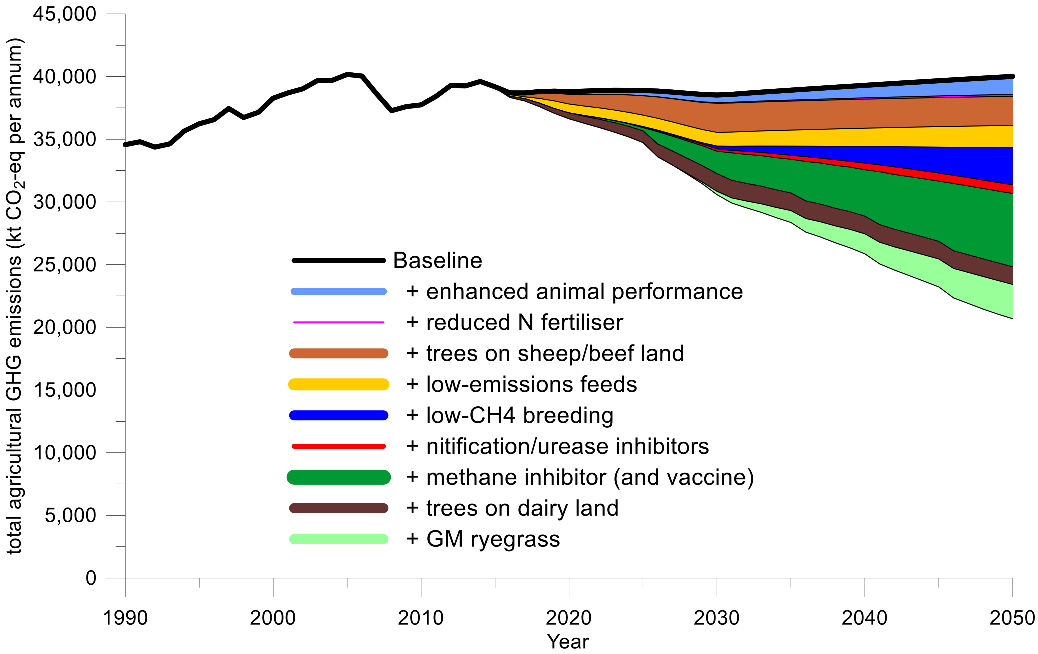

Figure I. Cumulative effect of a comprehensive package of mitigation options for dairy, beef and sheep, for maximum assumptions about efficacy and adoption rates for each mitigation option. For details, see full report.

The on-farm mitigation approaches that could have the largest potential impact on agricultural GHG emissions are not yet commercially available (e.g. CH_4 inhibitors and vaccine, nitrification inhibitors, and GM ryegrass). Some of those options have proof of concept (e.g. CH_4 inhibitor for feedlot animals), or proven benefits (e.g. nitrification inhibitors remain technically viable), while others are at various stages in development (GM ryegrass exists but its efficacy in actually reducing emissions has not yet been demonstrated; a CH_4 vaccine is in development but has not yet demonstrated an effect in live animals). Bringing those options to market suitable for New Zealand farming systems will require further development, with timelines of 5-20 years and uncertain end outcomes.

Challenges lie not only in the development of the technology but also regulatory settings and domestic as well as international market responses. Even where we have high or very high confidence that a technology will be available in principle in the future, market responses and/or regulatory barriers overseas could remove it from the portfolio of viable options for New Zealand (as is currently the case for DCD).

Without these novel technologies, the overall potential to reduce biological GHG emissions on-farm is reduced substantially. On-going investment in science and commercialisation pathways to develop such mitigations is therefore critical if the agriculture sector is to contribute to more ambitious mitigation goals without the use of costly offset mechanisms. Work to ensure acceptability of novel mitigation technologies in markets is crucial to delivering the mitigation potential of these novel technologies.

Overall, regardless of the specific direction taken, further changes in farm systems will be required to achieve efficient mitigation. This will mean farmers will need to adapt as both the impacts of climate change and climate and other relevant policies become a reality, and global markets respond to both. Investment into extension will be required to assist farmers with the system change that some of the mitigation options would imply, as well as investment into monitoring tools to ensure that positive actions by farmers can be counted. Farmers, export marketing companies and government will need to work together within a broader engagement process towards this future, including regulatory requirements.

We hope that this report provides a useful stepping stone on the path toward a broad, collective understanding of the potential and scope of future mitigation options.

1. Purpose and Context of this Report

1.1 Purpose and context

This report is one of several reports commissioned by the Biological Emissions Reference Group (BERG) to better understand options to reduce biological greenhouse gas (GHG) emissions in New Zealand, now and over the next several decades. This report seeks to provide a qualitative and, as far as possible, quantitative assessment of absolute GHG emission reductions that can be achieved at national scale by 2030 and 2050 from the adoption of modified farm practices.

- Our ***qualitative assessment*** considers (a) the confidence we have in mitigation options being or becoming available in future, and (b) the opportunities, barriers and risks for their national-scale adoption (considering but not limited to e.g. cost, market perceptions, other environmental or social outcomes, and applicability and accountability across New Zealand farming systems). Economic assessment of the different mitigation options was out of scope, but we have undertaken a qualitative discussion of economic costs and opportunities. These costs, including distributional effects, require further work before any recommendations regarding implementation can be made.
- Our ***quantitative assessment*** estimates the emissions reductions that could be achieved annually, relative to baseline trends, in 2030 and 2050 at national scale, under various assumptions about the efficacy and adoption rates for mitigation options individually and collectively. The quantification was undertaken using the national GHG inventory tool where possible, supplemented by additional modelling or spreadsheet-based approaches where necessary. Our quantification only captures the direct biological GHG emissions from agriculture, it does not constitute a full lifecycle assessment.[1]

The amount of mitigation that any on-farm intervention can achieve in future depends critically not only on the assumed efficacy on the intervention (which is uncertain, especially for technologies still under development) but also on the scale of adoption across the country. In the absence of economic or agent-based modelling, we have relied on our collective judgement to construct alternative scenarios of potential adoption rates and efficacy of individual interventions. Our report focuses on interventions that would reduce GHG emissions within New Zealand; it does not consider consequences for global emissions if New Zealand alters its exports of livestock products as a consequence of some of those interventions and thus changes its supply to global markets. Such considerations need to form an important part of judgements over which mitigation pathways may be preferable but this is considered outside the scope of this report.

In estimating the efficacy of future mitigation options, especially those reflecting new technologies such as methane inhibitors or a vaccine or nitrification inhibitors, we have assumed continued research investment to support their development and commercialisation, as well as regulatory support to enable their use within increasingly discerning global markets. Without such support, our confidence in those technologies becoming available and being effective would be much lower.

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1 Lifecycle assessments indicate that on-farm biological GHG emissions constitute by far the largest share of the total GHG footprint for dairy, sheep and beef production in New Zealand (about 85-90% for different farm systems up to the farm gate). Other, mostly CO_2 emissions account for the remainder of about 10 to 15% of this footprint; they arise largely from fossil fuel and electricity use on-farm (including emissions involved in the production of fertiliser) and land-use change (where forests are cleared for pastures or feed, including overseas). See e.g. Ledgard, S.F. et al (2011): Carbon footprinting of New Zealand lamb from the perspective of an exporting nation. *Animal Frontiers*, 1(1), 40-45; and Reisinger, A. et al (2017): Sensitivity of the carbon footprint of New Zealand milk to greenhouse gas metrics. *Ecological Indicators*, 81, 74-82.

Actual adoption rates will depend on incentives to farmers, including market conditions and climate and non-climate policies. These are particularly difficult to quantify in the absence of specific policy settings. For most mitigation options, we have therefore used alternative scenarios of high and low adoption rates to characterise a range of potential outcomes. The assumptions made in this report should not be seen as promoting or endorsing any particular policy or approach to mitigation or level of adoption, since this would require more detailed analysis of the economic, social and environmental implications at both farm and national level.

Our report *does not* consider land-use change as mitigation option (except where this is considered feasible within existing farm systems): for the purpose of this report, we assume that the area of land that is used for livestock farming in the baseline will continue to be used in all our mitigation scenarios. We understand that opportunities and challenges to reduce emissions via land-use change (with attendant changes in animal numbers) are addressed in other reports.

The development of plant-based proteins (i.e. synthetic meat and milk) could potentially result in a disruptive shift in New Zealand's land-use and pastoral sector. The magnitude of any such shift will depend on market responses to those novel foods (including their cost, nutritional value, wider ecological impacts and food safety) and the ability to produce them in New Zealand. Our report does not consider such novel foods since their widespread adoption would effectively constitute another type of land-use change, placing them outside the scope of this report. We also note that too little is known as yet about the GHG emissions, water demand etc. of plant-based or synthetic protein production to reliably include them in quantitative assessments if their production were to occur at scales comparable to current pastoral land-use.

The mitigation options considered in this report are relative to an assumed business-as-usual or baseline scenario. We used the latest projections issued by the New Zealand government in December 2017, in its Third Biennial Report to the United Nations Framework Convention on Climate Change (BUR3)[2]. This baseline scenario includes future changes in land area devoted to agriculture, animal numbers, production levels and fertiliser use that are expected to occur in the absence of any additional climate policies. See Section 1.2 for a summary of key features and important assumptions contained in this baseline scenario.

Some mitigation options are highly dependent on changes projected to occur in future under business-as-usual. We flag baseline assumptions that are particularly relevant in our discussion of specific mitigation options. In general, however, we note that future absolute GHG emissions will depend heavily on future changes in total animal numbers. Projected animal numbers in 2030, particularly dairy cattle, have been revised downward significantly over the past four years. Relatively small changes in animal numbers could outweigh the effect of many individual on-farm mitigation options. As a result, emissions reductions discussed in this report should be considered as relative to forecast baseline emissions rather than forecasts of absolute future emissions.

We also note that the upper end of mitigation ranges considered in this report (assuming high efficacy and high adoption rates) make very optimistic assumptions about future technologies that do not yet exist and where we do not yet have proof of concept. Achieving this full potential will rely on continued investment, regulatory support and incentives for uptake. But even with such support, technological or market barriers could prevent some of those technologies from being realised and applied, especially at the scale that we assume in our upper-end assumptions.

[2] www.mfe.govt.nz/publications/climate-change/new-zealands-third-biennial-report-under-united-nations-framework

1.2 Baseline scenarios of future GHG emissions

1.2.1 Official projections to 2030 and extensions to 2050

New Zealand's 7th National Communication and BUR3 to the UNFCCC, issued in December 2017, contain the latest official government GHG emissions trends and projections out to 2030. This report uses these projections as a baseline against which the efficacy of different mitigation options has been assessed (both qualitatively in terms of feasibility and likely adoption rates, and quantitatively by modelling their impact on emissions using the national GHG inventory tool).[3]

Figures 1 shows the historical and projected emissions from dairy, beef and sheep, as well as inorganic N fertiliser, urea and liming, and total agricultural emissions. Emissions from these sources collectively account for 97% of total agricultural emissions.[4] We do not consider mitigation options for deer explicitly in this report, given their minor share (less than 2%) of total biological GHG emissions. However, many of the mitigation options considered in this report would in principle be applicable to deer farming (subject to the use of relevant inputs and management practices).

Official projections extend only to 2030, but for the purpose of this report, we extended these projections further from 2030 to 2050, holding animal numbers constant beyond 2030 but assuming further improvements in performance per animal. Figure 2 shows historical and projected animal numbers, and Figure 3 illustrates some key animal performance statistics (milk yield per cow and lambing percentage) assumed in this baseline.

It is notable that in these latest baseline projections, total agricultural GHG emissions are expected to remain roughly flat and even fall slightly by 2030, with increasing emissions from dairy approximately balanced by a further decline in emissions from sheep. In this revised MPI baseline, the expansion of the dairy sector occurs at a much more moderate rate than what was seen over the past 25 years while the decline in sheep numbers continues at its historical rate. For this analysis we take those projections as a given but note that future expectations of industry, especially the sheep and beef sector, are significantly different to that reflected in those trends.

In our extension beyond 2030, we are holding all animal numbers constant but assume further increases in animal performance. Projecting changes in animal numbers is exceedingly difficult especially more than a decade into the future, as this relies on domestic climate and non-climate policy as well as international market and regulatory drivers. Continuing with constant animal numbers from 2030 onwards therefore was considered to be the most justifiable assumption that avoids speculative guesses.

The combination of constant animal numbers but increasing performance results in a rise in emissions after 2030, since e.g. even though dairy numbers are assumed to be constant after 2030 in our baseline, total emissions from dairy would continue to rise given the expected further increases in milk yield per animal, which implies further increases in feed intake and associated emissions per animal. However, the increase in emissions due to these continued performance gains is more moderate than the historical increase, which saw an increase in animal numbers combined with increased performance per animal. Total nitrogen fertiliser use in the MPI baseline reaches a maximum in 2016 and then decline slightly to 2030; after 2030, we assume N fertiliser use per animal remains constant in this baseline scenario.

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3 The Agricultural Inventory Advisory Panel in November 2017 identified a minor mistake in the inventory N_2O calculations; correcting this mistake leads to an adjustment in absolute emissions but relatively little change in emission trends. Calculations in this report use the corrected version of the inventory calculations. www.mpi.govt.nz/news-and-resources/open-data-and-forecasting/greenhouse-gas-reporting/agricultural-inventory-advisory-panel/

4 Agricultural emissions as defined in the GHG inventory and used in this report exclude any emission related to energy use on-farm. Options to reduce energy-related emissions are not considered in our report. Biological GHG emissions on-farm (methane and nitrous oxide) constitute the large majority of lifecycle emissions (85-90%; see footnote 1).

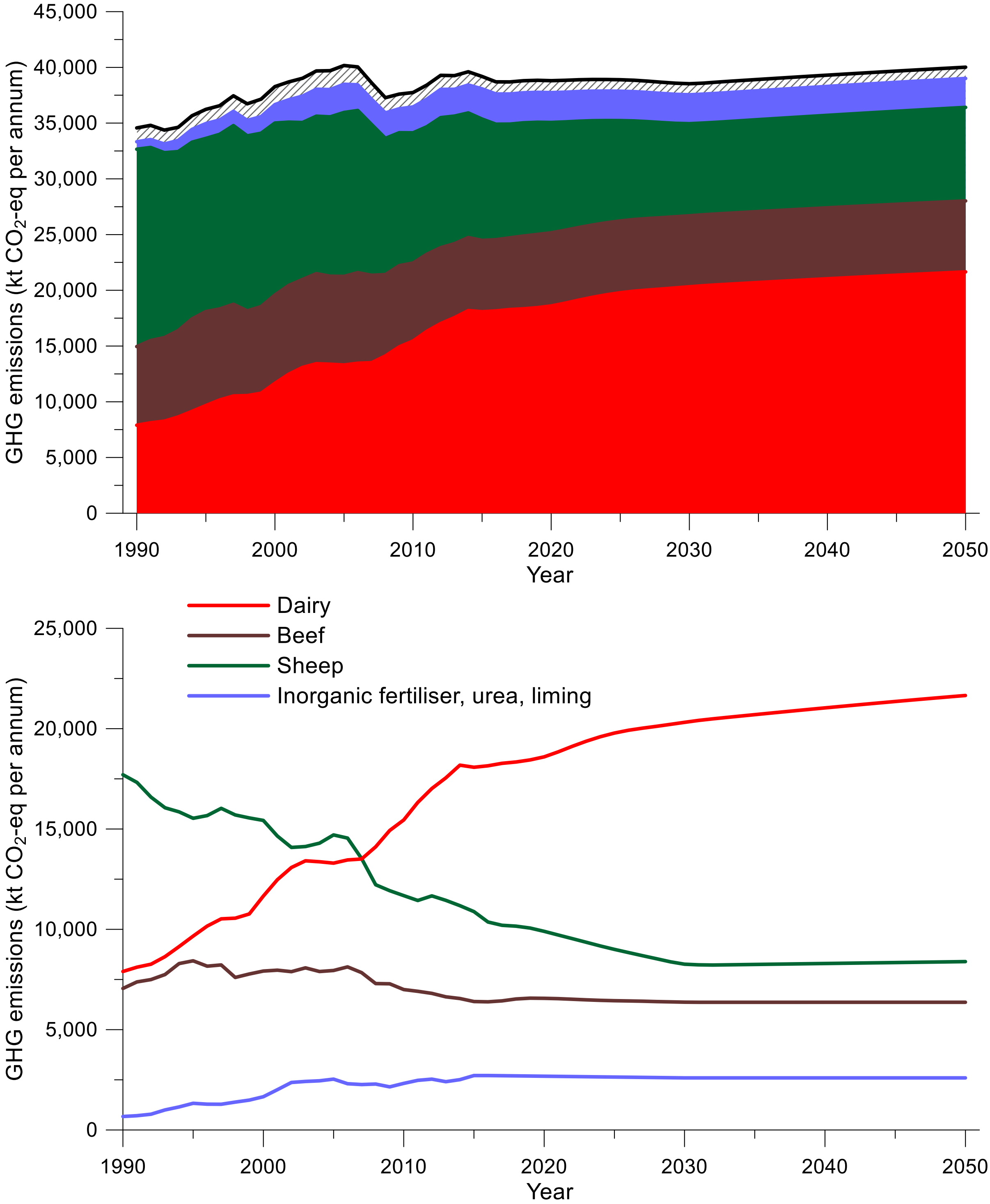

Figure 1: Historical and projected baseline emissions from key agricultural sources to 2050. The bottom panel shows the emissions for dairy, beef, sheep, and inorganic fertiliser, urea and liming, while top panel shows cumulative emissions from these sources (hashed area is for emissions from all other sources). Source: BUR3, corrected inventory; extensions beyond 2030 by the authors.

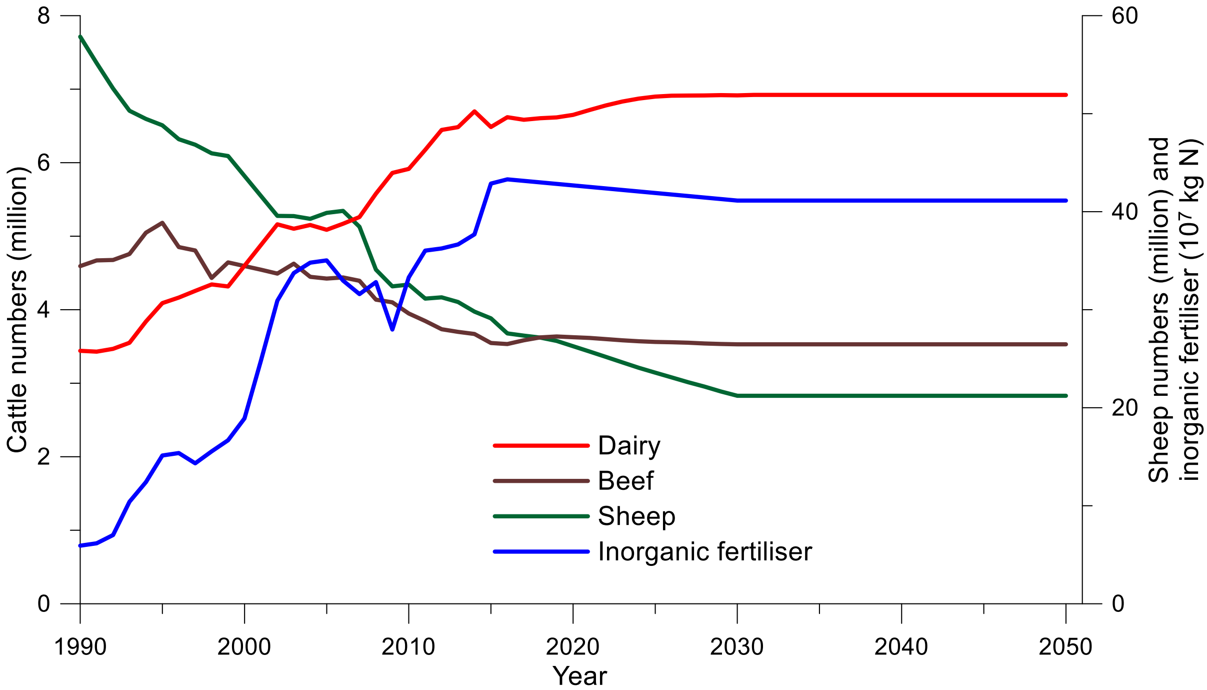

Figure 2: Historical and projected baseline animal numbers and inorganic (N) fertiliser use. Source: BUR3, extensions beyond 2030 by the authors.

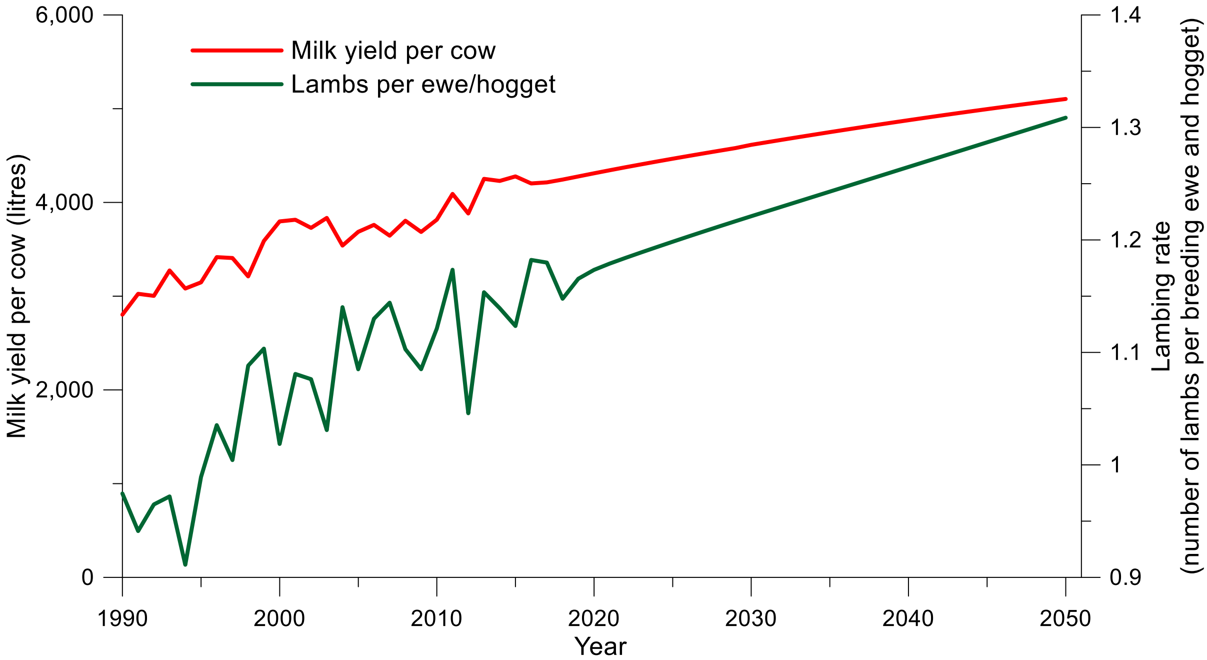

Figure 3: Historical and projected milk yield per cow, and lambing rate (defined here as the number of lambs alive in September divided by the number of breeding ewes and hoggets in July; note this agricultural statistics-based definition may differ from how the term lambing percentage is used on-farm). Source: BUR3, extensions beyond 2030 by the authors.

1.2.2 Importance of animal numbers for absolute emissions

Even though baseline projections are sometimes also referred to as “business as usual” (meaning that the baseline assumes no additional climate policies), the baseline incorporates the effect of existing climate and non-climate policies, as well as expectations about future commodity prices. Together, these can have a significant impact on animal numbers and, to a lesser extent, performance and hence total agricultural GHG emissions. This means that from a farmer perspective, the baseline scenario might not be regarded as anything like "business as usual".

It is particularly noteworthy that official baseline projections of emissions to 2030 have reduced sharply in successive forecasts over the last 4 years (by about 14% in the latest projection relative to the projection in 2013), as illustrated in Figure 4. These adjustments reflect changing expectations in commodity prices and international market trends, but also changes in water policy that act as increasing constraints on further dairy expansion. This report does not undertake to scrutinise the latest projections, and we simply offer an assessment of mitigation options relative to the official baseline trends (with our own extensions to 2050). However, we re-emphasise that because of the strong dependence of absolute emissions on animal numbers, our estimates of mitigation outcomes should be read as being relative to this baseline, not a forecast of absolute emissions.

Given the discrepancy between government projections and industry expectations and the necessary assumptions and uncertainty inherent in any projection, this report can give only limited guidance regarding the total mitigation effort needed to reduce absolute emissions from agriculture by a given amount below 1990 or 2005 levels, as this depends as much on alternative baseline projections as on the availability and efficacy of mitigation options. Figure 4 illustrates that changes in GHG emissions arising from changes in animal numbers have the potential to outweigh the effect of many of the mitigation options considered in this report especially at the lower end of assumed efficacy and adoption rates. For example, reducing total agricultural emissions by 5% below 2005 levels by 2030 would have appeared as a highly ambitious goal based on the projections in 2013. Yet based on the most recent projections published in 2017, such a reduction would simply reflect baseline trends, with almost no additional mitigation required. Conversely, if baseline emissions increase again based on future revised projections, then greater mitigation efforts and a wider portfolio of actions would be needed to achieve the same absolute emissions by 2030.

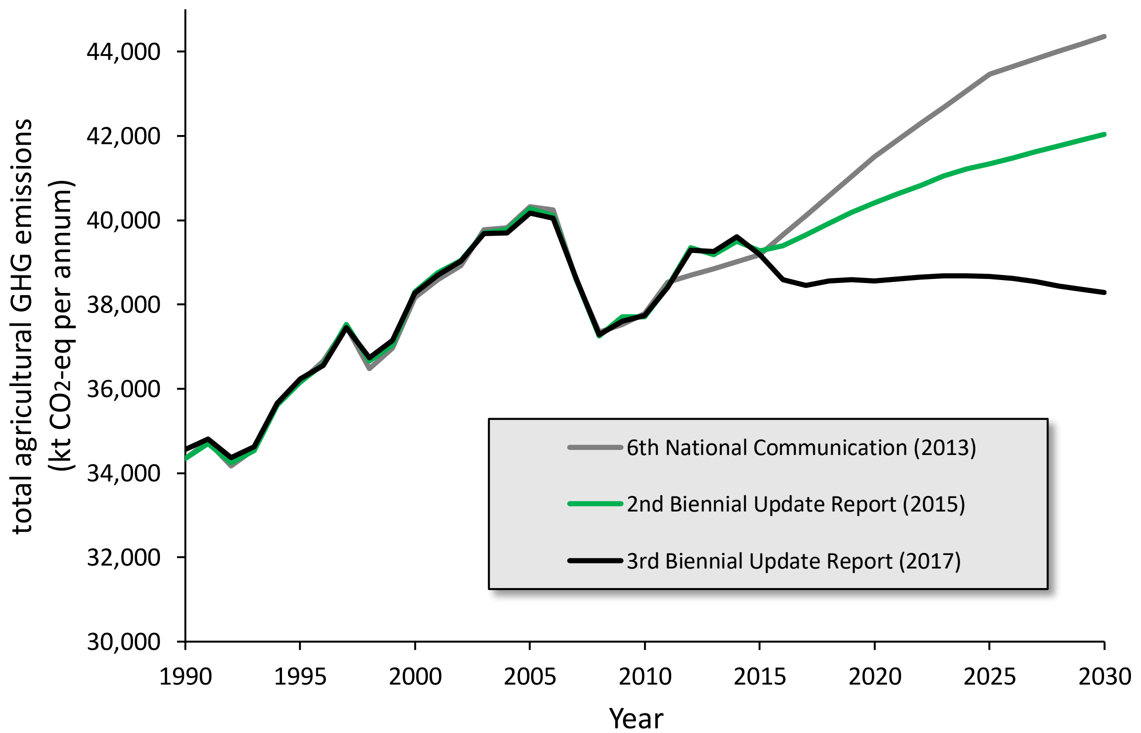

Figure 4: Historical and projected total agricultural GHG emissions in subsequent government reports, from 2013 to 2017. Note emissions estimates from the 6th National Communication have been updated to reflect the methodology applied in subsequent reports, mainly the change in the Global Warming Potential of methane used in reporting to the UNFCCC after 2013. The corrected inventory methodology has been used to represent projections from the 2017 report.

2. Individual mitigation options

2.1 Overview and approach to assessment

We considered a range of interventions that could in principle be adopted at large scales across farms around the country, and that would be visible at least in principle in the national GHG inventory. The mitigation options considered in this report are:

- Methane inhibitors
- Methane vaccine
- Breeding low-emissions animals
- Low-emissions feeds
- Nitrification and urease inhibitors
- Reduced N fertiliser use
- Increasing performance of individual animals
- Enhanced manure management
- De-intensification of dairy systems
- Once-A-Day milking
- Removal of breeding beef cows
- Increased tree planting (without negatively affecting production)

Each individual mitigation option is assessed using a consistent approach:

- A brief description of the mitigation option
- A qualitative discussion of our confidence that the option will in fact be available
- A quantification of its impact where implemented (efficacy or amount of change feasible)
- A qualitative discussion of drivers and constraints to its adoption
- A graphical display of the effect of mitigation, if applied on its own, on total agricultural GHG emissions compared with baseline emissions (using alternative assumptions as appropriate).
- Suggested further reading, including evidence that underpins our overall assessment

We do not consider changes in soil carbon within pastoral systems in our portfolio of mitigation options. The main reason is that the evidence base is still too limited to even know with reasonable certainty whether soil carbon is in fact changing in New Zealand's pastoral land as a whole, let alone what management practices could reliably and sustainably increase soil carbon (or avoid losses). The best evidence so far (based on relatively sparse measurements with high spatial variability) is that in the national average in the recent past soil carbon under dairy pastures is either stable or decreasing, and that irrigated soils tend to have lower soil carbon stocks than unirrigated soils at the same location. Carbon is certainly being lost from drained agricultural peat soils. By contrast, soil carbon in hill country appears to have previously increased on average, albeit based on samples from a very limited number of sites. The mechanisms by which the changes in soil carbon at irrigated sites and in hill country have occurred and whether these changes are ongoing remain insufficiently understood. This prevents a qualitative let alone quantitative assessment of mitigation options to be included in this report.

This national picture does not exclude the potential for some individual farms to increase their soil carbon stocks. For example, it is possible that irrigating some very dry soils with low carbon content could increase soil carbon, but there have not been sufficient studies to test this fully and this approach cannot be generalised to the national level where soil carbon stocks typically are high already. Similarly, there are options to reduce the amount of soil carbon lost from very carbon-rich peat soils, but these findings cannot be simply extrapolated across the New Zealand landscape.

A significant investment in baseline monitoring to determine trends, complementing current research into understanding fundamental processes and targeted mitigation options, would be needed to allow a more robust evaluation of soil carbon as mitigation option at the national level.

By contrast, the evidence base for soil carbon changes under *changes* in land use (e.g. from pastures into forests, and vice versa) is much stronger and this is already reflected in the national GHG inventory. On average and for the same soil type, soil carbon in pastures is higher than under forests, and cropland typically has the lowest amount of soil carbon.[5] This means that soil carbon is gained over time when forests are converted to pasture land, but equally soil carbon is lost when pasture land is converted back into forests. We therefore include changes in soil carbon when land-use is changed on-farm (e.g. from pastures into forests, and vice versa; see Section 2.13).

2.1.1 Qualitative characterisation of confidence

To describe our confidence that a mitigation option will in fact be available in future, we used a consistent set of qualitative descriptors, building on similar terminology used by the Intergovernmental Panel on Climate Change to characterise uncertainty and confidence.[6]

- *Very high confidence* ("we know it works"): e.g. technology is already available; clear and well tested track to commercialisation and increased adoption
- *High confidence* ("we think it will work"): e.g. proof of concept exists and efficacy has been demonstrated in repeat trials; up-scaling has yet to be fully demonstrated but no obvious risks
- *Medium confidence* ("it should work but there's some way to go"): e.g. proof of concept exists but efficacy remains to be demonstrated in repeat trials and at different scales; up-scaling feasibility and cost not yet clear
- *Low confidence* ("it might work but we certainly wouldn't want to promise"): e.g. no proof of concept obtained as yet, and persistent difficulties in obtaining this; may face fundamental physiological challenges; up-scaling feasibility or cost unresolved and potentially significant

The criteria listed that underpin each level of confidence are examples only; they do not represent a comprehensive list and they do not necessarily all apply simultaneously in any judgement.

2.1.2 Qualitative characterisation of drivers for and barriers to adoption

For the discussion of risks to adoption, we applied a standard set of criteria:

- Cost/benefit to farmers
- Market or regulatory drivers or barriers
- Environmental trade-offs
- Fit with farm systems
- Universality of applicability across different NZ farm systems
- Ease of monitoring and accounting

As well as a qualitative discussion of each point, we summarise our conclusions using a traffic-light system to visually represent the overall risk to adoption posed in each of those criteria. This categorisation is subjective and may not apply in all circumstances, but is offered to allow a quick overview of key issues relating to the potential adoption of each mitigation option.

5 See MfE (2017), New Zealand's Greenhouse Gas Inventory 1990-2015, Ministry for the Environment, Wellington, pp542: Section 6.3 and Table 6.3.2.

6 Mastrandrea, M.D., et. al. (2010): Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC), Geneva, pp5

Risk rating	Criteria leading to risk classification
high risk	*potentially significant barrier to adoption that requires early attention and, if unresolved, could jeopardise technology even with supporting policies*
medium risk	*barrier to widespread adoption, but barrier is not characterised well enough and/or not expected to be a show-stopper; but will need dedicated policy support*
low risk	*risks can be identified but may be partly compensated by other co-benefits; supporting policy may be needed to increase adoption rates*
no risk identified	*no currently identified or foreseeable side-effects (or negative implications are approximately balanced by positive ones)*

The traffic lights focus primarily on risks and barriers to adoption, but in some categories, there may be co-benefits with other (non-climate) objectives that will increase adoption. Particularly relevant examples include mitigation actions that reduce nutrient losses and hence help improve water quality, or measures that improve biodiversity. Such co-benefits are noted where relevant in the discussion and flagged within the traffic-light categorisation.

Some mitigation options would not be consistent with the current approach to reporting emissions (e.g. planting very sparse trees as shelter belts along pastures, or restricting the spreading of manure to dry periods only, when emissions of N_2O are expected to be lower), but they could be included in principle (subject to improvements in the national GHG inventory and improved data collection, and/or subject to changes in internationally agreed reporting and accounting rules). These options are marked as red in the traffic-light summary but included in our quantification of the mitigation.

Obviously, for any mitigation that does not yet exist or has not yet been demonstrated under New Zealand conditions, a range of field trials reflecting diverse New Zealand farm systems would need to be undertaken to demonstrate their actual impact on GHG emissions. Apart from such scientific trials, it will be equally important to develop and demonstrate methods to measure, monitor and verify their implementation at national scale to allow incorporation into the national GHG inventory. This could include a need to collect additional data at farm or national scales, which can be costly.

Our assessment of risks, barriers and co-benefits focuses on the dominant farm systems in New Zealand. Some of the mitigation options would offer particular challenges (or would not be applicable) to other systems. For example, certified organic farming would be not able to make use of nitrification or CH_4 inhibitors, or approaches involving synthetic fertiliser, but other options would offer strong synergies (e.g. de-intensification of dairy systems, since organic systems effectively sit at the extreme end of low-input systems). The relevance of these synergies and incompatibilities for emission trends at national scale depends on the evolution of the organic farming sector in New Zealand, which we did not explore in this report.

2.2 Methane inhibitors

A methane inhibitor is a chemical compound that blocks critical enzymatic pathways in methanogens and restricts their growth and ability to produce methane. To be effective an inhibitor needs to be present in the rumen while the ruminant is digesting its feed. An inhibitor could be delivered directly as a feed additive, but other options include delivery through a bolus inserted into the rumen or inclusion in water to ensure its presence during feed digestion.

When could it become available?

The current product closest to market is 3-nitrooxypropanol (3NOP) "Clean Cow", developed by the Dutch-owned firm DSM Nutritional Products. This inhibitor has been shown to be effective in several long-term trials and is expected to be released into the world market in 2019.

3NOP in its current formulation has been developed to work in the Total Mixed Ration (TMR) livestock systems predominant in Europe, North America and parts of South America. This means that the inhibitor is present in every mouthful of food. Its ability to reduce emissions in grazing systems such as New Zealand is likely to be much smaller, given that it breaks down quickly in the rumen and in most New Zealand situations it would be fed at discrete intervals (e.g. morning and afternoon milking). However, research into new formulations and delivery methods by DSM hold out the prospect of new products with increased efficacy even under systems where the feeding of supplements isn't routinely practiced. Under current New Zealand law, the use of 3NOP would be treated as a pharmaceutical and hence approval for its use would need to be sought under regulations for agricultural compound and veterinary medicines. This could create some delays in its practical use in New Zealand even if the product as such is commercially available.

There is an active programme of work in New Zealand funded by the PGGRC and NZAGRC aimed at developing inhibitors that would be more effective in grazing systems. This specifically focuses on the search for and development of inhibitors with higher efficacy at lower dosage rates and more latterly alternative slow-release delivery mechanisms. However, while proof-of-concept for such novel inhibitors has been obtained in animal trials, they require further development. Given the rigorous regulatory, safety and manufacture requirements for such products, these New Zealand developed inhibitors are unlikely to be on the market until 2025 and their successful development is not assured given the multiple potential pitfalls.

In summary, we have:

- ***high confidence*** **that an inhibitor will be available for in-shed feeding by 2020 that could be administered during milking in twice-a-day milking systems**
- ***medium confidence*** **that an inhibitor will be available for extensive grazing systems by 2025, rising to** ***medium-high confidence*** **by 2030 and** ***high confidence*** **by 2050** [7]

What would be its impact?

3NOP has and is being studied widely in overseas research on TMR systems, covering dairy and feedlot (beef) systems. A consistent minimum 30% reduction in methane has been confirmed in these systems over extended periods of three months. At this level of reduction normal animal performance has

[7] Note that our assumptions regarding the efficacy and adoption of an inhibitor by 2050 cover a wide range and are extremely optimistic at the upper end of the range. While we have *high confidence* that there will be an inhibitor suitable for extensive grazing by 2050 *in principle*, our confidence that this inhibitor will indeed achieve the emissions reductions assumed in our upper end scenario (efficacy as high as 50%, and high adoption) is considerably lower.

been observed with no detrimental impacts on animal welfare. Published dairy and beef cattle studies indicate improved liveweight gain although milk production seems to be little affected.

These significant enteric methane reduction levels apply only when animals are provided the inhibitor with every mouthful of feed they consume. One would expect that the efficacy would be reduced if the inhibitor was fed only twice a day during milking, perhaps offering only about a 5% reduction in a grazing system.[8]

For extensive grazing-based cattle and sheep systems, one of two approaches (or a combination of both) have to be employed:

1. an inhibitor needs to be formulated to remain in the rumen for at least 6 hours or more so that its efficacy is sustained across the rumen fermentation if it can only be supplied twice a day during milking, and
2. a slow-release mechanism to provide the inhibitor outside of milking times (including for animals that are not milked daily) needs to be developed. A slow-release bolus[9] is a prime candidate although supplementation via the water supply is a possible alternative. While boluses are not new, their use to deliver an inhibitor over extended periods (>100 days) will be technically challenging and increase the cost of the inhibitor. Such products aren't readily available at present.

If these challenges can be addressed, we consider that inhibitors have the potential to reduce methane emissions by 30% even in grazing systems by the year 2030. Further development of multiple inhibitors may even be able to increase the mitigation efficacy above 30%. Emissions reductions beyond this level are not technically impossible but carry an increasing risk of interfering with the rumen fermentation process itself and thus reducing animal performance or raising welfare concerns.

For the purpose of this report, we assume a mitigation efficacy of 5% for an inhibitor delivered twice daily during milking in dairy systems from 2020, rising to 30% by 2030. For an inhibitor delivered through a slow-release system to grazing animals (suitable for dairy, sheep and beef), we assume an efficacy of 30% in 2030, and a low and high estimate of 30% and 50% by 2050.

What are drivers, barriers and likely rates of adoption?

The economics of methane mitigation strategies have been mainly determined relative to the price of emissions: e.g. at \$30/tCO_2-eq, a 30% annual average reduction in enteric methane from a dairy cow would be worth about \$19 in avoided emissions, and from a sheep about \$2.70.[10]

The cost of administering an inhibitor (either in-shed during milking, or through a bolus that may need to be administered repeatedly during the year) therefore is a key challenge to ensure inhibitors in fact present a cost-effective mitigation option.

Apart from emission reductions, methane mitigation through an inhibitor could also result in an increase in performance if energy that is normally lost in the form of methane is retained and made available to the animal for growth and production. How much of this can in fact be recovered for performance is still uncertain and remains a key question for the level of impact achievable. For

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8 note this is a simple estimate based on a 3NOP lifetime of approx. 2 hours in the rumen, resulting in about 16% of diet being treated; no field trials of 3NOP in grazing systems have been published yet

9 a compact pill or capsule that is swallowed by the animal and ensures the active compound contained within the pill or capsule is released slowly over time from within the rumen

10 based on annual average emissions of 12 and 84kg CH_4/hd/yr for a mature sheep and dairy cow, respectively

example, a long-term trial with 3NOP with dairy cattle showed no increase in milk yield but an increase in body weight.

- **Cost/benefit to farmers:** costs: of the inhibitor itself and its administration (e.g. in feeds during milking, or with a slow release mechanism, which can imply labour and/or infrastructure costs); benefits: potential to enhance performance but more evidence needed to confirm this.
- **Market or regulatory drivers or barriers:** Significant food residue and safety challenges; inhibitors have to be nil or low residue and totally benign in food and to the processing process (dairy and meat). Daily supplementation may compromise the grass-fed credentials of New Zealand livestock products. Consumer perceptions about feed additives are significant and "antibiotic" feeding is considered negatively by consumers. There is therefore significant potential for negative market reactions even without clear evidence. Inhibitors would be incompatible with organic farm systems. On the other hand, use of an inhibitor could allow branding for environmentally and climate-friendly livestock production, although this may be more viable for overseas producers with less reliance on natural, grass-fed credentials.
- **Environmental trade-offs or co-benefits**: None known at present. 3NOP breaks down rapidly in the rumen into nitrite, which is converted into ammonia and excreted as urea, hence is not introducing a new substance into the environment. Other inhibitors will have different break-down products, and their environmental fate and impact will need to be evaluated on a case by case basis.
- **Fit with farm systems**: Routine administration of an inhibitor twice daily during milking could require additional capital investment for some dairy systems. Likely ineffective in Once A Day (OAD) milking systems. Boluses are used already for various purposes in NZ farm systems.
- **Universality of applicability across different NZ farm systems**: Dairy systems have the best opportunity given their management intensity, but inhibitors could be used in intensive beef or sheep finishing systems as well. The application of a bolus or other slow-release system will improve uptake with the latter but uptake may remain limited in extensive sheep and beef systems given their general low-intensity management.
- **Ease of monitoring and accounting:** No significant challenges, as the use could be tracked by inhibitor sales and auditing of supplements, but would require further testing and trials of efficacy if inhibitors are provided via different routes.

Summary of drivers for and barriers to adoption of CH_4 inhibitors in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
Inhibitors supplement						
Slow release						

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

The above factors will be critical for adoption rates of inhibitors even if the technology as such is commercially available; apart from direct cost implications, market responses to any concerns about feed additives and residues are likely to be dominant factors. We explore two alternative scenarios: one where the inhibitor works only as in-shed feeding supplement and thus is applicable to dairy systems only, and another one where the inhibitor is delivered initially via in-shed feeding in the dairy industry and subsequently via a slow-release mechanism and hence can be adopted (albeit at differing rates) in dairy, and intensive beef and sheep systems. For both scenarios, we adopt high and low assumptions for both efficacy and adoption rates to demonstrate the range of possible overall outcomes.

by when	emission reduction (enteric CH_4)	adoption rates
2020	Low 5% high 10% (TAD dairy in-shed feeding only)	TAD dairy in-shed feeding: low 5%, high 20%
2030	TAD dairy in-shed feeing only: Low 5% high 30% Slow-release all grazing: Low 10% high 30%	TAD dairy in-shed feeding, dairy only: low 20%, high 25% Slow-release (all grazing): • dairy low 20%, high 40% • Beef: low 0% high 10% • Sheep: 0%
2050	In-shed feeding and slow-release: Low 30% high 50%	TAD dairy in-shed feeding, dairy only: low 40% high 50% Slow-release (all grazing): • Dairy: low 50% high 75% • Beef/sheep (mature only): low 20% high 40%

Results

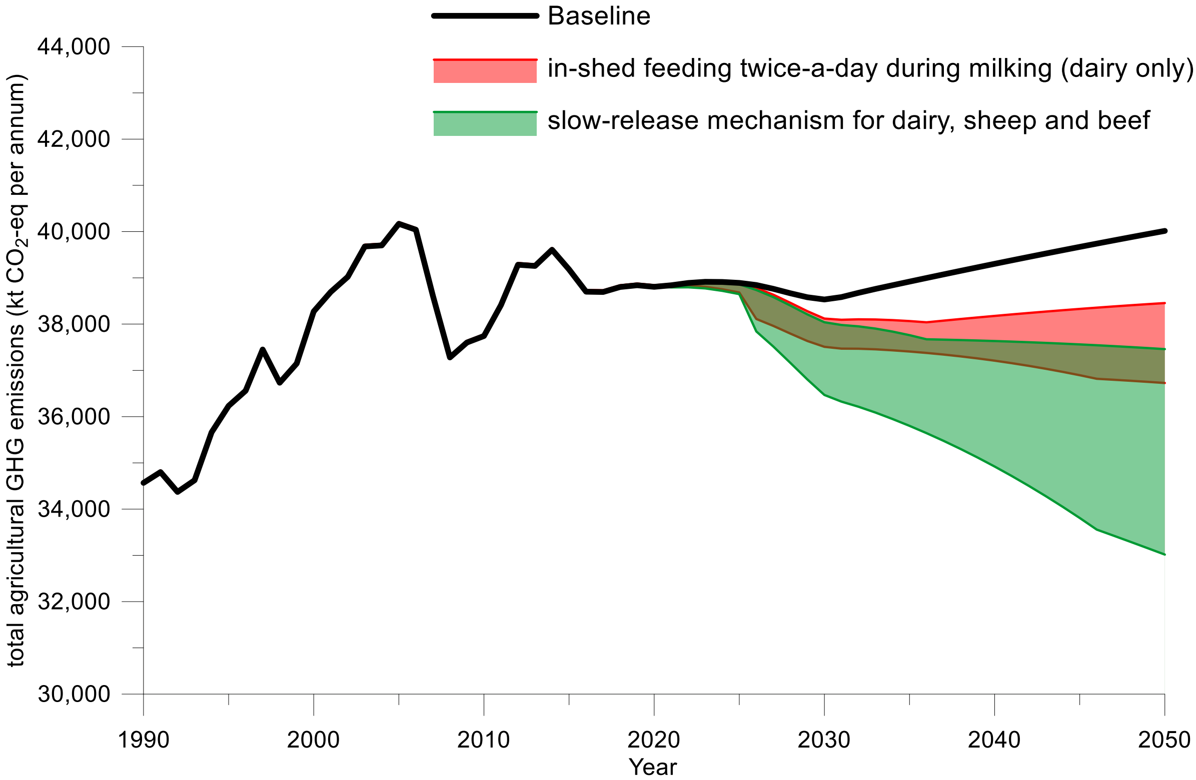

Figure 5: Total emissions in the MPI baseline and with a methane inhibitor applied, using alternative assumptions about the delivery mechanism and applicability to different systems (see text for details). The shaded areas indicate the range of outcomes under high and low efficacy and uptake. The upper end of each shaded area corresponds to low efficacy and low uptake, while the lower end of each shaded area corresponds to high efficacy and high uptake.

2.3 Methane vaccine

The ruminant immune system can be induced to produce antibodies that suppress the growth of methanogens. A methane vaccine is attempting to trigger an antibody response by the animal against specific methanogens. The antibodies would be produced in blood and saliva and delivered continuously into the rumen via saliva, and the amount and efficacy of antibodies needs to be strong enough to effectively suppress methane production by methanogens.

A methane vaccine is expected to be applicable to all ruminant species and could in principle be used across all farming systems globally.

When could it become available?

The vaccine is still in the development phase and has not demonstrated a measurable reduction in methane in animals, which is considered to be the minimum proof-of-concept. However, all recognised steps up to this point have been achieved (antibodies are created by host animals, antibodies detected in saliva and in the rumen, and antibodies against specific methanogens have been shown to suppress these species in pure cultures in the laboratory).

Vaccine development and use for livestock disease control is well understood and used internationally. However, creating a vaccine that delivers its payload via saliva and suppresses an organism that is a normal resident of the rumen ecosystem is a major challenge. The genomic sequencing of 11 rumen methanogens has identified common surface proteins (>300) that could be used to stimulate antibody production. These potential targets are being worked through systematically using a combination of laboratory and animal screening approaches.

Once a prototype vaccine has been shown to work then it is expected that there will be a further five to seven years to market. On that basis, we would be unlikely to have a vaccine commercially available before 2024.

In summary, we have:

- ***low confidence*** **that a vaccine will be available by 2030**
- ***medium-high confidence*** **that a vaccine will be available by 2050**

What would be its impact?

As no proof-of-concept has been obtained yet, the efficacy of a commercially available vaccine is necessarily speculative. The current vaccine under development is specifically targeting two methanogen species that are responsible for 70% of the total methane produced in most ruminants. Based on the demonstrated ability of reducing methane by 30% through inhibitors, we assume that a successful methane vaccine could achieve a similar level of reduction.

Based on other vaccines, it is hoped that after the initial vaccination protocol (primary followed by a booster) only one annual booster would be required to keep the vaccine performing at this level. There would likely be considerable resistance by farmers to vaccinating more regularly than this unless there was a direct benefit in terms of increased performance.

Given that methane inhibitors and a vaccine would target largely the same microbial species, their efficacy may not be additive. There is the potential that a combination of an inhibitor and vaccine could achieve slightly higher reductions than use of either on its own, but this is not assured and the additional effect could be very small given the diversity of methanogens outside the two dominant species. For this report we assume that there is no additive effect from use of methane inhibitors and a vaccine in combination; essentially, they are two different technologies to achieve the same goal. A vaccine may be particularly suitable to low-input and once-a-day milking systems where in-shed application of an inhibitor is not feasible, and may increase the uptake by farmers who might be reluctant to use e.g. a slow-release bolus system. Overall, the availability of a vaccine in combination with an inhibitor increases the likelihood of success overall (by spreading risks and increasing uptake across diverse systems) rather than the amount of emission reduction that can be achieved from an individual animal.

For the purpose of this report, we assume a mitigation efficacy of 30% from a vaccine in both 2030 and 2050, and no additional mitigation from the use of an inhibitor and a vaccine if applied together on the same animal.

What are drivers, barriers and likely rates of adoption?

Vaccination is a common practice used by farmers now but there will be an additional per animal cost which will depend on the number of vaccination events required and how it might be administered (if not by conventional injection). In principle, the cost of administering a vaccine should be low compared with the cost of administering an inhibitor.

Given the lack of proof-of-concept at this point and the mixed results from methane inhibitors, it is not currently clear if a vaccinated animal will demonstrate increased performance. There is no evidence or expectation that a methane vaccine would have other impacts on animal performance or welfare, but this remains to be tested once proof-of-concept has been obtained.

- **Cost/benefit to farmers:** costs: of the vaccine itself and its administration (hopefully limited); benefits: potential to enhance performance but empirical evidence is needed to confirm this once proof of concept has been obtained.
- **Market or regulatory drivers or barriers:** while vaccination is a common practice internationally, an additional vaccination that has no benefits to the animal and that targets a naturally occurring rumen organism may not be considered a natural approach, meaning it could face consumer, regulatory and animal welfare hurdles. At a minimum, a vaccine will need to demonstrate no effect on product quality or animal physiology and well-being. The risk of residues is very low, however, and a vaccinated animal should be able to be farmed in any system without further intervention and this will be regarded as a benefit. Successful routine vaccination could also support a climate-friendly branding of New Zealand livestock but there may be resistance in some markets focused on organic/natural production systems. Certified organic systems would not be able to use a vaccine unless rules relating to the use of vaccines as restricted practices are changed.
- **Environmental trade-offs or co-benefits:** none known at present; once proof-of-concept is obtained, testing will be needed on how a vaccine interacts with other mitigation options.
- **Fit with farm systems**: should have a universal fit with all farm systems if able to be treated in a similar way as standard animal health vaccines. If the timing and final delivery required more frequent boosters or different administration this could create challenges in some situations.
- **Universality of applicability across different NZ farm systems**: applicable to all farm systems in New Zealand and internationally at all scales. Organically certified systems may not be able to use it.
- **Ease of monitoring and accounting:** no significant challenges, as this could simply be based on the number of doses sold (likely single manufacturer) and can be audited if required.

Summary of drivers for and barriers to adoption of a CH_4 vaccine in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
Vaccine						

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

We assumed that a methane vaccine can be developed and with an impact of ~30% (based on approximately 50% reduction in 70% of the currently prevalent methane microbes). Barriers to uptake should be limited unless there are significant cost hurdles, negative side effects or negative market reactions. However, even animal health vaccines with demonstrated benefits to animals and that are cost-effective to farmers are not adopted 100%. Given the novelty of a methane vaccine, we therefore assume lower adoption rates in 2030 than in 2050, and adoption rates reflect the extent to which readily available animal health vaccines are used across the different sectors. We emphasise that both efficacy and adoption rates summarised below are highly speculative and will need to be refined once proof-of-concept has been obtained and larger scale field trials carried out.

by when	emission reduction (enteric CH_4)	adoption rates
(not proven yet)		
2030	30%	• Dairy: low 10%, high 50% • Beef/sheep: low 10% high 40%
2050	30%	• Dairy: low 50%, high 90% • Beef/sheep: low 40% high 80%

Results

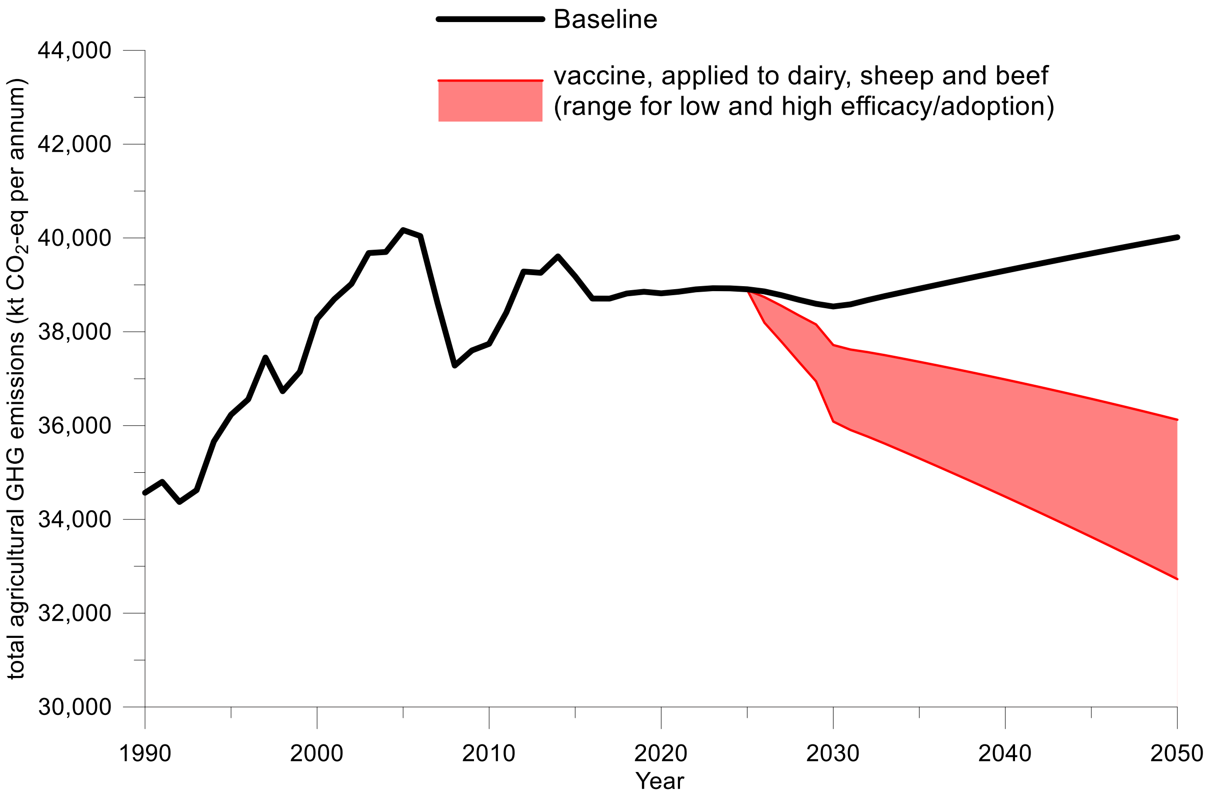

Figure 6: Total emissions in the MPI baseline and with a methane vaccine applied (see text for details). The shaded area indicates the range of outcomes under high and low efficacy and uptake. The upper end of the shaded area corresponds to low efficacy and low uptake, while the lower end of the shaded area corresponds to high efficacy and high uptake.

2.4 Breeding low-emissions animals

Animals vary naturally in the amount of methane they produce for every kg of dry matter they eat. Work has also commenced to look at whether ruminants also vary in the way they partition the nitrogen they ingest between excretion in dung and urine and retention in milk. These traits are heritable, meaning that over time, animals can be selected for low-emissions traits as part of on-going breeding programmes.

When could it become available?

Proof of concept exists that sheep vary naturally in their methane emissions per unit of dry matter intake, and that this is heritable. Existing high and low-emissions flocks are being maintained and their emissions continue to diverge. Genomic markers have been identified and can in principle be used to incorporate the low emission trait into breeding indices. Work continues on other, lower-cost options to rapidly and reliably identify low-emissions animals. Industry trials are under way to evaluate the benefits of incorporating the low methane trait into the current Sheep Improvement Selection system.

Indications from international studies are that cattle show a similar natural variation in their emissions per unit of dry matter intake, and genomic markers for this trait are also being identified. However, as measurement is more difficult/costly, no low-emissions herd has been established in New Zealand yet. Work is underway internationally to develop proxy indicators to enable cheap and rapid identification of low emitting animals. Given that no work is currently being undertaken in New Zealand to evaluate the feasibility of incorporating the low emitting trait into cattle selection indices it isn't possible to estimate when selection for low-emissions traits in cattle could become available. If targeted work were undertaken we consider that selection for low-emissions cattle could become possible by 2025.

In some international trials, Milk Urea Nitrogen (MUN) concentrations have been shown to be linearly related to rates of urinary nitrogen (UN) excretion although other research does not show this relationship. Semen of bulls marketed as having lower than average MUN became commercially available in New Zealand in 2017. However, it has not yet been demonstrated that offspring from these bulls will indeed result in lower nitrogen excretion in urine per unit of dry matter intake and hence lower nitrous oxide emissions; experimental work to test this commenced in 2017.

Gene editing, a rapidly advancing technology, could allow progress in this area to be made faster than by the current conventional breeding techniques, but could also encounter specific resistance from some markets. For this reason, we do not consider gene editing separately but it contributes to our confidence in the viability of this approach especially in the longer term when such approaches are likely to become more and more commonplace.

In summary, based on international evidence, we have:

- ***very high confidence* that methane emissions of sheep can be gradually lowered through genetic selection from 2020 onwards**
- ***high confidence* that methane emissions of cattle can be gradually lowered through genetic selection from 2025 onwards**
- ***low confidence* that nitrous oxide emissions from cattle can be lowered through genetic selection by 2020, rising to low-*medium confidence* in 2030**

What would be its impact?

Currently, methane emissions between high- and low-emission rams differ by approximately 10%, after 3 generations of selection meaning that if this trait were passed on to all sheep today, emissions could be ~5% lower than average. However, passing on this trait in full will require several generations.

This is because the offspring of a low-emissions animal, when mated with an animal with a typical emissions profile, would not show the same reduction in emissions as its low-emitting parent.

The difference between high and low emitters is expected to continue to grow with continued selection, but there may be physiological limits to what can be achieved before trade-offs with other traits (production, animal health, reproductive success etc.) occur. At present there is no evidence of systematic differences in production efficiency or health between high and low emitters. However, since the emissions status has been linked to the size of the rumen of the animal and rates of passage of feed it is possible that eventually there will be trade-offs between nutrient absorption and lowered emissions. For the purpose of this report, we assume that continued breeding could achieve a maximum divergence of 30% between high and low emitters (although this level of divergence is highly speculative at this point), meaning a reduction of enteric methane emissions of 15% below a baseline where no selection for emissions takes place.

Evidence is as yet more limited about the quantitative potential to breed low-emissions cattle, given the lower number of animals that have been screened internationally and the more limited information about any correlation with other production traits. For the purpose of this report, we assume the same quantitative potential in principle as for sheep.

A challenge with using a breeding approach in sheep is that there is a relatively large number of rams used for breeding. Hence diffusion of low-emissions animals into flocks is likely to take longer and will be more difficult to monitor and report (in the case of mixed parentage combining low-emissions and 'normal' animals) than in dairy, where the use of artificial insemination from a small number of bulls is widespread across the national herd and good records exist.

The reduction of nitrous oxide emissions that could be achieved from using low-MUN sires is as yet conjectural. Industry claims based on modelling are that widespread adoption of low-MUN cattle could reduce nitrate leaching by 20% and nitrous oxide emissions associated with urine excretion by 9% by 2030. However, in the absence of direct evidence for any impact on either nitrogen leaching or nitrous oxide emissions, we have not attempted to quantify emissions reductions that could be achieved by breeding for low MUN.

For the purpose of this report, we assume a methane mitigation efficacy from low-methane animals beginning in 2020/2025, rising to 3-7% in 2030 and 15% in 2050.

We are not aware of proof-of-concept linking MUN with lower nitrous oxide emissions and hence have not included this in our quantitative modelling.

What are drivers, barriers and likely rates of adoption?

Breeding programmes to improve livestock performance and resilience are well established in New Zealand with dedicated companies and support systems.

- **Cost/benefit to farmers:** Even though low-emissions sheep show no systematic difference in their performance, health and reproductive success compared to high-emissions animals, there could still be an opportunity cost for farmers to select for low-emissions traits. This is because giving weight to GHG emissions in a selection index necessarily means that lower weight is given to other economically important traits that farmers are seeking to improve. The opportunity costs of selecting for low-emissions animals are not fully established as they depend on minor identified correlations between emissions and other traits obtained from small numbers of animals, but could be a significant factor in decision-making by farmers. These correlations could also change over time with continued breeding, which could change the opportunity cost.
- **Market or regulatory drivers or barriers:** There are no known market barriers to selecting for low-emissions animals. Farmers that select low-emissions animals could potentially

benefit initially from a climate-friendly brand advantage, although the differences in emissions are of comparable magnitude or smaller than differences in lifecycle emissions between individual farms. This makes branding at the individual farm level difficult, and reliable brand benefits likely would require a more coordinated, regional or system-wide approach.

- **Environmental trade-offs or co-benefits:** There are no known environmental co-benefits or trade-offs of breeding for low-methane animals. There would be a significant co-benefit of selecting low-MUN animals for nitrate leaching, provided that a link between low-MUN in individual sires and low nitrogen excretion in urine is confirmed and no other impacts to other economically important traits are identified. In that case, the benefit in terms of reduced nitrate leaching could become the primary driver for uptake, with reduced nitrous oxide emissions (if any) regarded as a co-benefit.
- **Fit with farm systems and universality of applicability:** The dairy, beef and sheep sectors all have active breeding programmes and hence in principle, reducing emissions via selection of low-emitting animals fits well within existing industry practice. Breeding is particularly strong and coordinated in the dairy herd, with more diverse approaches across the sheep and parts of the beef sector.
- **Ease of monitoring and accounting:** It appears unlikely currently that the low-emissions status of individual animals will be recorded routinely, but will instead rely on progeny information related to animals where measurements or proxy traits exist. This is likely to be simplest in the dairy herd, where a relatively small number of individually recorded bulls sire the majority of the dairy herd, and hence monitoring and recording of the emissions status of individual animals will be relatively straightforward. The situation will be more problematic for sheep, where a greater number of rams is used, and where the emissions status of ewes may be more difficult to estimate due to mixed 'normal' and low-emissions pedigrees.

Summary of drivers for and barriers to adoption of low-emissions animals in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
Low-CH_4 cattle						
Low-CH_4 sheep						
Low-MUN cattle			**Co-benefit**			

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

The adoption of a low-emissions breeding strategy is strongly tied to breeding programmes in the sector overall, which differs between sectors. In addition, the slow but cumulative benefits from breeding make it a relevant long-term strategy, but it is unlikely to be a major response to sudden price signals. Uptake will depend strongly on net benefits to farmers of combined emissions and other production properties of animals.

by when	emission reduction (enteric CH_4)	adoption rates
now-2020	0%	
2030	3-7%	• Dairy: low 0%, high 10% • Beef: low 0% high 5% • Sheep: low 0% high 20%
2050	15%	• Dairy: low 50%, high 90% • Beef/sheep: low 30% high 50%

Results

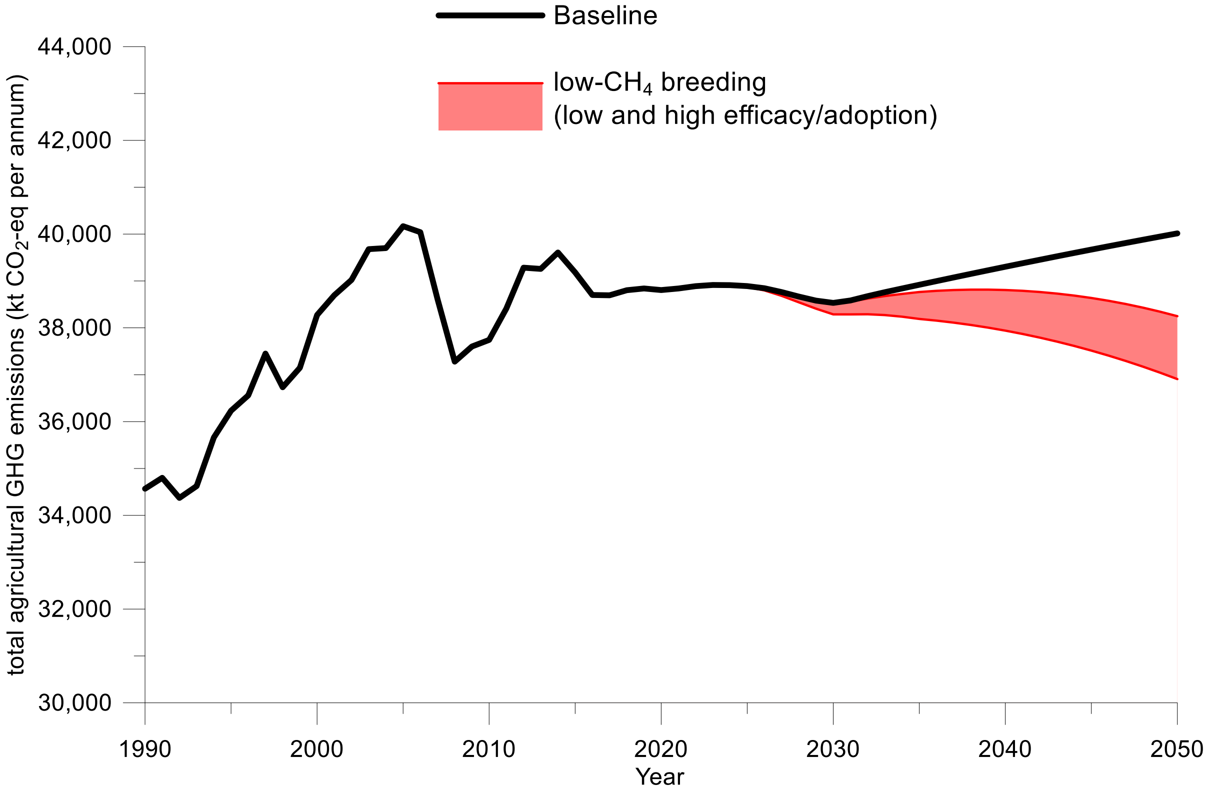

Figure 7: Total emissions in the MPI baseline and with low-CH_4 breeding applied (see text for details). The shaded area indicates the range of outcomes under high and low efficacy and uptake. The upper end of the shaded area corresponds to low efficacy and low uptake, while the lower end of the shaded area corresponds to high efficacy and high uptake.

2.5 Low-emissions feeds

Livestock in New Zealand continue to eat grass/legume pasture as their main feed source. Supplementary feeds provide additional energy and protein and thus help increase total intake and production. Unless these feeds have specific characteristics that influence emissions, adding supplementary feeds to the existing feed supplied to animals will result in increased total emissions.

Some feeds however do influence emissions per unit of feed intake. For example, some feeds ferment differently in the rumen and reduce CH_4 per unit of feed intake while others have a lower N concentration such that less N is excreted onto pastures and N_2O emissions are reduced. Feeds with higher energy levels can improve animal performance such that less total feed is needed to reach a given level of milk yield or liveweight gain; if less total feed is consumed as a result, emissions may reduce.

When could it become available?

Over the last decade there has been a considerable increase in the use of supplementary feed by New Zealand dairy farmers to improve cow condition and lift milk production. Some intensive sheep and beef farms are also making increased use of lucerne, chicory and plantain. In the dairy sector, the increased use of PKE, maize silage and more recently fodder beet has been particularly notable.

Two supplementary feeds relevant to New Zealand have been shown to reduce the amount of CH_4 produced by the animal per unit of feed consumed: forage rape and fodder beet. However, fodder beet is only effective at very high rates of inclusion (>75%), which makes it unsuitable as a methane mitigation option for New Zealand's pasture based systems and could raise animal welfare issues.

Maize and fodder beet are both feeds with N concentrations that are lower than the standard grass/clover diet. Increasing the proportion of these feeds in the diet would lower total dietary N concentration, lower N excretion and reduce N_2O emissions. However, in the case of maize this effect may be partly offset since the energy content of maize silage can be lower than that of fresh grass/clover pasture, meaning that the amount of dry matter consumed to reach a given level of production could increase. Similar trade-offs mean that feeding pasture hay and silage have very little effect on total emissions; they have slightly lower N content but also lower metabolisable energy, which results in roughly the same net emissions if total production is maintained.

If supplementary feeds simply increase the quantity of total feed, this will tend to increase emissions simply because dry matter intake will increase. Increasing the proportion of some supplements in the diet at the same level of total intake may reduce emissions at the individual animal scale but quantifying the effect at the farm system/supply chain scale is more problematic. If additional land is needed to grow these supplements this may result in additional emissions. If the supplement is imported it may increase emissions in the country of origin but not in New Zealand itself. This study is unable to capture the full system consequences of increasing the use of supplementary feeds.

A wide range of supplementary feeds are available now but only a few are likely to influence emissions when fed at the rates they are fed in New Zealand. For some feeds such as fodder beet, their use is limited to certain regions and farmers are still exploring the scale at which those feeds could be used in productive farm systems.

A high ME ryegrass being developed by AgResearch has been claimed to have the potential to reduce methane and N_2O emissions due to an increased lipid content and a lowered N concentration. As this is being developed using a genetically modified (GM) approach, these claims have not yet been tested rigorously in either the laboratory or the field. A change in legislation would be needed if these claims are to be tested under New Zealand field conditions and material subsequently released for commercial use. The ability of GM ryegrass (or any other genetically modified forage) to reduce emissions within New Zealand farm systems is therefore highly speculative at this stage, but the hypothesised mechanisms are reasonably well understood and quantifiable, hence we are including this as potential mitigation option post-2030.

In summary, we have:

- ***high confidence*** **in some low-N feeds (e.g. fodder beet) reducing N_2O emissions from urine patches, and in forage rape reducing CH_4 emissions from individual animals**
- ***medium confidence*** **that in theory a genetically modified rye grass could offer additional mitigation options, subject to regulatory decisions, after 2030**

What would be its impact?

Methane:

Fodder beet is only effective in reducing methane at an inclusion rate in excess of 75%, making it generally unsuitable for New Zealand's pasture based systems. Forage rape has been shown to reduce emissions by about 30% per unit of feed intake compared to standard grass/clover when fed as sole feeds. Lower rates of inclusion seem to scale the emissions reductions in direct proportion, i.e. a 10% inclusion of forage rape would reduce emissions by 3%.

Nitrous oxide:

The emissions reductions arising from the use of low-N feeds (maize, fodder beet, any other potential future low-N feed) will depend upon the amount eaten and the reduction in N content and any associated change in the energy content relative to that of pasture.

Future pasture plant options

Further developments in plant breeding and genetics, as well as field trials of existing forage crops for their ability to reduce emissions, could increase the range of low-emissions feeds. In the absence of solid evidence, the mitigation potential is necessarily speculative, but we discuss two particular options below that have attracted interest albeit for differing reasons.

- **Plantain:** Plantain has been identified as reducing nitrate leaching and potentially reducing N_2O emissions through a lower N excretion rate and perhaps through a specific interaction with soil microbial processes. So far measurements have mainly focussed on the impact on N leaching although initial results do suggest an impact on N_2O emissions. An intensive research effort is underway to substantiate this. In contrast to maize, the mechanism for N_2O reductions from plantain is related to the partitioning of N rather than a lower N content overall. In the absence of field trials, the effect on N_2O emissions is therefore difficult to quantify. Based on available information about the impact of plantain on N leaching, we estimate that it could have a similar impact on N_2O emissions as maize, and hence we have not modelled plantain separately. Work is underway to confirm its efficacy and how to best integrate it into New Zealand farm systems.

- **GM ryegrass:** In the absence of direct evidence, the effects of GM ryegrass on emissions are highly speculative. For the purpose of this report and drawing on limited information, we have assumed that GM ryegrass could reduce methane by 15%/kg DM consumed, that the energy concentration is increased by 1 unit of metabolisable energy/kg and that its N concentration is reduced by 10%. The latter two assumptions reduce energy and N intake for a given level of production and reduce N excretion rates, which will in turn reduce CH_4 and N_2O emissions. These assumptions quantify what the combined impacts of an increase in energy, a reduction in N content and the specific ability to reduce CH_4 emissions per unit of intake could be. These assumptions are at the optimistic end and, given the limited knowledge we currently have about the potential efficacy of a high energy, high lipid GM grass, should be considered an upper bound to emissions reductions.

Different supplementary feeds are typically fed out at different times during the year depending on their purpose in the overall farm system. However, the timing matters very little for the overall emissions reductions unless the traits that influence emissions are expressed differentially throughout the year. For simplicity we have therefore assumed in our calculations that the feeds would be used throughout the year and that the trait is expressed at the same level throughout the year.

For the purpose of this report, we assume the following mitigation efficacies:

- **for fodder beet:**
  - **no effect on methane emissions at plausible inclusion rates (< 75%)**
  - **N content 1.84% per kg dry matter (cf dairy pastures at 3.7%)**
- **for maize:**
  - **no effect on methane emissions**
  - **N content 1.28% per kg dry matter (cf dairy pastures at 3.7%)**
- **for forage rape:**
  - **methane reduction 30% for 100% inclusion, proportional at lower inclusion**
  - **same N content as pasture**
- **for GM ryegrass:**
  - **reduction of 15% CH_4, 10% N content per kg dry matter compared to pasture**
  - **1 unit higher metabolisable energy (MJ/kg DM) compared to pasture**

What are drivers, barriers and likely rates of adoption?

- **Cost/benefit to farmers:** Uptake of supplementary feeds is determined mainly by their cost relative to prices farmers receive for milk or meat. Feeding out and growing supplementary feed incurs additional costs for feed pads, harvesting and farm machinery. In addition, the increased complexity of farms utilising new supplementary feeds may require agronomic skills and/or new nutrition skills and thus raise indirect costs. Benefits of supplementary feeds, in addition to simply increasing total production, can be to increase flexibility in response to climate variability and market conditions. If it is assumed that current use of supplementary feeds balances economic benefits, costs and environmental constraints, further increase in the use of supplements could be expected to increase costs to farmers.

- **Market or regulatory drivers or barriers:** Fonterra and other dairy companies currently have “pasture fed” claims in the market. If reliance on supplementary feeds increases, this could challenge this position. Any new feeds may need to have significant GHG mitigation value to warrant on farm change and to ensure a market benefit from a “low emissions” vs “grass-based” production claim. Use of PKE has been challenged by environmental and social consequences of its production overseas, even though this does not affect New Zealand’s national GHG emissions reporting and accounting. Use of GM grasses is likely to encounter strong resistance from some markets overseas as well as within New Zealand.

- **Environmental trade-offs or co-benefits:** Low-N feeds would result in lower nutrient discharges to the environment; however, this may not be the case if increased use of supplementary feeds results in intensification and higher input systems (which could be mitigated through the use of infrastructure such as barns and feed pads). Heavy reliance on supplementary feeds can raise issues related to animal welfare, and intensive cropping can result in increased sediment run-off and hence compound water quality issues. Intensive cropping systems for animal feed can also increase reliance on irrigation, which could have adverse impacts on N losses and on soil carbon storage.

- **Fit with farm systems and universality of applicability across systems:** The dairy sector has increased its use of supplementary feeds substantially over the past two decades to enhance total production. The use of supplementary feeds is therefore well established, but farms differ in the amount of supplementary feed they use. About 35% of current dairy farms use no or little supplementary feed (other than pasture silage grown on-farm) and hence the scope to switch to low-emissions supplements is small. Sheep and beef farms on average derive 95% of their total feed from pastures and thus have very limited ability to make use of low-emissions feeds, except where feed is used tactically on intensive farms to support lambing/calving and finishing. The use of most crops shows strong regional diversity, reflecting variations in climatic and terrain suitability, economics of pasture and forage crop production and seasonal shortfalls.

- **Ease of monitoring and accounting:** national-scale data about the production and use of supplementary feeds is limited especially where they are grown on-farm, but could be obtained as part of annual agricultural statistics. At farm level, OVERSEER is able in principle to account for the GHG effects of different feeds but will require updates to ensure information from field trials is reflected. Obtaining data on the proportion of a GM ryegrass in the diet, including the proportion of GM ryegrass in a given pasture in the years following re-seeding, could present a considerable challenge.

Summary of drivers for and barriers to adoption of low-emission feeds in 2030:

	Cost/benefit	market	environmental	System-fit	universality	Monitoring
Dairy – existing forages						
Dairy – GM ryegrass						
S&B – existing forages						

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

Given the very limited use of supplementary feeds by the sheep and beef sector, and the low rates of pasture renewal, we did not include a quantitative analysis of a necessarily small increase in currently available supplementary feeds or future use of GM ryegrass in this sector. About 60% of total fodder beet and 90% of total forage rape are currently used in the sheep and beef sector. For the dairy sector, we assumed that up to 2030, only currently identified and proven forages (maize, fodder beet and forage rape) are used in substantial quantities above those assumed in the baseline scenario and offer net GHG mitigation benefits. After 2030, we include the introduction of GM ryegrass at the hypothetical mitigation efficacy described above. In terms of adoption rates, we modelled the following scenarios:

- Forage rape: total land area in forage rape increasing linearly from 34,000 ha in 1990 to 240,000 and 360,000 ha in 2050 for a high and low scenario (with a yield of 7t dry matter per hectare).
- Fodder beet: total land area in fodder beet increasing from 50 ha in 1990 to 130,000 and 260,000 ha in 2050 for a high and low scenario (with a yield of 22t dry matter per hectare).
- Maize: increased inclusion in the diet from 5.5% currently to 5.5% (low) and 15% (high) by 2050
- Plantain: not modelled explicitly but mitigation could be similar to maize
- GM ryegrass: introduction in 2030, occupying 25% (low) and 50% (high) of the total diet by 2050.

Results

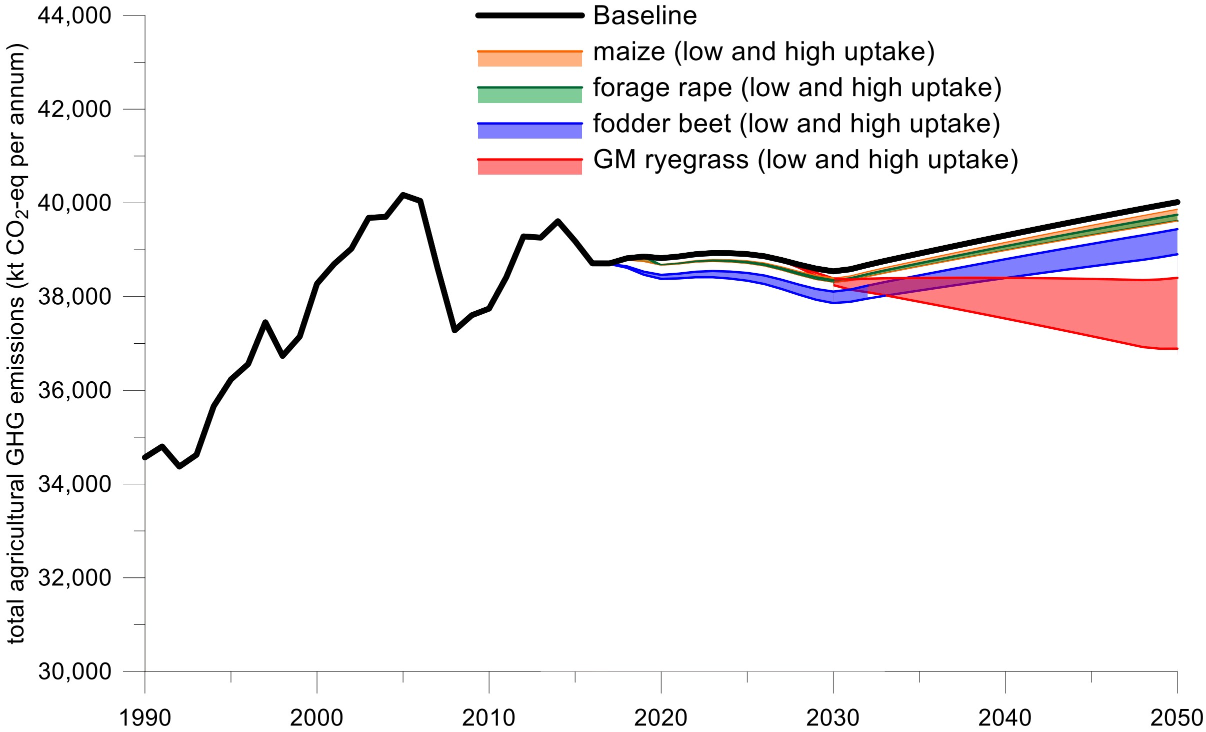

Figure 8: Total emissions in the MPI baseline and with various low-emissions feeds applied individually (see text for details). The shaded area indicates the range of outcomes under high and low efficacy and uptake for GM ryegrass, fodder beet and forage rape. The upper end of the shaded area corresponds to low efficacy and low uptake, while the lower end of the shaded area corresponds to high efficacy and high uptake.

2.6 Nitrification and urease inhibitors

Nitrification and urease inhibitors are chemical compounds that are intended to slow down the microbial conversion of nitrogen contained in N fertilisers (urea) or animal excreta into nitrate and nitrous oxide. Such inhibitors can be added to fertiliser or deposited directly onto grazed pasture.

When could it become available?

A range of nitrification and urease inhibitors exist already on the commercial market. The nitrification inhibitor DCD was used in New Zealand until 2011, until the discovery of residues in milk led to its withdrawal from use in New Zealand. Although DCD has been used in cropping for decades and is recognised as non-toxic, there is no declared Maximum Residue Limit under the *Codex Alimentarius* (international food safety standards), hence a default limit of zero residue applies. A process is currently underway to identify a threshold level of residues of compounds (like DCD and others) with a very low toxicology that could be introduced to the *Codex Alimentarius*. It is anticipated that the guidelines will be adopted as an international standard by July 2019. While such changes could allow the re-introduction of DCD in principle, perceptions in some markets are such that there is a very high likelihood in New Zealand that DCD as a specific inhibitory compound will not be re-introduced in future even if changes to the *Codex* are made.

Research led by Lincoln University is underway to identify and commercialise new nitrification inhibitors that have a wider applicability, lower cost and equally low or lower risk of residues as DCD. A suite of promising compounds has been identified in the laboratory, and testing has begun to deliver proof of concept in the field. Assuming that at least some of the most promising novel compounds prove effective in field conditions and don't encounter insurmountable hurdles in the commercialisation process, additional nitrification inhibitors could be on the market by 2025. Any new compound is likely to be put under intense scrutiny for residues in milk or meat, even if covered by an amended Codex, given the past experience with DCD and associated market resistance.

Urease inhibitors suppress a particular subset of the microbial processes that break down urea into nitrate and nitrous oxide. Urease inhibitors only reduce indirect emissions of N_2O, and clear evidence exists only for emissions associated with indirect emissions from synthetic (N) fertilisers but not for indirect emissions arising from directly deposited animal excreta. Urease inhibitors are already available and in 2016, 26.5% of all urea fertiliser sold in New Zealand was coated with a urease inhibitor. The proposed amendment to the *Codex Alimentarius*, which is not compound-specific, reduces the risk that any minor residues would limit use of urease inhibitors in future.

In summary, we have

- ***very high confidence* that urease inhibitors will be continue to be available in future**
- ***high confidence* (subject to international agreements on food safety standards) that nitrification inhibitors (DCD and novel compounds) will be available in principle from 2025, but *low confidence* that DCD specifically will re-gain market acceptability.**

What would be its impact?

DCD has proven to be highly effective where it can be applied, reducing N_2O emissions from urine patches by around 60%. However, its lifetime and hence efficacy is reduced under higher temperatures (to about 20-40% reduction), and its application has been targeted to the winter months (May to September) when nitrogen inputs tend to be lower since this is the period when the risk of nitrate leaching is highest. The fact that it needs to be broadcast means that its use is generally restricted to land where fertiliser is also applied by vehicle. The broadcast application of DCD also means that it requires a much higher application rate than what is necessary strictly for the objective of limiting N_2O emissions associated with urine patches, the dominant source of N_2O.

At the time DCD was withdrawn from the market in 2011 (before freshwater policy reform), it was used on an estimated 70,000 hectares out of the more than 2 million hectares of potentially suitable land, and this is estimated to have reduced total N_2O reductions in 2011 by 0.2 percent below baseline emissions, based on the current inventory methodology.

In future using alternative methods of delivery[11] and a more targeted application to urine patches could become possible and research is underway to better understand this potential. A more targeted application would reduce the amount that is required per hectare to achieve the same overall emissions reductions and thus offer cost reductions.

It is unknown whether novel nitrification inhibitors currently under development could achieve even greater relative emission reductions from urine patches; their main advantage could be lower costs and higher efficacy throughout the year especially during the peak milking season.

A urease inhibitor tackles only a minor loss route and in the current national inventory calculations is applied only to emissions from N fertiliser and not from urea deposited directly by animals. As a consequence, the emission reductions that can be achieved currently through urease inhibitors are very minor. An order-of-magnitude estimate using the national inventory tool suggests that even if all N fertiliser sold in New Zealand was coated with urease inhibitors, this would reduce total N_2O emissions from N fertiliser by less than 3.5%. Given that N fertiliser makes up only about one fifth of total N_2O emissions, and N_2O makes up about 25% of total biological on-farm emissions, the full use of urease inhibitors would thus reduce total national biological GHG emissions by less than 0.2%. While this reduction is essentially provided for free as a co-benefit to greater nitrogen retention achieved by urease inhibitors, the magnitude was considered too small to be included explicitly in our modelling for this report.

It cannot be ruled out that further improvements to urease inhibitors could mean that it is also proven to be effective in reducing indirect emissions associated with urine deposited directly onto pastures, but we consider this speculative at this point and did not quantify such a future option.

Recent evidence suggests that the use of nitrification inhibitors could increase ammonia volatilisation later in the season, resulting in indirect N_2O emissions. While this could limit its overall effectiveness in some intensive systems, the overall impact for New Zealand's grazing systems is thought to be limited.

For the purpose of this report, we assume that nitrification inhibitors achieve a reduction of 60% of N_2O emissions from urine patches and N fertilisers during the winter months. During the summer months, we mimic an approximate 30% reduction up to 2030 (consistent with DCD), and 60% by 2050 from novel inhibitors.

What are drivers, barriers and likely rates of adoption?

The main driver for adoption of DCD historically in New Zealand was the ability to reduce nitrate leaching. Farmers also sought additional pasture production from the retention of nitrate in soil profile although empirical evidence for this is mixed. In the absence of regulatory limits for nitrate leaching losses, the main barrier to its uptake was cost, and limited evidence of well-proven, consistent pasture benefits.

- **Cost/benefit to farmers:** if viewed purely as a GHG mitigation option, the cost of using DCD was in excess of \$200/tCO_2-eq avoided, suggesting that any mitigation outcome would be a co-benefit of DCD being used either to meet nutrient caps or to increase pasture production.

11 This could include application using drones or robots, or inclusion of inhibitors in animal feed

The cost of novel nitrification inhibitors is unknown at present. Costs could decrease substantially with alternative application methods.

- **Market or regulatory drivers or barriers:** the discovery of residues was the main reason for withdrawal of DCD from the market, and a similar challenge exists for novel inhibitors. Current work under the *Codex* could remove this regulatory barrier. However, there is likely to be resistance from some segments of consumer markets that preference 'chemical-free' perspectives in their purchasing behaviour (especially if inhibitors were delivered directly through animal feed). These barriers could persist in some markets even if novel nitrification inhibitors pass all relevant official hurdles relating to food safety and other relevant environmental standards. Some farmers could also be more reluctant to adopt nitrification inhibitors given the DCD experience.

- **Environmental trade-offs or co-benefits**: unless and until GHG prices increase significantly, the main driver for the use of DCD and novel inhibitors is likely to be the improvement of water quality through reduced nitrate leaching. DCD was detected in waterways and at the concentrations measured prior to its withdrawal it generally posed a low but measurable risk of interfering with natural N transformations in waterways. Such trade-offs will need to be weighed relative to the benefits of reduced nitrate concentrations in waterways, and re-evaluated for any novel generation of nitrification inhibitors.

- **Fit with farm systems and universality of applicability**: DCD, novel nitrification inhibitors and urease inhibitors are easily applicable in intensively managed dairy pastures that also receive broadcast fertiliser applications. With novel application technologies, delivery could eventually be expanded e.g. through the use of drone technology as part of a 'precision-farming' approach. Application of nitrification inhibitors in sheep/beef systems may have some application to drystock camp areas and intensively grazed sites, however is likely to remain infeasible on steep hill country and prohibitively costly on extensive (most sheep) farms. Organic production systems would be unable to use inhibitors.

- **Ease of monitoring and accounting:** Inhibitors have already been incorporated in the New Zealand emissions inventory and this has been accepted by expert reviews under the UNFCCC, with mitigation determined based on the total amount of inhibitor sold to farmers in each year. As such, a future generation of nitrification inhibitors should not encounter any significant obstacles to being incorporated in future inventory systems as long as applicable research and relevant activity data meets the required standards.

Summary of drivers for and barriers to adoption of nitrification and urease inhibitors in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
DCD			Co-benefit			
Novel inhibitors			Co-benefit			
Urease inhibitors						

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

For simplicity for the estimates in this report, we subsume DCD in novel nitrification inhibitors and assume that these will become commercially available (and consistent with the updated *Codex Alimentarius*) in 2025. Adoption rates will necessarily interact with non-climate pressures on the use of inhibitors from water quality as well as any market resistance that could persist for some markets beyond *Codex* standards. This has not been modelled separately, and our scenarios simply assume a low and a high-use scenario to reflect a range of adoption rates consider plausible.

The inventory model in its current form is not able to include nitrification inhibitors applied on beef farms. Even optimistically, if we assume that up to 10% of beef operations could make use of nitrification inhibitors, the total additional mitigation that would be achieved by this amounts to about 0.2% of total agricultural emissions by 2050. We therefore excluded application of nitrification inhibitors on beef farms from our modelled scenario. As and when nitrification inhibitors become a widely viable option again, the inventory should be updated to capture application on all land types.

by when	emission reduction (N_2O: urine and N fertiliser)	adoption rates (land area, dairy only)
2025	60% (winter)	
2030	60% (winter) 30% (summer)	• dairy only: low 10%, high 30% Winter application only
2050	60% (all year)	• Dairy only: low 20% high 50% Year-round application

Results

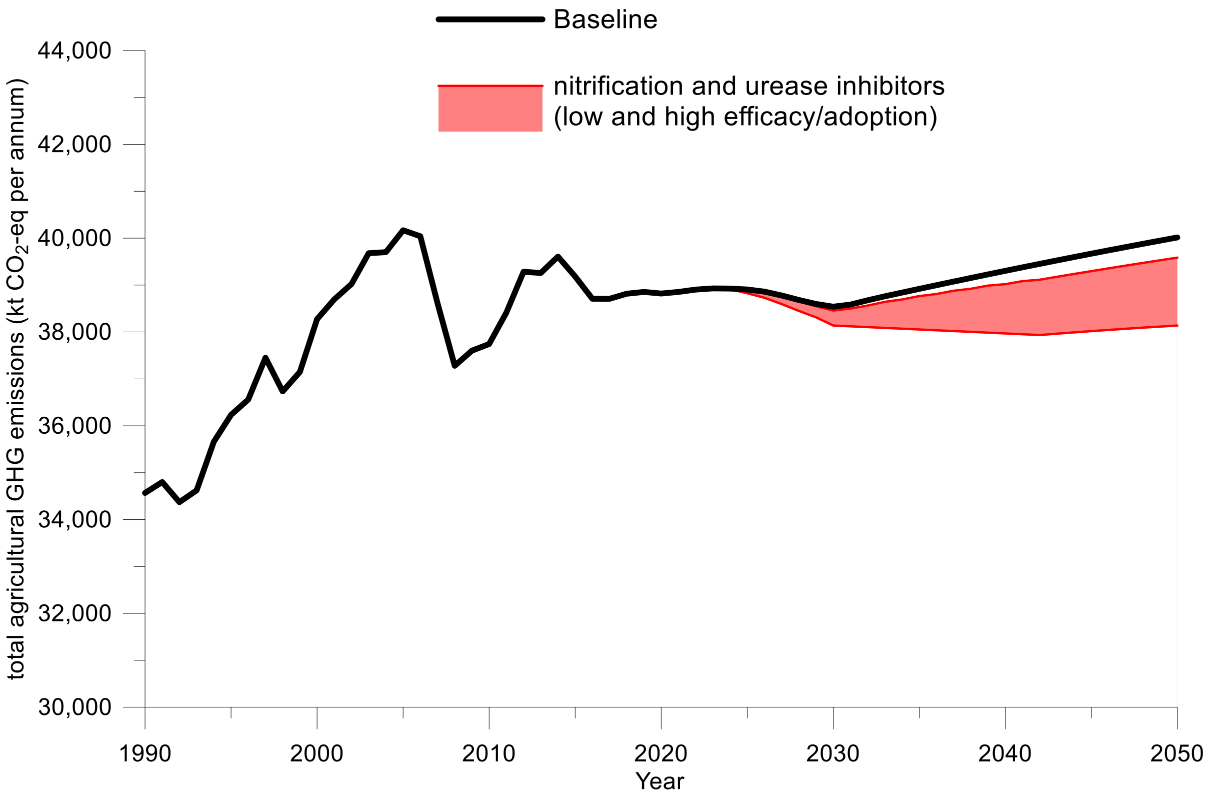

Figure 9: Total emissions in the MPI baseline and with nitrification and urease inhibitors applied (see text for details). The shaded area indicates the range of outcomes under high and low efficacy and uptake. The upper end of the shaded area corresponds to low efficacy and low uptake, while the lower end of the shaded area corresponds to high efficacy and high uptake.

2.7 Reduced N fertiliser use

Fertiliser increases pasture growth and thus allows higher feed intake and performance per animal and/or higher stocking rates. However, some fertiliser is lost through sub-optimal application and/or sub-optimal pasture production and consumption. Precision-farming techniques in principle can allow the reduction of fertiliser applied per hectare without an attendant reduction in livestock production. This section considers to what extent the amount of N fertiliser per animal could be reduced in future without reducing production per animal. More stringent reductions in fertiliser that would reduce total production are possible, but would require economic modelling to determine plausible levels, which was not possible within the scope of this report.

When could it become available?

Nitrogen fertiliser use per dairy cow (in the national average) increased about fourfold between 1990 and 2004, and has since fallen by about 15-20% while production per cow and cow numbers has continued to increase. Apart from the increased use of supplementary feeds, the main mechanisms for the reduced use of N fertiliser were targeted, strategic fertiliser use, managing timing of application to encourage a better response, improved delivery systems and the use of urease inhibitors increasing the efficacy of fertiliser application. A number of existing initiatives encourage and support the more efficient use of N fertiliser.

There is no indication that the current efficiency as achieved in the national average is a hard limit below which further reductions would necessarily result in reduced livestock production. However, the extent to which N fertiliser use per cow can be reduced further depends on the extent to which the type, amount and timing of N fertiliser application can be further optimised to match exactly the growth demand by plants. Further reductions thus depend on further improvements in precision-farming approaches related to timing and targeting of N fertiliser applications, as well as the ability and willingness of farmers to expose themselves to the risk of mismatching fertiliser application.

In summary, we have

- ***high confidence*** **that gradual further reductions in N fertiliser use per cow are possible now and into the future,**
- **but only *low confidence* in options for radical reductions in N fertiliser use without reducing performance per animal.**

What would be its impact?

Given that N fertiliser constitutes about one fifth of total N_2O emissions in New Zealand, meaningful reduction in total GHG emissions from the agriculture sector will only be modestly influenced by efficiencies in N fertiliser use. However, N fertiliser efficiencies have an important role to play in synergy with changed intensive farm systems to ensure they remain viable and productive.

Various studies in New Zealand indicate that through a range of enhanced testing of soil fertility, and spatially and temporally targeted applications of N fertiliser that considers soil condition and moisture status, reductions in N fertiliser use of 5–25% could be achieved, although the quantity depends heavily on baseline N fertiliser use and individual soil profiles. Most of the techniques relevant to support precision- and strategic application of N fertiliser exist in principle but are likely to expand in future through the increased use of sensor technology, targeted application mechanisms at increasingly fine spatial scales, drones, and information systems.

The further development of controlled/slow-release N fertilisers has the potential to reduce losses by extending the period over which plants receive increased N inputs that are better matched to their growth, and hence increasing the amount of N that is taken up by plants rather than lost through leaching and volatilisation.

The gains that can be made in these directions are most likely going to be gradual, since the precision and strategic application of N fertiliser is not just dependent on the use of new technologies but relies on farmer knowledge and experience. For this report we assume that reductions of 15% per cow below the levels assumed in the baseline scenario could be achieved by 2030, and 20% by 2050 on dairy farms and a small section of intensive beef finishing farms.

Significant reductions in N fertiliser use without attendant reductions in animal performance, beyond the gradual increase in efficiencies in the order of 15-20 % is unlikely without radically new and novel technologies (such as novel N-fixing grasses that would radically reduce the need for N fertiliser use). If significant benefits are provided by new technologies these are usually adopted rapidly, but no such technologies are anticipated in the near to medium future.

It should be noted that improvement in efficiency may not always directly translate to the equivalent reduction in N fertiliser use, but may provide for more performance with the same or less N fertiliser use. However, for the purpose of this report, we assume that an increase in performance would be matched by a reduction in inputs such that total plant dry matter production remains the same as in the baseline but at lower overall emissions due to reduced fertiliser input.

For pastoral systems where fodder crops may be introduced as an alternative to nitrogen supplemented pasture, a full life cycle analysis would be required to understand nitrogen use, and GHG implications in producing the feed supply.

For the purpose of this report, we assume that N fertiliser use per cow (mostly dairy) can be reduced by 15% by 2030, and by 20% by 2050 compared to 2015 without reducing performance per cow.

What are drivers, barriers and likely rates of adoption?

Apart from feed and labour, N fertiliser is one of the largest dairy farm expenses, so there have always been clear commercial drivers for efficient use. Regional council regulations addressing water quality management are imposing limits and requirements for documented accountability in nitrogen loss, which are driving many of the efficiencies changes which have impacted and will continue to impact on N fertiliser use. Adoption of new technologies to support precision farming relies on capital, information and training, as well as periods of trial and error to support gradual introduction of new approaches while managing the risk of failure.

- **Cost/benefit to farmers:** reductions in N fertiliser use reduce direct input costs but need to be balanced by the cost of any reduction in production (or simply the risk of a loss of production if too little rather than too much fertiliser is applied), as well as the cost of infrastructure and training to support more targeted and precision application.
- **Market or regulatory drivers or barriers:** reduced use of N fertiliser can support market branding related to natural, environmentally friendly, low-input livestock production. Increased demands for total environmental footprint reporting (including eutrophication) could increase the adoption of reduced N fertiliser practices. There are no market barriers to reduced N fertiliser use.
- **Environmental trade-offs or co-benefits**: Regional council water quality regulation constrains expansion and intensification of land use where there might be significant increases in nitrogen cycling and nitrogen leaching losses. Mitigations which are known to provide for efficient use of N fertiliser and reduce leaching losses currently provide strong drivers for uptake. GHG efficiency from reduced N fertiliser application is likely to be a co-benefit of water quality policy and regulation. However, water quality acts as a constraint only in some catchments, whereas N_2O emissions contribute to total GHG emissions regardless of their location. Also, if reductions in N fertiliser inputs are compensated for by

increased supplementary feeds then total N inputs, N_2O emissions and nitrate leaching may be little changed.

- **Fit with farm systems and universality of applicability**: precision and strategic application of N fertiliser is consistent with all except the lowest input and organic dairy farm systems. Most beef farms use N fertiliser only tactically during some seasons, often to manage climate variability, and hence only a small section of beef finishing farms is likely to be able to use increased precision application approaches. The use of N fertiliser on sheep farms is so limited that it is unlikely that there are ready pathways for adoption for precision approaches.
- **Ease of monitoring and accounting:** in the current New Zealand GHG emissions inventory, N_2O emissions from N fertiliser are directly related to amount of N fertiliser sold and applied, and hence a reduction in the total amount of N fertiliser applied due to greater efficiency would be readily captured in the inventory.

Summary of drivers for and barriers to adoption of reduce N fertiliser use in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
Reduced N fertiliser use			Co-benefit			

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

The MPI baseline scenario already assumes a reduction of fertiliser use per cow of about 10% per cow (mostly in dairy), consistent with constraints arising from nutrient limits. The additional mitigation that would be achieved within our assumptions relative to this baseline is limited.

At the adoption rates considered here, these scenarios translate into a reduction of total synthetic fertiliser use of 3-4% below business as usual in 2030, and 4-7% below business as usual in 2050.

by when	Quantification (reduction in N fertiliser use per cow, relative to 2015)	adoption rates (land area)
now		
2030	15% reduction per cow	• dairy low 50%, high 80% • Beef: low 0% high 5% • Sheep: 0%
2050	20% reduction per cow	• Dairy: low 50% high 80% • Beef: low 0% high 5% • Sheep: 0%

Results

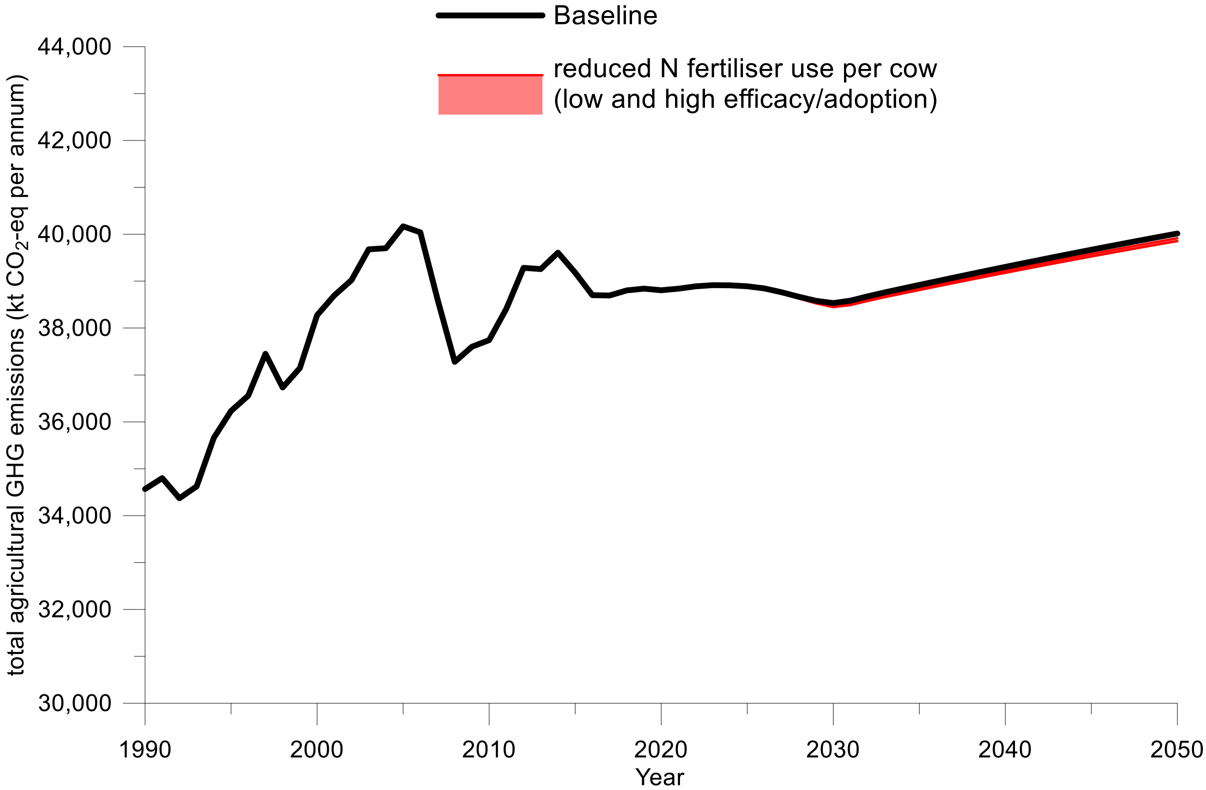

Figure 10: Total emissions in the MPI baseline and with reduced N fertiliser per cow applied (see text for details). The shaded area indicates the range of outcomes under high and low efficacy and uptake (nearly indistinguishable from the baseline).

2.8 Increasing performance of individual animals

Performance per animal (kg milk solids per cow, kg lamb slaughtered per ewe, kg beef slaughtered per cow) has increased steadily in New Zealand over the past 25 years. Further improvements in performance are expected under business as usual, but could potentially be accelerated.

Whether increasing performance per animal at a faster rate reduces total GHG emissions depends strongly on concurrent adjustments in animal numbers. If performance per animal increases and animal numbers remain unchanged, GHG emissions increase; if animal numbers or feed inputs are reduced, emissions can decrease. For the purpose of this report, we assume that any increases in performance per animal beyond business as usual would be compensated by an equivalent reduction in animal numbers such that total production (of milk or meat) remains at the same levels as in the baseline scenario.

When could it become available?

Performance has increased historically and such improvements are on-going through continued improvements in genetic merit and management practices. Critical issues are quantifying the rates of future improvements under business as usual, and how much those rates could be accelerated further across New Zealand farms, including how such efforts would interact with other mitigation options.

In summary, we have:

- ***very high confidence*** **that increasing individual animal performance is available as a potential mitigation option, but the extent to which this will occur already under business as usual is uncertain and must be explored through a range of scenarios.**

Note this is only a mitigation option if the enhanced individual animal performance is compensated by a reduction in animal numbers such that total product output is maintained.

What would be its impact?

Dairy

Milk solids per cow have increased on average by +1.4% or 4.5 kg MS/cow per year over the past 28 years. Milk solids increased much more rapidly between 2007 and 2016 (7.5 kg MS/cow) reflecting improved genetics, changes in breed ratios (more crossbred and less Friesians) and increased feed supply and consumption. Milk solids/cow could be increased substantially (the genetic potential of New Zealand animals is far higher than that achieved in commercial situations) through increasing use of supplementary feeds, but the potential rate of increase is constrained in practice by the general desire to continue producing milk under low cost pasture based systems. Environmental pressures related to not only GHG emissions but also nutrient discharges mean that there is a question mark over whether future growth rates will match those recorded over the last decade.

The MPI baseline forecast growth in performance is for an increase in MS/cow of 3.1 kg/cow per year to 2030. We extended the baseline to 2050, assuming that performance increase would follow the same pattern as in the 2018-2030 period i.e. it would continue to grow albeit at a reduced rate. The annual growth rate falls to 2.4 kg MS/cow per year by 2050.

As a mitigation scenario, we assume that milk solids per cow increase by 4kg (rather than 3.1kg) MS/cow per year between now and 2030, and increase by 3kg (rather than 2.4kg) MS/cow per year between 2030 and 2050. However, given uncertainties in baseline assumptions, we also test a scenario where performance increases only at a lower rate of 2kg MS/cow per year from now through to 2050. In addition, we assumed that the number of replacement breeding stock would be reduced by 2 percentage points by 2030 and by 4 percentage points by 2050 (the proportion of replacement breeding stock is constant over time in the MPI business as usual scenario).

Sheep

The percentage of lambs born per ewe has increased substantially by about 0.7% per year since 1990. At the same time, lamb carcase weights at slaughter have increased by > 4kg. Improved pasture management and feeding, genetics, and increased hogget mating are the main drivers behind these improvements. As a result of these improvements, total lamb meat production has remained roughly constant despite breeding ewe numbers halving since 1990.

The MPI baseline assumes only moderate further increases in lamb weight reflecting market constraints, and a further improvement in lambing percentage at a reduced rate of about 0.4% per year to 2030. We extended this baseline to 2050 by assuming no further increase in lamb weights after 2030, and a continued improvement of lambing percentages of 0.4% per year, reaching 130% in 2050 (from about 95% in 1990).

As a mitigation scenario, we assumed that lambing percentages improve faster than in the baseline at 0.5% per year, reaching 140% across the sector by 2050. Given uncertainties in baseline assumptions, we also test a scenario where lambing percentages reach only 125% in 2050. Note that the lambing percentages used here are based on national agricultural statistics, defined as the number of lambs alive in September divided by the number of breeding ewes and hoggets in July (see also Figure 3). This definition is a useful metric at the national scale but may differ from how the term lambing percentage is used on-farm and in industry performance measures.

We assumed that lamb weights remain as in the baseline since international markets constrain the ability to significantly increase weights. In principle, faster rates of weight gain could allow earlier slaughter dates at constant slaughter weight but we could not quantify this option (due to limitations of the current GHG inventory model).

Beef

In the beef sector, similar performance gains as for sheep are possible by improving beef calving rates and accelerating weight gain through improved feeding and pasture management. The MPI baseline assumes a constant calving rate of 82%, consistent with historical averages. Some farmers achieve significantly higher rates, however, so we assumed as a mitigation scenario that calving percentage increases significantly to 90% by 2030 and to 92% by 2050 mainly as a result of improved management, and the number of breeding cows and replacements is reduced accordingly to maintain the same total number of beef calves produced as in the baseline.

The MPI baseline assumes moderate further increases in slaughter weights. As part of our mitigation scenario, we assumed that weight gains could be accelerated further through improved pasture management and genetics to bring slaughter dates forward by 1 month by 2030, and by another month by 2050, at the same slaughter weights that are assumed in the MPI baseline.

Unfortunately, the national GHG inventory is currently not able to reflect such a change in the time of slaughter, and hence we were not able to include this mitigation option in our quantitative modelling. Based on the feed intake of animals at the time of slaughter, we estimate that bringing the time of slaughter forward would reduce total emissions by roughly 0.5% in 2030 and 1% in 2050.

For the purpose of this report, we assume:

- **for dairy:**
    - **milk solids per cow increase by approx. 1kg/cow per year above baseline rates**
    - **replacement rates reduce by 2 and 4 percentage points by 2030 and 2050**
- **for sheep:**
    - **lambing percentages increase by 0.5%/year compared to 0.4% in the baseline**
    - **slaughter weights remain as in the baseline; changes in slaughter dates combined with accelerated weight gain were not modelled**
- **for beef:**
    - **beef calving percentage increases to 90% by 2030, and to 92% by 2050**

Note that achieving the assumed on-going increases in performance under business as usual, let alone the accelerated rates assumed in mitigation scenarios, relies on ongoing improvements in supplementary feeds, crop yields, pasture production and animal genetics and no adverse impacts from climate change that could challenge these improvements. Some of those changes imply an increased reliance on feed storage to maintain high feed intake year-round, which along with enhanced pasture management could have repercussions on CO_2 emissions from farm operations that have not been quantified in this report.

What are drivers, barriers and likely rates of adoption?

As noted above, increasing performance will only reduce absolute GHG emissions if animal numbers are reduced at the same time. The motivation for farmers to do this will rely on a range of climate and non-climate policy as well as market signals. Major factors will be the ratio of input cost to product price as well as any constraints on animal numbers and/or nutrient flows from water quality regulations. For this report, we do not consider the specific policy settings that would be necessary to achieve compensatory reductions in total animal numbers but simply assume that drivers are in place to achieve these reductions such that overall production levels are maintained at increased performance per animal.

- **Cost/benefit to farmers:** Increasing performance generally has economic benefits to farmers and has been the main driver for improvements over the past 25 years, along with increased resource efficiency. This is assumed to continue, but there will be a point where the costs associated with further accelerating performance (e.g. cost of feed and infrastructure, genetic selection of high value animals) begin to outweigh the economic benefits.
- **Market or regulatory drivers or barriers:** For dairy systems, increasing milk yields solely through reducing stocking rates, improved pasture management and improved genetics is challenging, and most farmers will rely on increasing supplementary feed per cow. However, such an approach could clash with a desire to market New Zealand milk as pasture fed and potentially with nutrient limits. Market perceptions, for example, have contributed to farmers being asked to reduce their reliance on palm kernel expeller (PKE) even though it is a cheap and easy to use feed source.
- **Environmental trade-offs or co-benefits:** A shift towards fewer but more productive cows would support lower nutrient discharges in line with water and Regional Council regulations. Increased drought risk related to climate change could reduce the opportunity for sustained growth in animal performance especially in sheep and beef systems in some regions; higher input dairy systems may increase their reliance on supplementary feed provided this is available and affordable.
- **Fit with farm systems:** Increasing performance fits naturally with economic and environmental pressures on New Zealand farmers. However, the increased skills needed and significantly increased complexity in managing highly productive farms, including the greater attention needed for genetic selection of high-performing animals, would likely be a significant challenge for some lower-performing farms.
- **Universality of applicability across different NZ farm systems:** All systems and all regions can increase their performance, but the potential rates of improvement are likely to differ. Low-input dairy systems face greater challenges to increase milk solids/cow than medium or high input systems. Increasing milk solids/cow is also likely to be more challenging for already high producing regions such as Canterbury relative to lower producing regions such as West Coast or Northland. The ability to improve performance of sheep and beef systems relies heavily on climatic and soil conditions as well as farmer skill and access to information and willingness to trial fundamental changes, with a wide diversity across the country.
- **Ease of monitoring and accounting:** Changes in average animal performance are readily captured through national statistics and would flow directly into the inventory. Changes in

slaughter dates cannot currently be captured in the national inventory model but the modifications needed to allow this are relatively simple. The same information would be available at farm level. About two thirds of dairy farmers herd-test so know how much each cow is producing quarterly. Approximately 15% of dairy herds have daily in-shed monitoring systems. At the national level dairy companies provide data on the total quantity of milk processed annually and data on the number of milking cows can be obtained from both industry and government sources.

Summary of drivers for and barriers to adoption of accelerated performance gains in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
Dairy						
Beef						
Sheep						

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

For all systems, we assume that animal numbers would be adjusted downward as animal/herd performance increases such that total national production of milk solids, beef and lamb meat remains the same as in the baseline in the years 2030 and 2050.

Note that this is a strong assumption used solely to quantify the potential mitigation benefits of increasing performance. Actual changes in animal numbers will depend on a range of other drivers and policies – reductions in animal numbers are not a necessary consequence of efforts to increase performance per animal, even though there can be interactions e.g. where farmers reduce stocking rates to increase pasture availability per animal or remove animals from less productive land.

We assume that the feed mix needed to drive the increased performance per animal can be produced without incurring additional emissions. This can be justified based on the assumption that total animal numbers will be reduced meaning that the total quantity of feed needed is actually reduced compared to business as usual.

by when	Quantification (animal/herd performance)	adoption rates
now		
2030	Dairy: • Rate of increase in MS per cow about 1 percentage point above baseline • Replacement rate reduced by 2 percentage points below baseline Sheep: • Lambing percentage increases by 0.5% per year Beef: • Calving percentage increases to 90%	Changes are for national average performance
2050	Dairy: • Rate of increase in MS per cow about 1 percentage point above baseline • Replacement rate reduced by 4 percentage points below baseline Sheep: • Lambing percentage increases by 0.5% per year Beef: • Calving percentage increases to 92%	Changes are for national average performance

Results

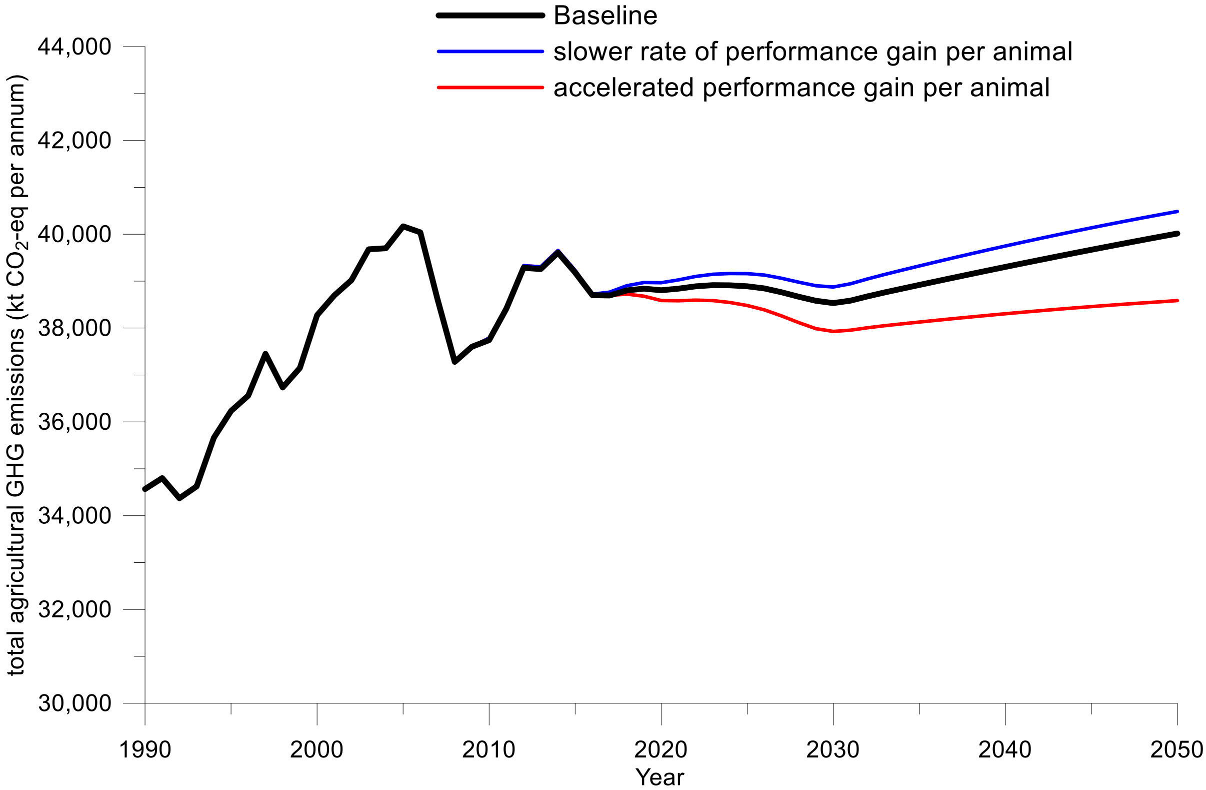

Figure 11: Total emissions in the MPI baseline and with increased animal performance applied, with animal numbers adjusted downwards such that total production remains as in the baseline (see text for details). The blue line illustrates the sensitivity of the baseline to assumptions about animal performance: emissions would increase if animal performance increases by less than assumed in the baseline and animal numbers are increased to maintain total production.

2.9 Enhanced manure management in dairy systems

Emissions related to the management of livestock manure (collected in milking sheds, stand-off and feeding pads) arise in the form of CH_4 from anaerobic storage of manure, and in the form of N_2O from volatilisation of nitrogen contained in manure, and N_2O when manure is spread back onto soils.

Options to reduce manure emissions exist in principle through capturing CH_4 produced in anaerobic ponds (where it can then act as a biofuel), and by managing the storage and spreading of manure to minimise subsequent N_2O emissions. While some gains are possible, currently manure overall contributes only a small part (less than 4%, mostly from CH_4) to total biological GHG emissions from agriculture.

When could it become available?

Most manure management options are well established in principle and available now. The bio-digestion and subsequent capture of CH_4 from anaerobic ponds via bio-digesters is an established technology. However, the economics of bio-digesters are extremely challenging and the main constraint is the minimum size of herds required to make this approach cost-effective in a country like New Zealand. Uptake in developing countries has mostly relied on financial incentives and/or the ability to provide fuel where there is no reticulated fuel supply. Research has also been undertaken on the development of bio-filters that would break down the methane via bacteria (i.e. without capturing the CH_4 to produce a biofuel). While this approach has been shown to be possible in principle, it is still at an early stage of development and it will be challenging to develop this into a cost-effective technology. Management options also exist to minimise the volatilisation of nitrogen contained in manure into ammonia (which subsequently is transformed into N_2O), but manure storage generally has to occur at larger scales than in typical New Zealand (mostly pig) farms to make additional management techniques viable; total emissions from the volatilisation of manure in New Zealand account for only about 0.2% of total agricultural emissions.

There is a well-established relationship between soil moisture and the amount of N_2O emissions that are generated from a given amount of N deposited onto pastures; the wetter the soil, the greater the fraction of N that is turned into N_2O. Timing the spreading of stored manures to coincide with dry conditions (i.e. mostly summer/autumn months) therefore can help reduce emissions compared with spreading manure randomly throughout the year. However, the New Zealand emissions inventory does not currently take soil moisture into account when estimating these emissions. This may change in the future but costs of obtaining the data required is a major barrier.

Additional options to reduce emissions related to animal excreta arise from grazing management, e.g. by minimising grazing during wet conditions, which would reduce nitrate leaching and N_2O emissions. However, such an approach requires the installation of stand-off and feed pads, as well as increased manure storage capacity, with consequent emissions arising from manure storage. Studies to date indicate that it is technically feasible to reduce emissions using this approach, but only on poorly drained soils in some regions. Even so, the cost associated with such a system change would greatly outweigh the GHG mitigation benefits in most regions, although water quality constraints could nonetheless increase adoption in some catchments.

In summary, we have:

- ***very high confidence*** **that options to reduce CH_4 from anaerobic ponds are available now and in future**
- ***high confidence*** **that N_2O emissions from the spreading of manure can be reduced through strategic timing and accounted for in future, subject to improvements to NZ's emissions inventory (but inventory improvements may not be cost-effective).**

What would be its impact?

Existing bio-digesters avoid most of the CH_4 that is normally produced and released from anaerobic ponds, although incomplete digestion, leakage and accidental releases mean that the reduction is generally less than 100%. If CH_4 is used as a biofuel to generate electricity (or avoid the use of other fossil fuels), it could generate additional emission reductions, although the amount of reduction depends on the carbon content of the fuel it replaces. For our analysis, and given the relatively small magnitude overall of CH_4 emissions from manure storage, we assume that in those facilities that employ bio-digesters or similar technologies, 100% of the CH_4 normally released would be captured. We do not consider additional benefits from the displacement of fossil fuels since the actual use of CH_4 is uncertain (it could simply be flared rather than used as a fuel, and the emissions reductions would also depend on the future carbon intensity of electricity supply).

For N_2O emissions, farmers who adopt best practice would spread manure collected on dairy stand-off pads only during dry periods. Actual outcomes depend on soil moisture throughout the year as well as grazing practices. The effect on total emissions is minimal, however, given that manure spread back onto pastures constitutes only about 0.2% of total agricultural emissions in 2030. Even if those emissions could be avoided entirely through improved management practices (which is not plausible), the mitigation effect would remain very small. This mitigation option was therefore not included in our quantitative modelling.

If dairy farmers increase their use of stand-off pads during wet conditions, net N_2O emissions from deposition of excreta onto pastures would be reduced due to restriction of grazing during wet conditions, but this reduction would be partly compensated by increased N_2O emissions from the spreading of manure plus CH_4 emissions from manure storage. A recent study estimated that there would be a net reduction in emissions only for farms with poorly drained soils that have more than 150 wet days per year, with reductions between 3 and 14% in net farm-scale N_2O and manure-derived CH_4 emissions depending on the region and duration that cows are removed from pastures.[12] Up to about one quarter of dairy land is considered as heavy soils, although the modelled mitigation would unlikely apply to all these soils.

The net GHG mitigation depends on a significant change to the national GHG inventory, both to capture the timing effect of grazing and manure deposition during dry or wet conditions throughout the year, and to change emissions estimates of CH_4 from manure from stand-off pads. These changes would also need to be applied to baseline projections for all farms. If the inventory is not changed, increased use of stand-off pads would increase net emissions for all farms. Even if fully adopted and the GHG inventory were changed to reflect the gains, this approach is estimated to reduce total agricultural emissions by less than 0.4 percent. The cost of stand-off pads may limit their adoption (except where necessary to comply with nutrient discharge limits). Given the small amount of mitigation and the significant and complex changes to the inventory required, we did not include this option in our quantitative assessment.

For the purpose of this report, we assume:

- **farms with bio-digesters eliminate their CH_4 emissions from manure**
- **restricted grazing together with best practice manure management could reduce net farm GHG emissions by 5-10% for farms on poorly drained soils with more than 150 wet days per year, but these have not been included in our modelling given the small reductions at national scale and/or complex changes required in the inventory including in baseline projections**

12 van der Weerden et al. (2017), Mitigating nitrous oxide and manure-derived methane emissions by removing cows in response to wet soil conditions. *Agricultural Systems* 156, 126-138

What are drivers, barriers and likely rates of adoption?

- **Cost/benefit to farmers:** Ninety-five percent New Zealand dairy farms are too small (under 1,000 cows) to make bio-digesters cost-effective.
- **Market or regulatory drivers or barriers:** Manure-related emissions are only a minor part of the overall GHG footprint of New Zealand farms, but they can be highly visible and could allow some farmers to demonstrate a commitment to action. However, it is unlikely that farmers could gain much brand advantage by more advanced manure management systems, given the competing grass-fed market claim.
- **Environmental trade-offs or co-benefits:** Improved management of manure through bio-digesters and subsequent spreading would result in only minor reductions in N leaching, as most N losses occur from direct deposition of excreta during grazing. Restricting grazing during wet conditions tends to have much bigger effects on N leaching and soil compaction and these are likely to be the main drivers for changes in practices.
- **Fit with farm systems:** All dairy systems have some form of manure management, but the scale and volume of manure collected influences management options including maximum storage times. Manure management is not a viable option for most sheep and beef systems.
- **Universality of applicability across different NZ farm systems:** Installation of bio-digesters is likely to only be commercially viable on large farms approaching 1000 animals collecting a large amount of effluent under consistent conditions. Currently 5 per cent of New Zealand dairy herds are over 1,000 cows, with the majority of these in the South Island. Restriction of grazing to reduce N_2O emissions during wet conditions is only effective on poorly drained soils, and incentives to adoption will depend heavily on water quality regulations since the approach tends to be not cost-effective from a GHG mitigation perspective only.
- **Ease of monitoring and accounting:** Emissions reductions from the installation of bio-digesters could be monitored and reported relatively easily in the national inventory, provided that individual farm data are reported. Improvements to the inventory to reflect differential emissions for manure from stand-off pads, and deposition of excreta during dry and wet conditions, require additional measurements and confirmation of an internationally acceptable inventory methodology, and monitoring and verification of restricted grazing during wet conditions would require additional on-farm reporting.

Summary of drivers for and barriers to adoption of improved manure management in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
Bio-digesters						
Manure spread			Co-benefits			
Restricted grazing			Co-benefits			

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

For bio-digesters, we assumed that 5% of all stored dairy manure would be treated in bio-digesters in 2030, rising to 7.5% of all stored dairy manure in 2050. These small percentages roughly reflect the proportion of New Zealand dairy herds over 1,000 cows.

We did not include improved manure management or restricted grazing during wet conditions in our model results due to the difficulty of including this in the inventory estimates at present, the limited applicability and limited overall impact as outlined above.

Results

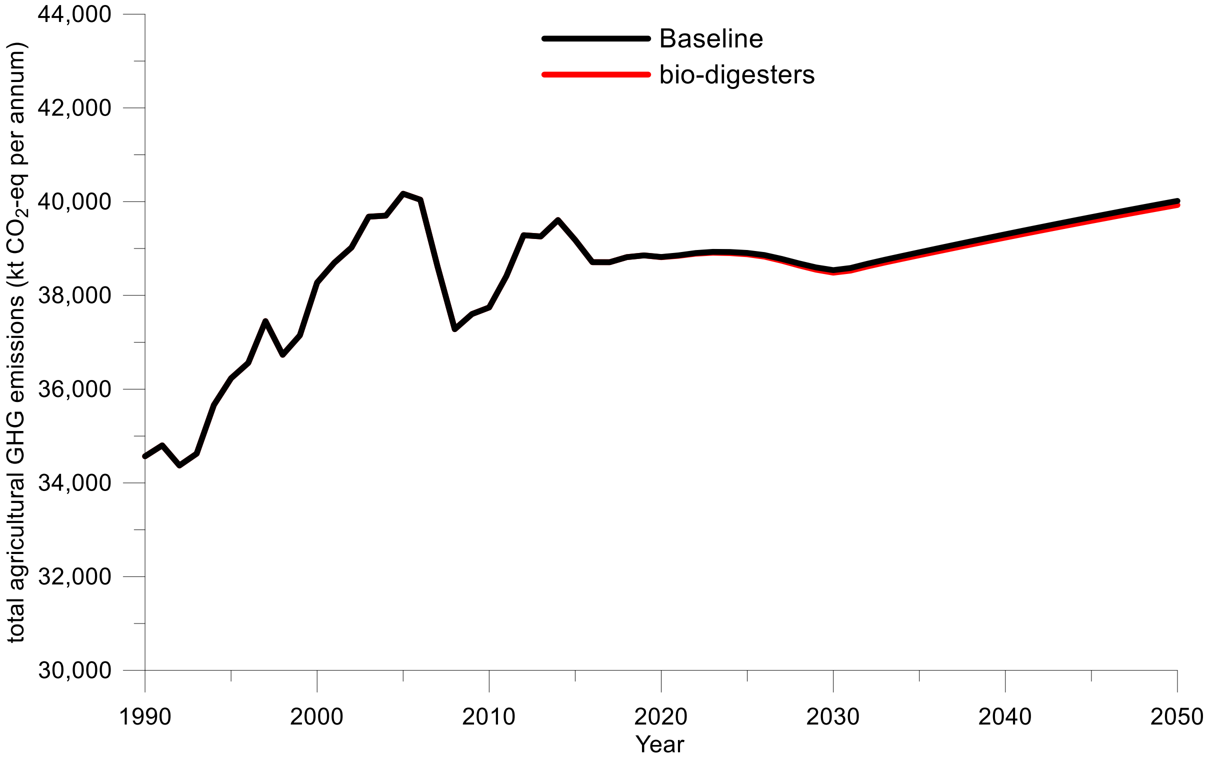

Figure 12: Total emissions in the MPI baseline and with enhanced manure management using bio-digesters (see text for details). Within the assumptions made, the outcome is almost indistinguishable from the baseline.

2.10 De-intensification of dairy systems

The New Zealand dairy industry has intensified over the last decade with increased use of supplementary feed and cropping. This has led to increased milk production per hectare and per animal but also increased GHG emissions. This mitigation option considers the effect of unwinding dairy systems back towards lower stocking rates, feed inputs and consequently milk production and GHG emissions. This level of farm system change would be very challenging to achieve in practice and an increase in capability in the industry would be required to manage this transition. In addition, this approach could have significant economic impacts, which will vary depending on factors such as milk prices, current levels of intensification, investment in capital infrastructure on farms and debt levels. We have not tried to model this quantitatively.

When could it become available?

This mitigation is technically available now as farms in New Zealand operate on a spectrum from low-input (called system 1, relying entirely on grass grown on-farm) to intensive systems where typically about 25-40% of the total feed is imported to the farm year-round (called system 5). Some farmers have opted to undertake this due to challenges of managing climate, reducing exposure to feed prices, and some are considering this to lower N losses for N and water quality challenges in Regional Plans. However, transitioning an existing intensive farm towards lower intensity (e.g. system 5 to system 3, or system 3 to system 1) requires considerable management skill to adjust the farm system down while ensuring that the farm remains efficient, economic and climate resilient (supplementary feed is also used tactically to cope with climate variability such as drought).

Major questions are the scale at which this mitigation could be applied across New Zealand farms and the implications for profitability. Reducing intensity means lower farm revenue on average and a reduced overall volume of milk production, which could challenge New Zealand's export income, trade balance and therefore international market strategy (dairy export revenue equals approximately 40 % of primary industry export revenue). Existing infrastructure, capital investments and market conditions mean that we do not consider it realistic to have no high-input systems at all, even in the medium to long term future. It is likely to take a decade or longer for national-scale system adjustments to occur at significant scales.

We expect that many other mitigation options would be more attractive, especially to those farmers who are clearly benefitting financially from high input systems. Nonetheless, this scenario shows one potential route that could be possible (alongside some other mitigations as required) where there is a clear willingness and ability to de-intensify. Different levels of de-intensification are also possible, but we selected only one scenario to demonstrate in-principle the potential magnitude of change in GHG emissions that could be achieved.

Note that our scenario does not explicitly include a shift to certified organic systems (which also typically have lower stocking rates and receive no synthetic fertiliser at all). We have insufficient data to reliably explicitly quantify the impacts of certified organic systems on production and emissions if adopted at scale.

In summary, we have:

- ***high confidence*** **that de-intensification is technically available now,**
- **but only** ***medium confidence*** **that it could be achieved at the scale used to illustrate this scenario by 2030, given likely costs of adjustment, capability in the industry to manage such a transition and impact on overall milk production**

What would be its impact?

Emissions per cow are strongly correlated with total feed intake. Feed intake in turn depends on the energy requirements of the animal, which consist of a reasonably fixed component (energy that the animal requires to maintain itself) and a component that correlates strongly with the amount of milk the cow produces (including energy needed for a successful pregnancy). De-intensifying dairy systems means reducing the number of farms where cows receive extra feed to produce high volumes of milk towards farms where cows consume mainly the grass grown on-farm and as a result produce less milk and fewer animals are kept per hectare.

While theoretically any amount of de-intensification is possible, we considered a scenario where the number of farms and farm hectares remains unchanged, but where the percentage of intensive dairy farms reduces and the percentage of low-input farms increases over time; this also results in a reduction of overall cow numbers since low-input farms generally have lower stocking rates.

To test the impact of a hypothetical scenario on emissions, we assume that the percentage of intensive (system 4-5) farms reduces from currently 25% to 20% in 2030 and 10% in 2050. Conversely, the percentage of low intensity (system 1-2) farms increases from currently 35% to 45% in 2030 and 70% in 2050. The percentage of medium-intensity (~system 3) farms is currently 40% and would drop to 35% in 2030 and 20% by 2050. Note that the reductions assumed for 2050 would, more or less, be a return to the 2000-01 percentages for the three levels of intensity.

Cow numbers (assuming a constant baseline) would reduce in the above scenario by just over 1% in 2030 and 4% in 2050 (we assume that the total number of herds and the total land area under dairy production would remain the same, i.e. our scenario excludes land-use change). The reduced cow numbers and feed intake in low-input systems would lower total milk production by around just over 2% by 2030 and 8% by 2050, all else being held equal. At present the dairy industry's milk growth target is a growth of ~1.5% per year so this would constitute a reversal and would have significant financial implications for regional economies and milk companies.

One consequence of this scenario is that milk production becomes less efficient than in the baseline (i.e. milk production decreases more than cow numbers). This means that biological on-farm emissions intensity (emissions per kg MS) would increase relative to the baseline. However, the carbon footprint of milk production from a lifecycle perspective (which includes off-farm emissions including from energy use, and also emissions arising from feed production overseas) is very similar between farm systems of differing intensity. As a result, de-intensification of the dairy sector would not be expected to significantly change the national average carbon footprint of milk production, although trends could differ between regions depending on their feed sources and energy use.[13]

For the purpose of this report, we assume a systematic reduction in the percentage of high intensity farms from 25% to 10%, and a systematic increase in the number of low-intensity farms from 35% to 70% in 2050. Our scenario assumes a gradual de-intensification to 2030 and more rapid change to 2050, reflecting the time it would take to transition current high-input farms with high capital investments, along with their skill sets and supply chains, towards lower input systems. Current farm production statistics are used to infer the resulting changes in total cow numbers and total milk production, and the national GHG inventory is used to estimate the resulting change in national GHG emissions.

What are drivers, barriers and likely rates of adoption?

A number of scientific system trials have been conducted over the last 20 years to test the impacts of low and high input farm systems, but many of these trials were designed to increase or at least hold production while reducing N losses.

13 See e.g. Reisinger, A. et al (2017): Sensitivity of the carbon footprint of New Zealand milk to greenhouse gas metrics. *Ecological Indicators*, 81, 74-82

- **Cost/benefit to farmers:** Economic effects of shifting to lower intensity systems depend on milk payouts and existing capital investments, but could be profit neutral for farms with lower animal demands/feeds, labour costs and repairs and maintenance. Even though low-input farms can be as profitable as high-input farms (depending on the above factors), the cost of transitioning from a high-input to a low-input system can be significant and potentially prohibitive in the near term especially for farms with high capital investments and debt levels. Shifting to lower input systems would also reduce the ability of farmers and the industry to capitalise on high-payout seasons and can add more pressure during adverse weather events but reduces the risk of over-gearing. Reducing total milk volume would have wider impacts than just on-farm, as it would reduce spending and employment in rural communities, but could also reduce human resource pressures on farmers. De-intensification may also impose costs on dairy companies if volumes drop below design capacity for milk processing (risk of stranded assets).
- **Market or regulatory drivers or barriers:** A widespread shift towards less intensive farming could increase the potential for pasture-based/organic farming and associated branding for more "natural" systems. Consumer reaction to the use of palm kernel expeller serves as a useful example even though it serves as a cheap and easy to use feed source. Nutrient limits may also naturally drive a shift back to lower input systems. However, reduced milk volumes could adversely affect New Zealand's international market position (competitiveness and ability to meet market demands).
- **Environmental trade-offs or co-benefits:** lower intensity systems generally have lower N loss (given the same biophysical characteristics of soils, rainfall and slope) and thus support water quality and Regional Council regulations, although housing and feed pads associated with intensive systems can also help manage N losses. Lower intensity systems reduce exposure to market variability as stocking rates will be more based on natural capital, however, risk to climate variability can be increased during times of drought/flood events depending on the source of supplementary feeds.
- **Fit with farm systems:** While changing farm system is doable, in reality this level and scale of change would require considerable industry support, and there would likely be a significant gap between the capability needed and currently available. Significant consultant advisory effort would be required to increase the skills of farmers needed to maintain pasture growth and quality with lower stocking rates. New technology may assist once remote monitoring of pastures becomes operable.
- **Universality of applicability across different NZ farm systems:** mostly applicable to lower intensity dairy farms (i.e. shifting system 3 to system 1-2); some unwinding is possible on system 4/5 farms but may take more time where capital infrastructure exists to reduce cost (risk of stranded capital).
- **Ease of monitoring and accounting:** Emissions reduction would be readily reflected at national scale based on national agricultural statistics and milk production. Requires on-farm data capture of herd performance for on-farm accounting. Systems are in development now and will get better with use. This option is available in OVERSEER now.

Summary of drivers for and barriers to adoption of dairy de-intensification in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
2030						
2050			Co-benefit			

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

Our scenario assumes the same total land area devoted to dairy as in the MPI baseline scenario, but with fewer cows and the reduced use of supplementary feed. Production per animal would still increase in each farm system consistent with the MPI baseline, but the total national milk production would increase by less given the greater proportion of lower intensity systems as outlined above. We assume farmers can and are willing to make such system changes quickly and will adopt current farm and production characteristics. Absolute emissions rise still in this scenario beyond 2030 despite an increasing shift towards de-intensification, because the increasing performance per animal that is assumed in the baseline and carried through into the mitigation scenario more than offsets the reductions resulting from less intensive systems.

Results

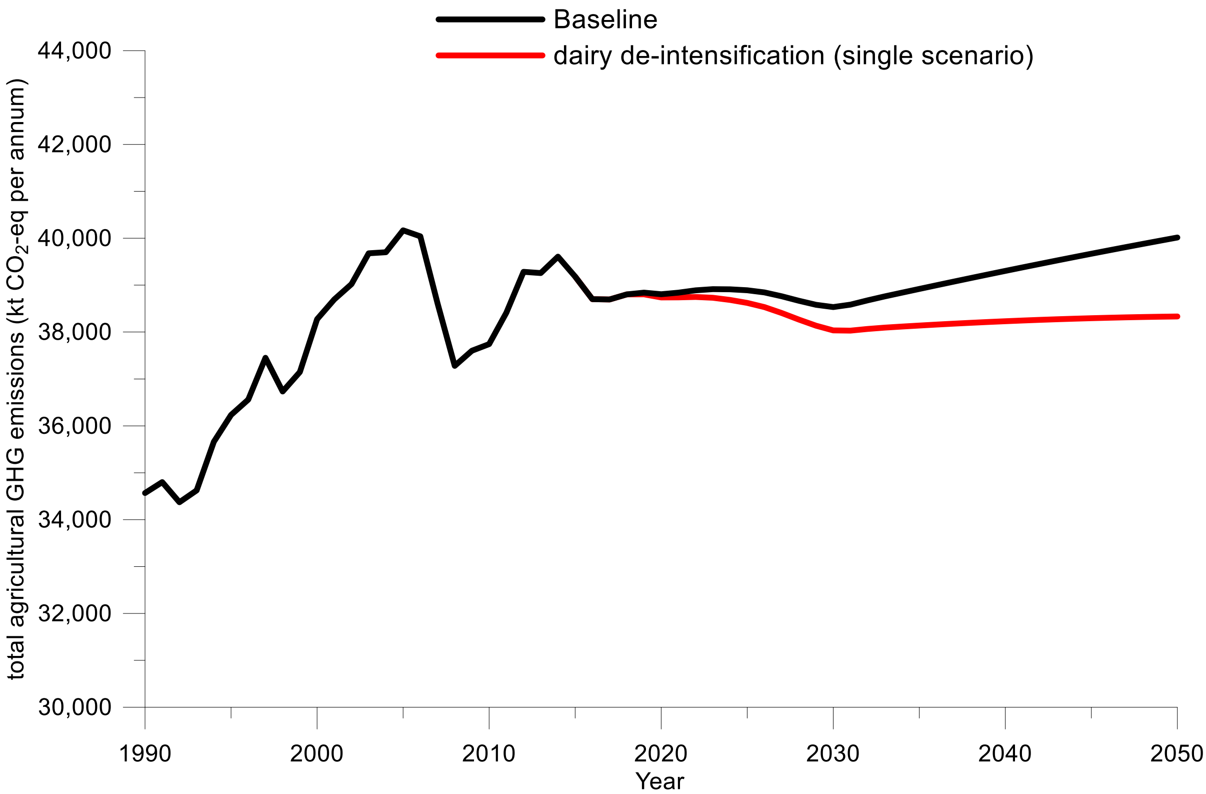

Figure 13: Total emissions in the MPI baseline and with de-intensification of the dairy sector (see text for details).

2.11 Once-A-Day milking

Once a Day Milking (OAD) is a decision by dairy farmers to only milk a herd once a day throughout the season. There are a number of variations for reducing the frequency of milking from the common twice-daily, with some farmers beginning the season milking twice a day and reducing to OAD at the end of December, or others milking every 18 hours (three milkings in two days).

The main effect of reduced milking frequency (for simplicity referred to as OAD throughout) on emissions is a reduction in daily milk yield per cow, resulting in reduced energy demand by cows and hence reduced emissions. The economic impact of reduced production may to some extent be compensated by reduced input costs.

When could it become available?

Once a Day milking is currently available and it is estimated that between 5 and 10% of dairy farms currently use OAD milking. Some farmers use OAD strategically as it best suits their property size and shape, milking shed configuration or the particulars of running their business. It is also commonly undertaken as an intervention when feed is short (such as during a drought) or other unforeseen events such as a labour shortage, or high numbers of lame or sick cows.

While currently available, there have been few systematic research trials conducted on OAD. As OAD milking is suited mainly to farms of low intensity, it is unlikely to be adopted by more than about a third of the industry. Farms in Canterbury and Otago-Southland, farms with Friesian cows and/or high input systems elsewhere producing high milk solids per cow will be unlikely to adopt OAD for the whole season. In these cases, negative business impacts from reduced production would likely outweigh cost-saving benefits.

In summary, we have:

- ***very high confidence* that OAD milking is currently available and will be available in future as a mitigation option for up to about one third of New Zealand dairy farms**

What would be its impact?

From a climate change perspective, OAD milking would reduce GHG emissions only to the extent that animals consume less feed, as a result of lower overall milk production. Although some farmers have managed to maintain milk production, in most cases it is expected that this would drop by a few percent. It is still recommended to feed cows that are on OAD milking the same amount, which may result in increasing body condition and reduce the benefits for reduced emissions or energy savings from less feed requirements. However, this may be a transitional measure rather than a permanent feature since it would not make sense for cows to increase body condition indefinitely. The benefits from OAD milking are widely known.[14] Apart from reduced feed demand as a result of lower milk production, there are also other emission and energy savings from one less milking per day. For example the amount of effluent in the cowshed and water used for wash-down, which is also a source of emissions from effluent disposal is halved. There is also less energy used to run the cow shed, cool the milk and less vehicle running for bringing the cows in, and fewer tanker loads of milk transported on the road. At the same time, one less milking means more urine being deposited directly on pasture, which may limit the indirect emission benefits and reduces options to manage manure emissions and nitrate leaching.

Some farmers are managing to increase pregnancy rates and hence reduce replacement rates as a result of increasing body condition of cows. Some farms may increase stocking rates when moving to OAD. If stocking rates are increased to compensate for the reduced milk production per cow, then

[14] https://www.dairynz.co.nz/milking/once-a-day-milking/full-season-once-a-day-oad-milking/

this will eliminate any GHG reductions and could even result in an increase in overall emissions as the OAD cows are less efficient. Overall for the average farm, reductions in GHG emissions from moving to OAD are expected to be around 5%, depending on animal performance, replacement rates and consequential adjustments to stocking rates and feed inputs.

For the purpose of this report, we assume two scenarios. First milk production per animal would reduce by 10% initially reducing to 5% by 2050 as animals better adapted to OAD dominate the herd. Stocking rates are kept at the same level as during twice a day milking, but replacement rates are reduced by 4 percentage points compared with the baseline.

What are drivers, barriers and likely rates of adoption?

The limited systematic trials mean that information about costs, benefits, drivers and barriers for adoption of OAD milking remains somewhat anecdotal, but a few messages can be summarised:

- **Cost/benefit to farmers:** the main cost to farmers is the expected reduction in milk production from the property over the year. Some herds and properties are more suited to OAD than others, and selection for the best performing animals means that the drop in milk production could be greater during the first few years of the transition than in the long term. The drop in milk yield is expected to be from 5 to 15% in the first year, but over time production may increase again to close to where it was with TAD milking. The benefits to farmers include reductions in farm working expenses, particularly less money spent on wages, vehicles, fuel, power, veterinary bills, breeding and race and paddock management and maintenance.
- **Market or regulatory drivers or barriers:** Given the generally lower inputs, OAD can be promoted as a move towards sustainability by the industry. It could also make dairy farming more attractive to the labour market with shorter hours, so there are some co-benefits for labour.
- **Environmental trade-offs or co-benefits:** OAD milking is inherently less resource intensive, with lower demand for water and energy associated with milking. Effects on animal welfare are mixed, with lower replacement rates but higher pressure on animals that get milked once a day only with similar milk yields. Benefits in terms of nutrient losses could be mixed; OAD reduces pressure on storage of manure collected in the milking shed but means that more N is deposited directly by animals on pasture.
- **Fit with farm:** OAD milking suits mainly farmers looking towards de-intensification not only in terms of feed but also labour inputs and capital investment, and is therefore dependent on the overall business development strategy.
- **Universality of applicability across different NZ farm systems:** we consider that OAD milking is plausibly applicable only to dairy farms that produce less than 400 kg MS/cow, herds in the North Island and West Coast South Island and Crossbred or jersey herds. Farms that have long walking distances for cows to the milking shed are most suited as these offer the most significant savings.
- **Ease of monitoring and accounting:** it is relatively difficult to predict the benefits in terms of reduced emissions, given the number of variables and management choices that determine final outcomes, and reductions are expected to be only a few percent. However, accounting at farm and national inventory scale would be straightforward as ultimately GHG emissions depend on total milk production and associated feed intake.

Summary of drivers for and barriers to adoption of once-a-day milking in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
OAD milking				Co-benefit		

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

As a mitigation scenario, we assumed that 5% additional farms could move to OAD milking immediately, and by 2030, a low estimate of 10% and a high estimate of 30% of farms could adopt OAD milking. The same percentages were kept for 2050 since the potential scale of adoption is not primarily driven by technological progress but the overall economic balance of farms.

We assumed the same percentages for adoption in a package of interventions combined with de-intensification (see Section 3), since farm size and animal performance is not the sole, and possibly not even the main driver for adoption since farmer goals and labour supply also play key roles.

by when	Reduction in milk production (resulting in lower GHG emissions)	adoption rates
Now	5% - 10%	5%
2030	5%	Low 10%, high 30%
2050	5%	Low 10%, high 30%

Results

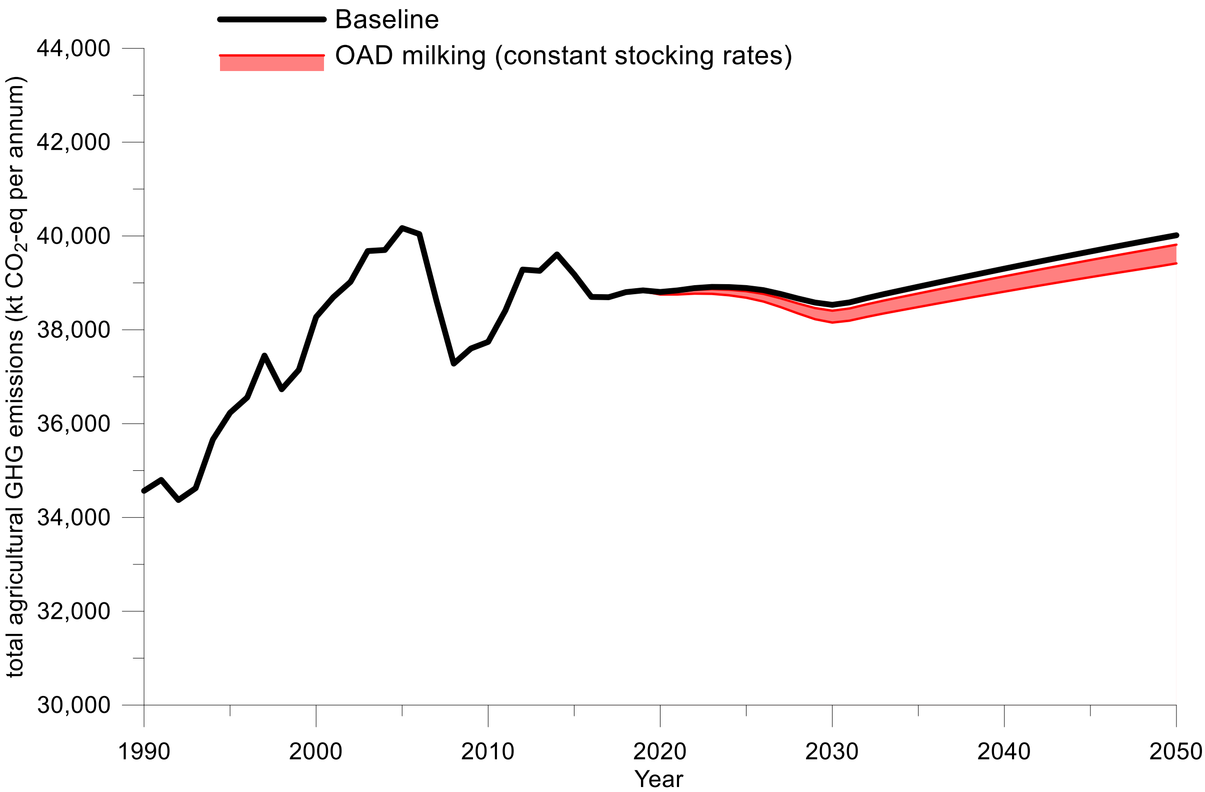

Figure 14: Total emissions in the MPI baseline and with once-a-day milking applied (see text for details). The shaded area indicates the range of outcomes under high and low uptake. The upper end of the shaded area corresponds to low uptake, while the lower end of the shaded area corresponds to high uptake. If stocking rates are adjusted such that total milk production remains as in the baseline, which would increase total emissions marginally but results are indistinguishable from the baseline and not shown in this graph.

2.12 Removal of breeding beef cows

This option considers the potential to reduce emissions from beef systems by reducing the number of breeding beef cows and making greater use of surplus calves from the national dairy herd. The beef sector is already strongly integrated with the dairy sector, but even greater reductions in beef cow numbers would be possible based on the number of surplus dairy calves that are currently produced but not finished.

When could it become available?

New Zealand currently has about 1 million breeding beef cows, down from about 1.4 million in 1990. At the same time, total beef production increased by about 20% above 1990 levels. These changes reflect both improvements in performance (increased fertility rates and weight gain) but also increased use of surplus dairy calves as a source of young stock into the beef sector. Most farms that have moved in this direction tend to focus on finishing bulls (offering the highest product prices), with some also finishing heifers and steers. At present, it is estimated that the beef sector imports just under half a million calves from the dairy sector and finishes them for meat, but almost 2 million bobby calves are processed without finishing.

In theory, the option for moving further in this direction therefore is well established. Artificial insemination and semen sexing offers the potential to produce calves from the dairy sector with higher beef values and reduce costs, and these options can be expected to increase with further advances in genetics and breeding techniques.

The further reduction of breeding beef cows, and additional import of surplus calves from the dairy herd, will reduce total GHG emissions since fewer cows need to be carried. However, the emission reductions to be expected would be quite small (only a few percent), since it is assumed that the available pasture would be eaten by finishing rather than breeding animals.[15] The largest gains from such a shift would lie in the reduced emissions intensity of beef production (i.e. significantly lower emissions per kg of meat), and possible increases in farm profitability per hectare.

The biggest question is how much further breeding beef cow population could be reduced before other qualities of beef cows (in particular their ability to make use of low-quality pasture and control the spread of weeds), and whether farmers have the ability and willingness to manage bulls (requiring upgrades in infrastructure and more intensive management practices).

The MPI baseline scenario already envisages a further 14 percent drop in the number of breeding beef cows from currently about 1 million to about 860,000 in 2030. Given the important services of breeding beef cows to manage pasture quality especially during autumn and winter, we consider that this drop largely exhausts the potential for change.

In summary, we have:

- ***very high confidence*** **that further reductions in breeding beef cow numbers are possible in principle, but consider that the MPI baseline largely exhausts the potential for further changes within the current extent of beef systems**

Significantly greater reductions than what is already implied in the MPI business as usual scenario would imply substantial land-use change (i.e. reduction of beef farming as an activity), which was not considered within this report. This mitigation option was therefore not modelled quantitatively for this report and the above summary is included merely for completeness.

[15] See separate report to the BERG: Reisinger et al. (2017), On-farm options to reduce agricultural GHG emissions in New Zealand. MPI Wellington, pp69.

2.13 Increased tree planting

This option considers the potential to incorporate more trees into the pastoral landscape in ways that would not negatively affect overall livestock production. This includes planting trees and natural reversion on paddock margins, sidlings, riparian strips, erosion control plantings, and biodiversity projects. Many such plantings would not currently meet the definition of afforestation in the ETS[16] but are considered here since they would nonetheless constitute real carbon sinks. Most of those trees would not be intended for harvest but some of these plantings could be used for bioenergy. Expansion of the accounting approach would also incur liabilities for any clearance of vegetation on farm land that is not currently counted in the ETS or included in the national GHG inventory.

When could it become available?

Planting trees for shelter belts and along riparian strips, for erosion control and biodiversity projects are all well-established practices. The potential exists for more trees and other plants (lower growing plants under irrigation centre pivots) to be planted in our pastoral landscape without a negative impact on the productive potential of farms. The majority of New Zealand farms were historically mostly cleared of trees, and in recent times shelterbelts in the Canterbury Plains were removed to make way for centre pivot irrigators and other bigger machinery. Where centre pivot irrigation is installed replanting could take place on the paddock edges, with lower growing plants underneath the irrigators.

The advent of remote driverless farm equipment may reduce the trend towards large machinery on pastures, which means that shade trees in the middle of paddocks will no longer be a hindrance.

We do not consider in this scenario the targeted large-scale planting of novel exotic or indigenous trees for harvest, or more dedicated agro-forestry approaches. Such approaches would reduce livestock production but could maintain overall farm profitability and resilience of farm systems from the more diverse income streams, considering land-use suitability and optimisation across all pastoral land (including e.g. Manuka for mixed carbon and honey income streams). Such strategic land-use change options towards high-value forestry or carbon-sequestration focused planting were outside the scope of this report but to our knowledge are addressed by other reports prepared for the Biological Emissions Reference Group.

In summary, we have:

- ***very high confidence*** **that increased tree planting can take place on established farms that would bring co-benefits for livestock and/or other environmental objectives and would not impact negatively on livestock production**

What would be its impact?

The main question is how many trees can be planted into a farm without affecting its primary livestock production. This will obviously differ between farm types and depend heavily on individual farms (topography, layout, existing trees, and water courses). Subsequent questions are how much carbon the different tree species might be able to sequester, and the extent to which this could ever be accounted for in domestic let alone international systems.

Riparian plantings are a key example of current efforts to increase trees especially on dairy farms. However, since the main driver for this is the protection of water quality, we assume that such

16 Under current definitions, forests eligible for carbon credits and as defined in the national GHG inventory must be a minimum of 30 metres wide and cover one hectare, with the crowns of the trees covering more than 30% of each hectare, and the trees must have the potential to grow to a height of at least five metres.

plantings will continue to increase in future without additional incentives from climate policy, and their additional impact on total carbon storage may be limited.

Instead for dairy farms, we focus on the ability to plant additional trees on paddocks and along paddock margins to provide shade and shelter, on sidlings and small non-productive areas. While the potential for this will obviously vary significantly from farm to farm, we estimate that perhaps up to 15 trees could be planted per hectare on some farms. If we assume that the tree species for this would be poplar, this approach would give (as a very rough estimate) approximately 0.9 t CO_2 sequestration per hectare and per year, offsetting about 7% of the biological GHG emissions of about 12.6 t CO_2-e per hectare from an average Waikato dairy farm.[17] The percentage of biological emissions that a given amount of trees can offset depends on the farm intensity and differs between farm types and regions.

The feasible planting rate that does not constrain production may be considerably lower for some farms, and we use a high scenario with 15 stems/ha and a low scenario with half that amount. Note that this would be a one-off sequestration option, based in the above estimate on a period of 30 years. Additional sequestration beyond this time horizon would depend on continued tree growth (which depends on species, climate and exposure) and whether additional trees are planted once the initial planting has matured.

Soil carbon under forests is typically lower than under pastures and this loss would have to be taken into account; however, for sparse trees, there could also be benefit to soil carbon in pasture areas that are more sheltered from wind and excessive drying; for the purpose of this estimation we did not consider a change in soil carbon associated with such plantings. Many other tree species could be suitable for such plantings. We assumed a poplar species simply to allow us to make a rough estimate, not as a recommendation for poplars as preferred trees for such purposes.

A major implication of adopting such an approach would be that farmers that wish to remove individual trees or other woody vegetation (including scrub) on what currently is considered grazing land would become liable for the carbon lost (e.g. clearing land for more intensive farm operations). We have not evaluated the net benefits or costs from such a change in accounting approaches, nor the costs of monitoring if the accounting were to occur at the level of individual or sparse trees.

On sheep and beef farms, there is much higher potential to plant small blocks of unimproved land into trees without significantly affecting overall production of the farm. In some cases, this land will be steep and not suitable to harvest, whereas in others harvesting would be possible. To get a sense of magnitude, for this report we assume that about 6% of current sheep and beef land (amounting to about half of the unimproved land on a typical farm) could be planted in trees, with half of this intended for harvesting and the other half planted for conservation purposes. For the purpose of this estimate, we assume that such planting or revegetation would occur on land that is currently considered grazing land and hence would be counted as land-use change and potentially eligible for carbon credits under the ETS and visible in the national GHG inventory.

For an average North Island sheep and beef hill country farm, afforestation as outlined above would result in the sequestration of about 6-12.7 t CO_2 per hectare per year from plantation forestry

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17 This estimate is based on Guevara-Escobar et al (2002), *Soil Research*, 40(5), 873-886, indicating a carbon sequestration rate of 2.3 t CO_2/ha/year for a poplar planting at 37 stems/ha. We assumed that the sequestration rate scales linearly with the number of stems per hectare for sparser planting and that there are no negative impacts on pasture production and soil carbon at 15 stems/ha. This is an indicative estimate only. Note that wood density and thickness varies widely among poplar species and even more if other tree species were chosen.

averaged over a 28 year harvest cycle[18]. Note the assumptions underlying those numbers are conservative; commercial forestry operations often exceed the amount of carbon stored we have assumed, and those commercial figures exclude carbon stored in harvested wood products. If harvested wood products are included, then the average carbon sequestered over successive planting and harvest cycles can be as high as 600 t CO_2 per hectare[19], or about 21 t CO_2 per hectare per year over the same 28 year period. Regardless of the specific assumptions accounting approach, radiata plantations constitute a one-off mitigation option extending over a period 28 years. After this period, the mitigation would cease unless additional land is planted.

By comparison, planting indigenous forests would sequester carbon at a lower rate of about 6.4 t CO_2 per hectare per year, but averaged over the first 50 years after planting. Conservation forests continue to accumulate well beyond 50 years albeit at declining rates. Conservation forests thus constitute a more long-term mitigation option but at lower rates than what can be achieved with radiata plantations.

From an inventory perspective, a reduction in soil carbon stocks when trees are planted on pasture land also needs to be taken into account.[20] This reduces the above net sequestration rates to 4.2-10.9 and 4.6 t CO_2/ha for radiata plantations and indigenous forest, respectively. Even though land-owners are not liable for soil carbon losses under the ETS, we include soil carbon losses to reflect the changes that would be seen at the national scale in the GHG emissions inventory and international reporting.

These sequestration rates, each applied to 3% of the total farm area, would offset 7.5-13.2% (depending on accounting approach) of the biological GHG emissions from an average North Island hill country sheep and beef farm of about 3.5 t CO_2-e per hectare per annum. If commercial forestry practices are assumed for radiata plantations and carbon stored in harvested wood products is included in the overall accounting of the average carbon stored over successive harvesting cycles, the percentage removal from the same forest areas could be as high as 20%.

For the purpose of this report, we assume that

- **7.5-15 poplar trees per hectare could be planted on the average dairy farm,**
- **6% of the land of the average sheep and beef hill country farm (excluding tussock areas in the South Island) could be planted in trees, with half of this area planted for harvesting (using different accounting approaches) and half for conservation purposes,**

without negatively impacting on the overall livestock production of those farms. Carbon sequestration rates for forestry activities on sheep and beef land were calculated using MfE look-up tables, which are conservative and exclude harvested wood products.

18 Country averages based on MfE look-up tables for radiata pine. Note there are significant variations between regions, and estimates from look-up tables generally are conservative. Sequestration of 6 t CO_2 per year reflects the 'safe carbon' level, i.e. the minimum amount of carbon that remains on and in the ground when the trees are first harvested and replanted. Accounting instead for the *average* carbon sequestered over successive harvest cycles would increase the amount sequestered to about 12.7 t CO_2 per year over 28 years. However, this averaging approach results in a temporary liability at each harvest and surplus carbon just before harvest. We use both approaches to obtain a low and high estimate for radiata pine plantations.

19 See PCE (2016), Climate change and agriculture: understanding the biological greenhouse gases. Parliamentary Commissioner for the Environment, Wellington, pp100

20 The steady-state carbon stock in grasslands is 105.66 tC/ha, while that of post-1989 forest land is 91.92 tC/ha (Table 6.3.2, MfE 2016). As a result, converting pasture into forest results on average in an overall loss of soil carbon of 13.74 tC/ha (50.38 tCO_2/ha), or 1.8 tCO_2/ha/yr spread out over a 28-year harvest cycle. This loss occurs only once and would not be repeated for subsequent rotations.

What are drivers, barriers and likely rates of adoption?

There are potentially strong incentives for farmers to plant trees driven by animal welfare perspectives, climate resilience benefits, for soil and water conservation purposes, possible economic benefits and both consumer and farmer interest in biodiversity. However, disincentives exist in terms of lack of knowledge and experience for some farmers, initial costs and reduced land-use flexibility (including reluctance to compromise easy irrigation), as well as regulatory uncertainty about carbon returns and the ability to remove trees at future times.

- **Cost/benefit to farmers:** apart from direct financial costs, a major constraint is the time to undertake plantings, as well as investment in fencing and protection (although these may be offset by reduced labour to manage marginal lands). Benefits include animal welfare (translating into production benefits), soil and water conservation (especially in the context of climate variability and change), alternative income streams, for example from honey but also visual appearance of the farm. While the latter is difficult to monetize it can have an important effect on farmer well-being and ability to handle stress. Other barriers will be lack of knowledge and experience, including knowing what trees to plant for what effect, and how best to integrate into the farm without affecting farm operations or production.
- **Market or regulatory drivers or barriers:** Consumer expectations around animal welfare and biodiversity can act as important drivers. Tree plantings may also support climate-friendly branding, but depend on the ability to formally account for the sequestration they offer.
- **Environmental trade-offs or co-benefits:** Co-benefits arise particularly for biodiversity, including e.g. the 'Trees for Bees' programme. There may be mixed results with regard to nitrate leaching, as on one hand stock may end up 'camping' under trees, which depending on their location could result in higher nitrogen loading with increased risk of run-off, but trees can also help sequester additional nitrogen. The net effect will depend on individual circumstances including tree locations, farm topography, climate, stock type and behaviour.
- **Fit with farm systems:** the approach fits a growing focus on diversification, animal welfare and demonstrating other environmental benefits of trees on farms such as biodiversity and catchment protection. Research is looking into turning woody plants into bio-energy, and cuttings could be fed into bio-digesters. There is also potential for specialist timbers and honey production in some systems.
- **Universality of applicability across different NZ farm systems:** every farm has unique features, but the approach in principle can be applied on all farm systems. The biggest challenge will be around centre pivot irrigators, and farms with a more varied topography tend to have greater opportunities. The most suitable trees will depend on region and soil type, as well as particular biodiversity goals or end-uses for bio-energy or timber.
- **Ease of monitoring and accounting:** The major barrier from a carbon perspective is that currently individual and highly sparse trees cannot be counted under the NZ-ETS or international accounting rules. However, it is conceivable that with improved mapping using remote sensing and drone technologies the technical barriers to accurate accounting could be removed; it would then be a political decision whether to provide carbon-based incentives for farmers even if these don't match international GHG accounting rules. We are not in a position to comment whether international rules have any prospect of recognising such sparse plantings in the near or even more distant future. A major implication of this approach would be that farmers could become liable for carbon lost if individual trees or other woody vegetation that don't currently meet the definition of a forest are cleared on their properties. Accounting for carbon stored in individual trees, or woody vegetation too sparse to meet the current definition of forest land, could thus create significant debits for

some land-owners while benefitting others. The feasibility as well as costs of monitoring such changes at national scale would also need careful consideration.

Summary of drivers for and barriers to adoption of increased tree planting in 2030:

	Cost/benefit	market	environmental	System-fit	Universality	Monitoring
Trees on dairy farms			Co-benefits			
Small-scale plantings on S&B farms			Co-benefits			

See Section 2.1.2 for an explanation of the colour coding of risks to adoption

What did we assume in our mitigation scenarios?

Since the national GHG inventory tool is not a spatial tool, we assume that the above sequestration rates scale at national level to a CO_2 sequestration of 3.5-7% CO_2 of total dairy emissions in 2015, and 7.5-13.2% of total sheep and beef emissions in 2015 (low and high estimates). Note that high assumption for sheep and beef is based on accounting for the average carbon sequestered in plantation forests over multiple rotation cycles. This entails a liability for carbon lost when trees are harvested, which is re-generated in the next rotation.

We assume that the additional planting begins gradually after 2015, such that the full annual sequestration potential is achieved by 2030 and sustained at a constant annual rate to 2050. We emphasise our assumptions are rough estimates, intended only to derive the approximate magnitude of this mitigation approach at national scale and in comparison with other options, not a detailed assessment of the potential on individual farms.

We use the conservative assumptions about carbon sequestered in forests on sheep and beef land using the official look-up tables, noting that commercial operations could achieve higher sequestration rates and that accounting for harvested wood products could further increase sequestration achieved over successive harvest cycles. At the same time, we assume an accounting scheme that includes credits for individual trees planted on dairy land but does not generate any additional debits arising from the clearance of individual trees, scrub or other woody vegetation. We were not in a position to quantify the net effects of those alternative assumptions and emphasise that the numbers generated by this scenario should be viewed as indicative and exploratory only.

by when	CO_2 sequestration	adoption rates
Now		Starting now and being upscaled linearly to 2030
2030	dairy: individual trees on margins (poplars as example) sheep/beef: small-scale plots (plantation and conservation)	dairy: 7.5-15 trees per hectare sheep/beef: 6% of land area (3% radiata for harvest (safe/average carbon), 3% indigenous for conservation), with sequestration rates from look-up tables
2050	same as 2030	same as 2030

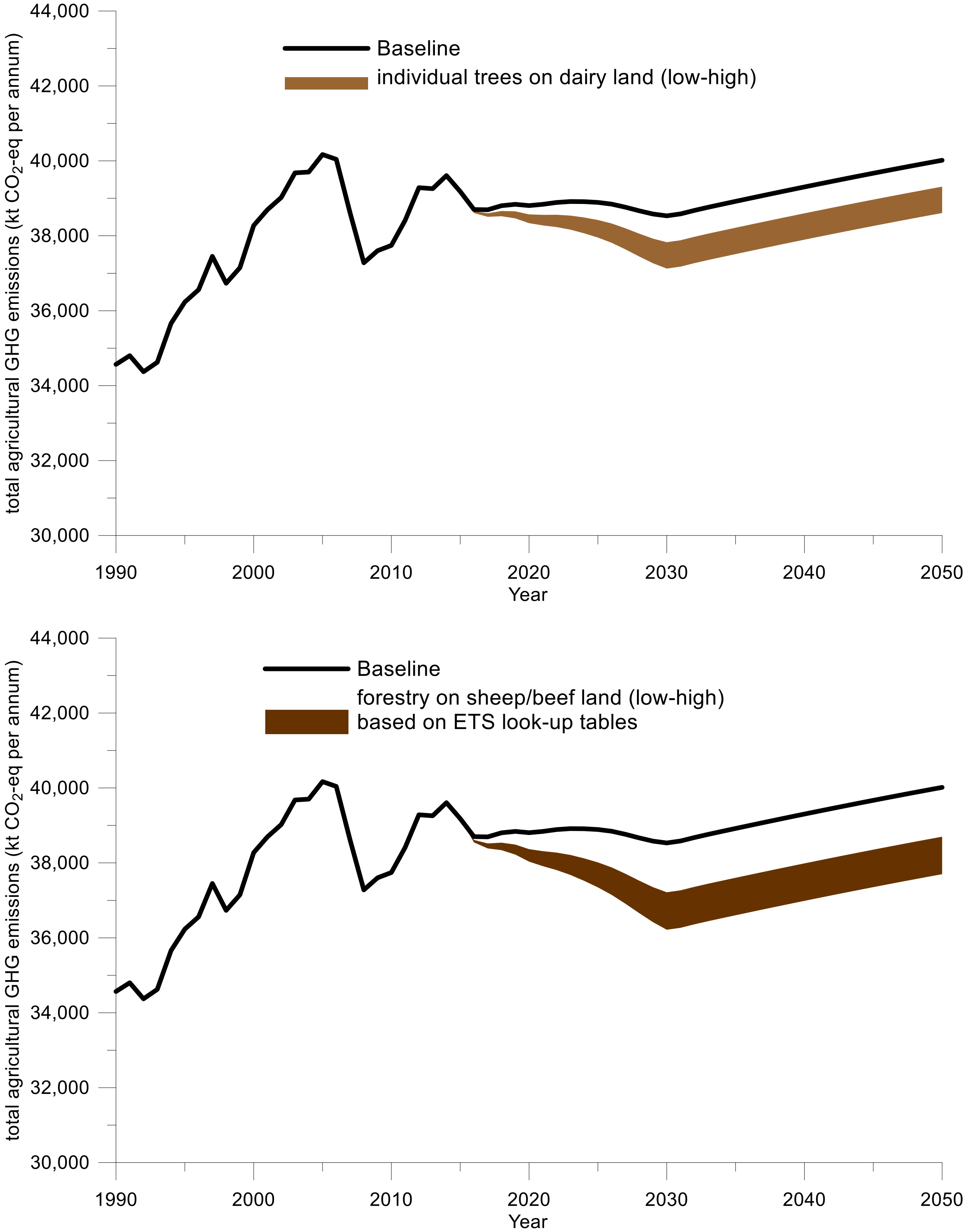

Figure 15: Total emissions in the MPI baseline and with additional tree planting, low and high sequestration scenarios. Top panel indicates potential for individual (sparse) trees on dairy land, and the bottom panel indicates the potential for forestry blocks on sheep and beef land (see text for details).

3. Packages of mitigation options

3.1 Overview

A critical question for overall mitigation outcomes is which of the individual mitigation options could be combined with others, and whether their effect would be additive or offers diminishing returns.

The effect of mitigation options targeting the same emission source can obviously never be additive in absolute terms e.g. if breeding low-emissions animals reduces enteric CH_4 emissions by 15%, and application of an inhibitor reduces enteric CH_4 emissions by 30%, then the total emission reduction that can be achieved by a combination of both interventions would not be 45% of the baseline enteric fermentation emissions, but only about 40%.[21] In practice, the adoption of mitigations will not be spread uniformly – some farmers may adopt one mitigation option and other farmers may adopt another one. In our calculations, we assume conservatively that mitigation options that address the same source (e.g. CH_4 from enteric fermentation) will always have reduced combined efficacy. The actual mitigation effect may be slightly greater if adoption of different mitigation options is spread across different farm types but we have not quantified the potential gain.

In terms of overall emissions reductions, it does not matter in which order mitigations that address the same emissions source are applied. However, if several mitigation options are presented in a so-called wedge diagram showing their cumulative mitigation effect, then the order in which they are applied influences their ***apparent*** contribution to the overall reduction. This is illustrated in Figure 16, which shows the apparent contribution to the overall mitigation outcome if breeding is applied first and then an inhibitor, or if an inhibitor is applied first and then breeding.

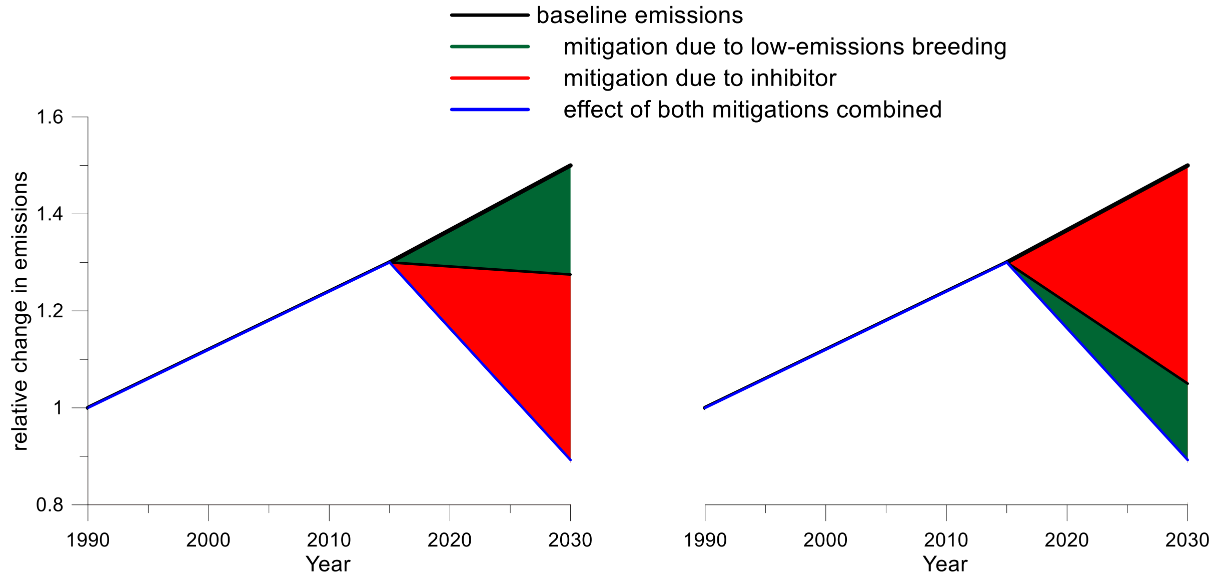

Figure 16: illustration of the different apparent contributions of individual mitigation options to the overall mitigation, depending on the order in which they are applied. In the left panel, low-emissions breeding is applied first followed by an inhibitor, whereas in the right panel, the inhibitor is applied first followed by breeding. The contribution from breeding to the total mitigation outcome appears significantly greater in the left-hand panel than in the right-hand panel, even though the relative mitigation efficacy of both options is the same in both panels.

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21 Using low-emissions animals at a mitigation efficacy of 15% would result in enteric CH_4 being reduced to 85% of the baseline emissions, and an inhibitor would then remove 30% of those emissions, leaving 0.7 × 85% = 59.5% of the baseline emissions, or a 40.5% reduction relative to baseline.

There is, however, a biological logic in that an inhibitor can only be applied to the CH_4 that is actually emitted by an animal, meaning that biologically, low-emissions breeding (which influences the amount of CH_4 an animal generates in its rumen) should be applied *before* an inhibitor is then applied to further reduce the CH_4 that the animal would have generated naturally. From an implementation perspective, it could make sense to visualise an order of mitigation options from easiest (or cheapest) to hardest (or most expensive). Yet another sequencing option is to show mitigation options based on the timing of, or confidence in, their future availability.

For this report, which deals with mitigation options that have widely differing levels of technological and commercial maturity, we show first the mitigation options where we have the highest confidence in their availability in 2030, followed by those with lower confidence. We use the biological logic to order mitigation options where we have the same confidence in their availability.

As noted above, different sequences affect the apparent contribution of individual options to the total outcome, with the mitigations done first always having an apparently bigger effect on the total mitigation than those done last (if they tackle the same emission source, e.g. enteric methane). We re-iterate that this is not the case, and wedge diagrams should not be relied on to determine the importance of individual mitigations to achieve the overall outcome.

Some mitigation options may not only tackle the same source but even address the same underlying mechanism, e.g. a CH_4 inhibitor and a CH_4 vaccine would both seek to alter the population of methane-producing micro-organisms in the rumen. In our mitigation packages, we therefore assume that applying both a CH_4 inhibitor and vaccine would not increase the overall mitigation efficacy, but that this would increase confidence that the combined approach indeed works and increase uptake across different systems. For quantitative modelling, we assume the efficacy and adoption rates for an inhibitor only, but consider this to encompass both technologies.

Some individual mitigation options would be contradictory to each other, since they assume opposing changes in farm systems. For example, once-a- day-milking would not be a viable mitigation option if combined with an increased use of supplementary low-emissions feeds, since OAD is effective in less intensive systems while the latter approach generally relies on more intensive production systems. On the other hand, some mitigation options can be synergistic, e.g. general de-intensification of the dairy system would imply a greater percentage of farms with lower performance per animal (based on current performance of different systems), and hence a greater chance of adopting once-a-day milking.

In practice, a wide variety of 'packages' of mitigation options could be constructed based on the individual options considered in Section 2. In this report, we present one overall package that combines the use of increased performance and efficiency, low-emissions feeds and breeding, and CH_4 and N_2O inhibitors as well as tree planting, reflecting an agricultural system that continues to emphasise performance and total production.

We also show an alternative package built around de-intensification of the dairy system only, showing an alternative mitigation approach based on de-intensification and once-a-day milking, plus interventions that appear plausible in such a reduced-intensity agricultural system.

As this alternative dairy mitigation package includes no mitigation of the sheep and beef sector, we also show the mitigation that would be achieved by the full set of options for the sheep and beef sector only, without mitigation in the dairy sector.

Together, these packages show possible and, in the case of dairy, alternative (but not mutually exclusive, as different farms could chose different paths) approaches to mitigation in the dairy, sheep and beef sectors. We emphasise that the upper end of assumed efficacy and adoption rates in these packages are highly ambitious, including the use of some mitigation options that have not yet reached proof of concept and their realisation would require technological break-throughs, confirmation of the assumed efficacies and in some cases regulatory changes.

3.2 A comprehensive mitigation package

This package considers the maximum feasible combination of mitigation options that were considered mutually compatible and consistent with current farming systems with increasing performance and total production as a continuing driver.

In detail, this package of mitigation options considers:

- Increasing performance
- Reducing N fertiliser use
- Increased planting of trees on farms (sheep and beef)
- Low-emission supplementary feeds (conventional)
- Breeding low-emissions animals
- Use of nitrification inhibitor
- Enhanced manure management
- Use of CH_4 inhibitor (and vaccine)
- Increased planting of trees on farms (dairy)
- Low-emissions feeds (GM ryegrass)

As noted above, this sequence follows our confidence that the individual mitigations options will be available in principle, and within this a biological logic from changing inputs first, then changing animals making use of inputs, and then changing ways to manage outputs (with trees being a separate measure). The use of a CH_4 inhibitor/vaccine is placed near the end of this sequence because even though we have medium-high confidence in an inhibitor being available by 2030 for grazing systems, the high efficacy and high adoption rates assumed at the upper end of our scenario are extremely ambitious. Trees on dairy farms are placed second to last due to the significant change in accounting this would require (assuming that trees on dairy farms would generally be too sparse to be counted as forests under current rules), and GM ryegrass as low-emissions feed is placed last given the absence of proof of concept plus significant regulatory change its use would require.

We note that there could be some tensions between mitigation options within this package, e.g. increasing performance of animals could make it more difficult to reduce the amount of N fertiliser used per animal (at least where fertiliser is used tactically to ensure high performance even during adverse climatic conditions). However, given that the overall contribution to emissions reductions from reduced N fertiliser use is small (where this is consistent with sustained total production), the overall results would be very similar with and without this mitigation included.

Figure 17 shows the total mitigation that could be achieved by this package under different assumptions about efficacy and adoption rates, using the maximum and minimum mitigation outcomes assumed in the discussion of each individual option. Figure 18 shows the contributions from individual mitigation options to the total mitigation outcome, for the maximum efficacy and adoption rate assumptions (note that the relative contribution depends to some extent on the order in which mitigation options are applied, see preceding discussion in Section 3.1).

The comprehensive package of mitigation options would reduce total biological GHG emissions from agriculture by 10-21% in 2030, and by 22-48% in 2050, relative to the MPI baseline projections.[22]

[22] This equates to reductions of 14-24% in 2030 relative to 2005 levels, and of 10-40% in 2050 relative to 1990 levels, but as noted in section 1.2, these emissions reductions relative fixed base years are less robust because they depend on uncertain baseline projections.

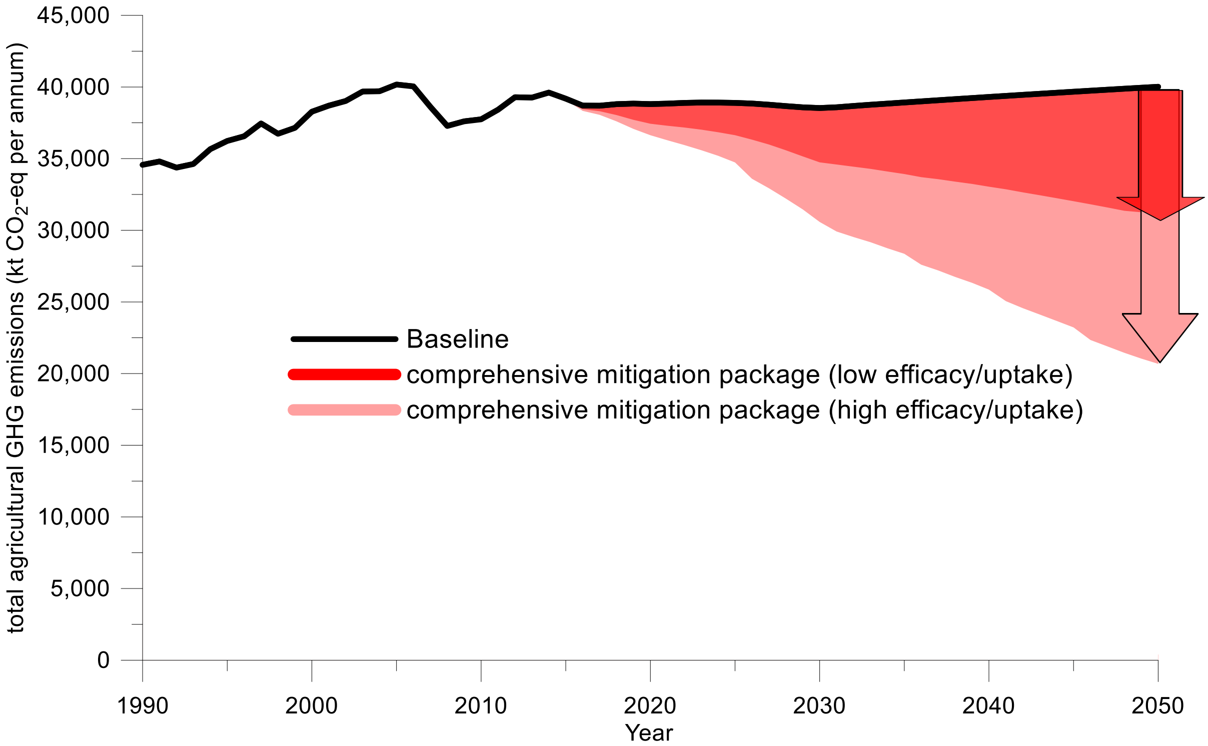

Figure 17. Effect of a comprehensive package of mitigation options across the dairy, beef and sheep sectors, relative to the MPI baseline projections. The shaded area shows the range of outcomes based on high and low assumptions about efficacy and adoption rates for all mitigation options. For details, see text.

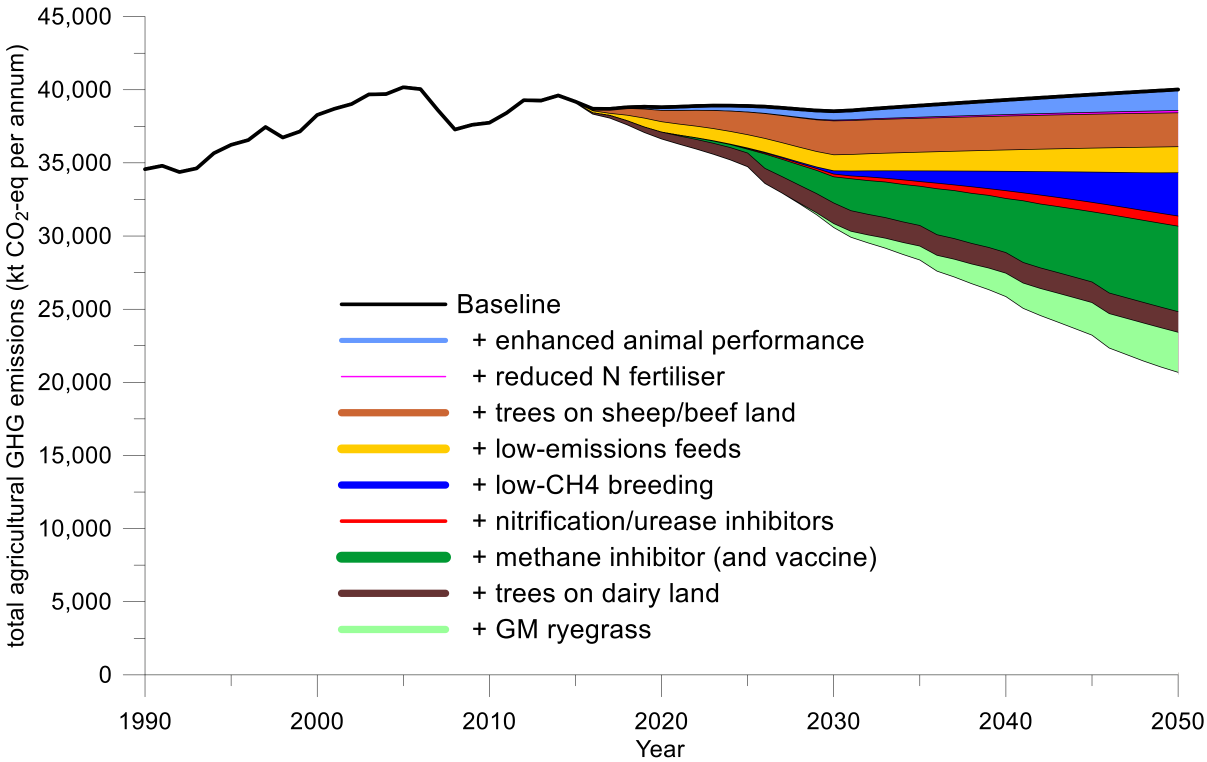

Figure 18. Cumulative effect of a comprehensive package of mitigation options for dairy, beef and sheep, for maximum assumptions about efficacy and adoption rates for each mitigation option. For details, see text.

Figure 18 shows that with high efficacy and adoption rates, about half of the total reduction in 2030 could be achieved by currently available technologies and practices, and the other half with technologies that are contingent on substantial further development and/or regulatory and inventory changes (methane inhibitors/vaccine, individual trees on dairy land, GM ryegrass). By 2050, the proportion of mitigation potentially delivered by novel technologies or approaches increases to three quarters of the total mitigation. The fraction of mitigation contributed by currently existing technologies would be greater at the lower end of assumptions.

Applying this package in full would have considerable consequences for the intensity of farm management as well potentially for infrastructure; e.g. significant increases in animal performance along with routine application of a CH_4 inhibitor to animals (whether at grazing or during milking) plus routine applications of nitrification inhibitors to pastures, increased use of low-emissions feeds, and enhanced manure management, all entail significantly more labour intensive and skill-demanding farm operations as well as in some cases an increase in the total labour force. While this is not impossible, targeted support and training programmes would be needed to turn this scenario into a feasible scenario. We reiterate that we have not been able as part of this report to estimate the impact of such a package of mitigations on farm profitability or the distributional effects on different farms. The key contribution of an inhibitor/vaccine to this mitigation package is noteworthy (Figure 18).

3.3 A package for dairy de-intensification

An alternative package of mitigation options for the dairy sector only is clustered around a general de-intensification approach, essentially reversing the intensification trend over the past two and a half decades. This package considers:

- Reduced N fertiliser use
- Dairy de-intensification
- Once-A-Day milking
- Low-emissions breeding
- Use of nitrification inhibitor
- Use of CH_4 inhibitor (and vaccine)
- Increased planting of trees on farms (dairy)

This package excludes the use of low-emission feeds since they generally depend on more intensive systems making use of supplements, as well as enhanced manure management. GM ryegrass is also excluded because less intensive systems have much lower rates of re-seeding, thus slowing any uptake of new grass species, and because we assume that a key driver for a de-intensification of the dairy system would be a focus on natural, grass-fed production systems and market claims. Farms milking only once-a-day would likely depend on a methane inhibitor being administered via a slow-release mechanism (and/or a vaccine) rather than during milking, given the lower frequency of milking and hence reduced efficacy over the course of a full day of an inhibitor. The methane inhibitor/vaccine is again placed near the end of the sequence largely because our limited confidence in the most ambitious assumptions regarding efficacy and adoption rates, which might be even more challenged in less intensive management systems.

While further improvements in animal performance beyond those already assumed in the baseline scenario certainly would be possible in lower intensity and OAD milking systems, our optimistic assumptions of total milk yield reducing by only 5% per animal in the long run under OAD to some extent already include such improvements. Hence increased performance beyond that assumed in the baseline is not included as additional mitigation option in this package.

Figure 19 shows the total mitigation that could be achieved by this package under different assumptions about efficacy and adoption rates, using the maximum and minimum mitigation outcomes assumed in the discussion of each individual option. Note that in this sectoral package, no mitigations are modelled in the sheep and beef sector. Figure 20 shows the contributions from individual mitigation options to the total mitigation outcome, for the maximum efficacy and adoption rate assumptions (note that the relative contribution depends to some extent on the order in which mitigation options are applied, see preceding discussion in Section 3.1).

This dairy de-intensification package reduces emissions from the dairy sector by 9-26 % by 2030 and 23-48% by 2050 and total biological GHG emissions from agriculture by 5–13% by 2030 and 15–28% in 2050, relative to the MPI baseline projections in those years.

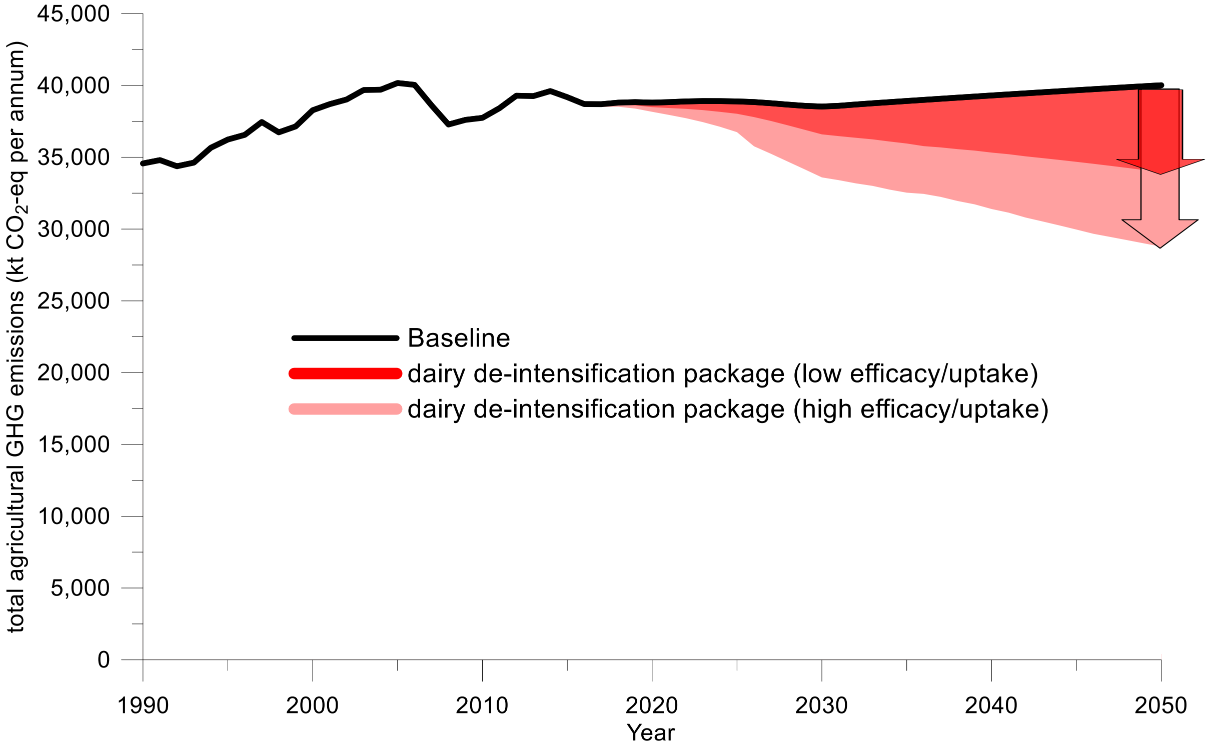

Figure 19. Effect of a package for dairy de-intensification, relative to the MPI baseline projections. The shaded area shows the range of outcomes based on high and low assumptions about efficacy and adoption rates for all mitigation options. For details, see text.

Figure 20 illustrates that this package of mitigations could lower total agricultural GHG emissions well below 1990 levels if rates of adoption and efficacy of individual interventions are at the high end of our range of assumptions. In this case, most of the mitigation is the result of de-intensification of the dairy sector together with applying highly effective CH_4 inhibitors/vaccine and low-emissions breeding, as well as tree planting. OAD milking and nitrification inhibitors have a more moderate effect on total emissions, with minimal additional gains from reductions in N fertiliser use per cow. This means that apart from the challenges and transitional costs associated with de-intensifying the dairy sector, which could be significant, the overall mitigation outcome in this package would still be highly contingent on successful development and application of as-yet-to-be commercialised mitigation technologies and accounting methods (for individual trees).

At the lower end of assumptions for mitigation efficacy and adoption rates, especially with a less ambitious outcome for methane inhibitors, dairy de-intensification and OAD milking would provide a greater share of the total mitigation achieved by this package (although we used only one scenario for dairy de-intensification and tree planting, and other assumptions, and hence contributions from individual mitigation options, would be possible).

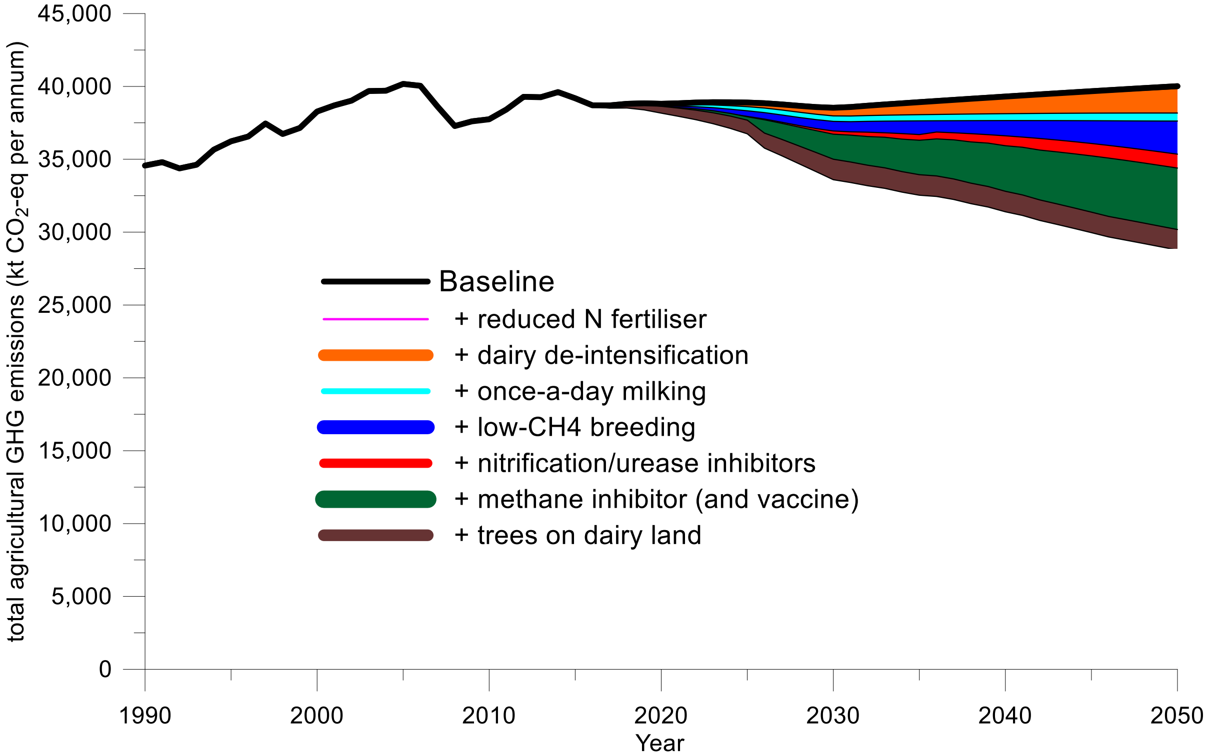

Figure 20. Cumulative effect of a package of mitigation options focused on de-intensifying the dairy sector, for maximum assumptions about efficacy and adoption rates. For details, see text.

3.4 A package for improving sheep and beef sector performance

For completeness, we present a package of mitigation options for the sheep and beef sector only, replicating the applicable individual mitigations included in the comprehensive package:

- Increasing performance
- Reducing N fertiliser use[23]
- Increased planting of trees on farms (sheep and beef)
- Low-emission supplementary feeds (conventional)
- Breeding low-emissions animals
- Use of nitrification inhibitor[23]
- Use of CH_4 inhibitor (and vaccine)

Reducing N fertiliser use is included in this package for completeness (since its applicability is not zero especially for intensive finishing systems), but the contribution to mitigation is negligible (less than 0.01% percent of total emissions). Nitrification inhibitors could potentially be applied to a small fraction of beef land, but this cannot currently be represented in the GHG inventory model and has not been included in the modelled emission reductions (the amount of mitigation would likely be less than 0.2% of total agricultural emissions). GM ryegrass is not included in this package for the sheep and beef sector due to the small area of beef land that is re-sown annually.

Figure 21 shows the total mitigation that could be achieved by this package under different assumptions about efficacy and adoption rates, using the maximum and minimum mitigation outcomes assumed in the discussion of each individual option. Note that in this sectoral package, no

[23] does not contribute appreciably to overall mitigation within our assumptions

mitigations are modelled in the dairy sector. Figure 22 shows the contributions from individual mitigation options to the total, for the maximum efficacy and adoption rate assumptions.

This sheep and beef package on its own would reduce emissions from the sheep and beef sector by 9-20% by 2030 and 17-36% by 2050, and total biological GHG from the agriculture sector by 4–8% by 2030 and 6– 14% by 2050, relative to the MPI baseline projections.

Most of this mitigation comes from increased tree planting, with the next highest mitigations from breeding low-emissions animals and use of an inhibitor/vaccine. If less conservative assumptions were used for carbon sequestered in radiata plantations (see Section 2.13), the mitigation from increased tree planting could be even greater. Performance improvements make a minor contribution, but this is partly because we were not able to model the mitigation that could be achieved by increasing weight gain and bringing forward slaughter dates (see Section 2.8). If this were included, we estimate that performance improvements could make a contribution comparable to that estimated for low-emissions breeding in Figure 22.

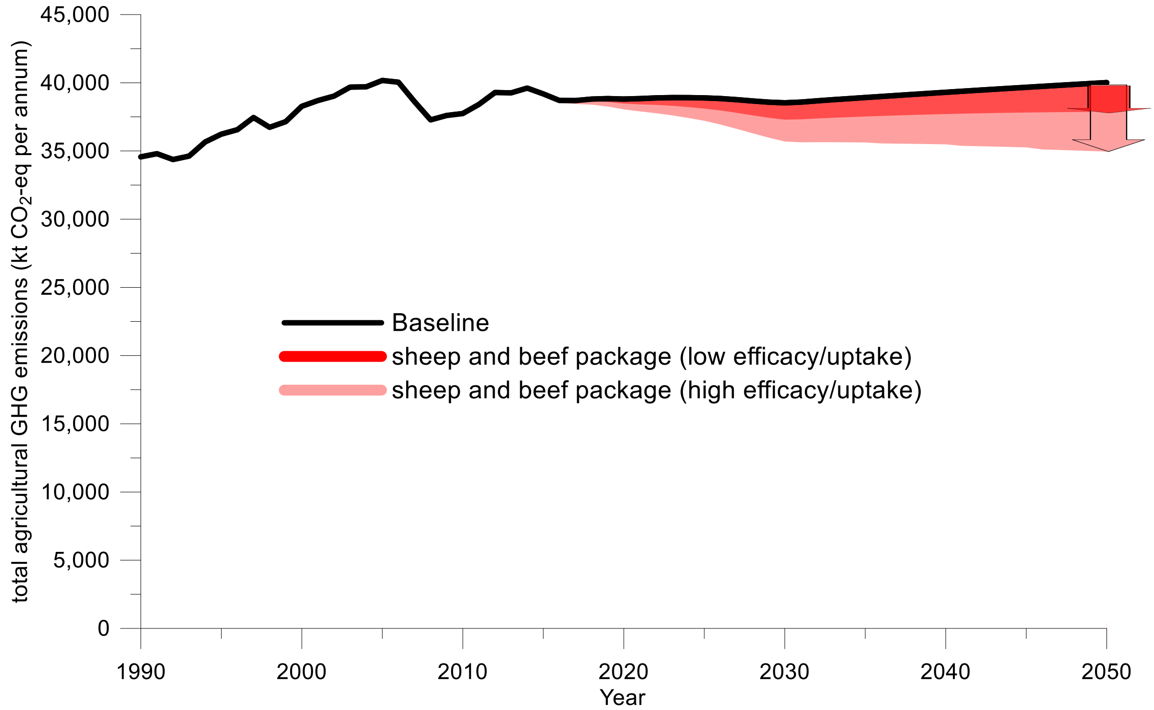

Figure 21. Effect of a package for the sheep and beef sector, relative to the MPI baseline projections. The shaded area shows the range of outcomes based on high and low assumptions about efficacy and adoption rates for all mitigation options.[24] For details, see text.

[24] The modelled mitigation does not include increasing weight gain and bringing forward the slaughter date (see Section 2.8) or the use of nitrification inhibitors (see Section 2.6).

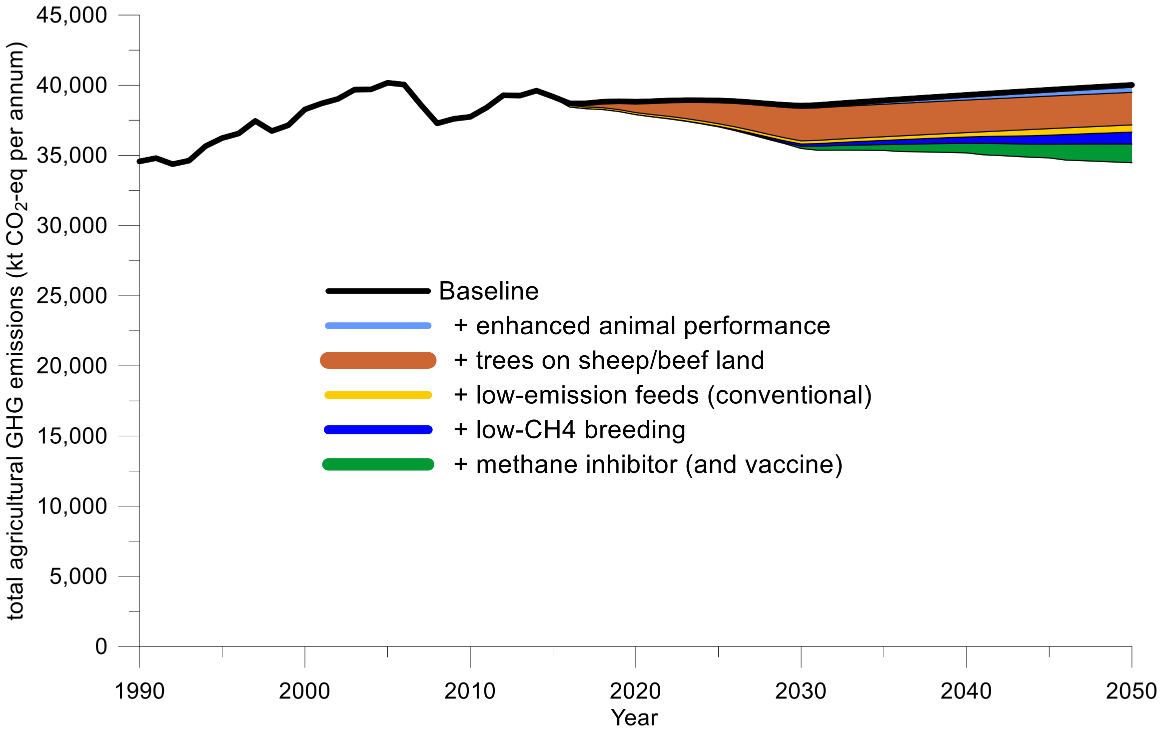

Figure 22. Cumulative effect of a package of mitigation options for the sheep and beef sector, for maximum assumptions about efficacy and adoption rates for each mitigation option.[24] For details, see text.

3.5 An alternative mitigation package for dairy, sheep and beef

The modelled mitigations from de-intensification of the dairy sector and the sheep and beef package can be added up to provide an alternative comprehensive mitigation package, based on de-intensification of the dairy sector and increasing performance in the sheep and beef sector plus technological interventions where feasible in both sectors. This combined approach would achieve a reduction of 9-21% relative to the MPI baseline in 2030, and 21-42% in 2050.[25] About two thirds of the total emissions reductions achieved by this approach would come from the dairy sector.

This alternative comprehensive mitigation package achieves about three quarters of the comprehensive mitigation package presented in Section 3.2. The main reason for this is the absence of low-emission feeds (both conventional and GM ryegrass) as mitigation option as well as the absence of additional productivity gains for the dairy sector in the de-intensification approach. Of course, as noted above, other packages are conceivable, depending on the specific goals, marketing approach and relevant non-climate policies and regulations. The packages presented here only provide examples of possible combinations and are intended to illustrate interconnections and consequences of particular approaches rather than being 'recommended' mitigation packages.

[25] This equates to reductions of 12-24% in 2030 relative to 2005 levels, and of 9-33% in 2050 relative to 1990 levels, but as noted in section 1.2, these emissions reductions relative fixed base years are less robust because they depend on uncertain baseline projections.

4. Conclusions

4.1 Context

Our report evaluated options that may be available in future to reduce biological GHG emissions on-farm, focusing on the consequences for emissions in 2030 and 2050. We considered qualitatively our confidence that the various options would be technically available, the drivers and barriers to uptake of each option, and evaluated quantitatively how much each option might reduce GHG emissions.

Emissions reductions were estimated using the national GHG inventory tool and are relative to baseline projections provided by MPI to 2030, which we extended for this report to 2050. For this quantitative assessment, we had to make assumptions about both the efficacy of future mitigation options that are not yet available commercially, and for each mitigation option, assume a rate of adoption (considering potential cost/benefit as well as a range of other drivers and barriers).

We emphasise that our assumptions about future efficacy and adoption rates are simply that: they reflect our collective judgement but are not based on detailed economic or other modelling; another group may well have assumptions that differ considerably from ours. Some mitigation options are well proven and already implemented today, while others are the subject of active research and have not yet reached proof of concept; for the latter, any assumption about their availability, efficacy and adoption rate involves a large amount of subjective judgement. Given the uncertainty in those assumptions, we provide high and low estimates for several options.

For any option that is not commercially available at present, on-going research and development will be needed to bring these technologies to market. For some options, the amount of investment needed to achieve this could be substantial. Our assumptions about future efficacy and adoption rates are based on such investments indeed being made and the necessary technological breakthroughs being achieved.

We also emphasise that some mitigation options considered in this report could be very costly at farm level or have significant economic impacts if adopted nationally and affect New Zealand's international trade position or environmental credentials (where these considerations apply). Other options could offer strong synergies with non-climate and marketing objectives. We focused on domestic emissions only and did not consider the likely effect on global emissions from mitigation options that would alter the total amount of livestock product exported by New Zealand. The actual cost, benefits and feasibility of any mitigation option and package of mitigations will depend heavily on domestic and international climate and non-climate policies and market responses. Our inclusion of any individual mitigation option or assumption about future efficacy or adoption rate does not imply a recommendation on our side to actively pursue or implement this option. More detailed evaluation of their economic, social and environmental impacts will be needed before recommendations about preferred mitigation options and packages can be made.

Our report focuses on future on-farm mitigation options only, it did not include substantial and deliberate land-use change either between different livestock systems or away from livestock entirely. Any amount of mitigation is possible for biological GHG emissions if New Zealand simply reduces its total livestock production, but understanding the potential and desirability to do so requires a fundamentally different conversation that was outside the scope of this report.

4.2 Quantitative summary

Of the total biological GHG emissions from agriculture in New Zealand, about 75% occurs in the form of methane (mostly from enteric fermentation), and 25% in the form of nitrous oxide (mostly from excreta deposited directly onto pastures). Our assessment indicates that a number of technologies and practices are currently available, and some are under development or appear as a promise on the horizon, that can assist farmers to reduce biological GHG emissions on-farm. These options vary in their current availability, efficacy and likely adoption rates. Many mitigation options require further development to reach their potential, and some may fail to reach the market despite further development efforts due to technological, market or regulatory barriers.

With all the mitigation options assumed in this report in the two different packages and using the high end assumptions for efficacy and adoption rate for each option, biological GHG emissions from New Zealand's pastoral sector would be around 23-24% below 2005 levels by 2030, and 32-46% below 1990 levels by 2050. The same packages of mitigation options but with the least optimistic assumptions would reduce emissions by about 13% below 2005 levels by 2030 and by 7-8% below 1990 levels by 2050. If some mitigation options are excluded from the package, the relative mitigation would be less.

Given the significant challenges implied in the both the technical and commercial realisation and implementation of some of the mitigation options, these figures illustrate the challenges for the pastoral sector to contribute to New Zealand's overall mitigation targets under the Paris Agreement and more ambitious targets in the longer term. The heavy reliance on new technologies is a feature of all the modelled mitigation packages (see below Section 4.3).

Table 1 summarises the estimated percentage reductions that the different mitigation packages considered in this report would achieve under different assumptions about efficacy and adoption rates. It is notable that the amount of mitigation achieved in 2030 at the lower end of assumptions would be less than or comparable to the amount by which projected baseline emissions for 2030 have changed under subsequent MPI forecasts over the past 4 years (from 2013 to 2017).

This illustrates that broader conversations about the role of pastoral agriculture in New Zealand's economy, as well as sources and mitigation options for other sectors, are needed to understand potential future absolute GHG emissions through new additional mitigations and /or changes to the farm system. We re-iterate that the absolute reductions that can be achieved in 2030 and 2050 relative to a historical base year (1990 or 2005) depend heavily on future changes in animal numbers and total production that would occur under projected 'business as usual'. Official government projections underlying this report differ in some cases from expectations of industry. The results from our report are more robust with regard to the relative reductions of on-farm GHG emissions below a given baseline, not as a projection of absolute emission. Absolute emissions depend on overall land-use choices, which we did not address in this report. Increasing transparency and robustness of government baseline projections and their alignment with industry forecasts would be highly desirable as different choices have a significant impact on the absolute emissions reductions that can be achieved relative to historical reference years.

Table 1: Summary of estimated emissions reductions achieved by different mitigation packages. "High" and "low" refers to the high and low end of assumptions about efficacy and adoption rates for individual mitigation options.

Mitigation package	Comment	2030 (relative to 2005)	2050 (relative to 1990)
Full package	All options except dairy de-intensification approaches	- 14% (low) - 24% (high)	- 10% (low) - 40% (high)
Sectoral packages	Dairy de-intensification package	- 9% (low) - 16% (high)	- 2% (low) - 17% (high)
	Sheep/beef package	- 8% (low) - 12% (high)	+ 8% (low) ± 0% (high)
Alternative full package	Dairy de-intensification plus sheep/beef package	- 12% (low) - 24% (high)	- 9% (low) - 33% (high)

4.3 Existing versus novel technologies and practices

Within the overall packages of mitigations, increasing the uptake of current technologies (e.g. optimising productivity, reducing nitrogen fertiliser, manure management) bring about only small incremental gains (see Figures 18, 20 and 22). Even if our assumptions about adoption rates for those approaches underestimate their full potential, they are unlikely to achieve a large shift in overall emissions. Other currently available mitigation approaches like dairy de-intensification combined with once-a-day milking could reduce emissions more significantly, but carry market challenges and potentially large economic and social risks for the country associated with such a transition. An economic and social analysis of these options, if applied at scale, would be necessary but was outside the scope of this report.

The other current technology available, planting more trees on farms, is possible. Existing technology could even account for individual trees. If deployed at scale this could make a difference, but would require policy changes to enable carbon accounting for individual trees as these are unlikely to be planted in contiguous blocks on dairy land (whereas on sheep and beef land, trees are more likely to be planted in contiguous and dense enough blocks to meet the current definition of forest land and thus don't face the same accounting challenges). Importantly, a change in accounting rules to enable crediting for carbon stored in individual and sparse trees would also imply a liability in cases where any land-owner (regardless of whether dairy, sheep or beef) wishes to remove individual trees or other woody vegetation. We are not in a position to comment on whether an approach could be designed that is workable and consistent domestically and credible internationally. Additionally, its impacts across different sectors as well as costs of monitoring would need to be considered carefully.

Apart from planting trees and de-intensifying the dairy sector, the on-farm mitigation approaches that could have the largest potential impact on agricultural GHG emissions in our assessment remain under development in New Zealand and overseas (CH_4 inhibitors and vaccine, nitrification inhibitors, and GM ryegrass). Some of those options have proof of concept (e.g. CH_4 inhibitor for feedlot animals), or proven benefits (e.g. DCD as nitrification inhibitor remains technically viable), while others are at various stages in development (GM ryegrass exists but its efficacy in actually reducing emissions has not yet been demonstrated, with field trials currently not possible in New Zealand; a CH_4 vaccine is in development but has not yet demonstrated an effect in live animals). Bringing those options to market suitable for New Zealand farming systems will require further development, with timelines of 5-20 years and uncertain end outcomes given their scientific complexity.

In the case of not only GM ryegrass but any novel substance entering the food chain, challenges lie not only in the development of the technology but also regulatory settings and domestic as well as international market responses (which could extend well beyond the dairy sector as the most likely user of the grass). Even where we have high or very high confidence that a technology will be available in principle in future and applicable to New Zealand farm systems, market responses and/or regulatory barriers overseas could remove it from the portfolio of viable options for New Zealand (as is currently the case for DCD).

Without these novel technologies, the potential to reduce biological GHG emissions on-farm is reduced substantially. On-going investment in science and commercialisation pathways to develop such mitigations is therefore critical if the agriculture sector is to contribute to more ambitious mitigation goals without the use of costly offset mechanisms. Work to ensure acceptability of novel mitigation technologies in markets, and giving farmers confidence when adopting such novel approaches, will be of equal importance to deliver this mitigation potential.

4.4 Drivers and barriers to adoption

While the efficacy of mitigation options is primarily a scientific and technical problem, their ability to reduce emissions depends on their actual adoption by farmers. This will be influenced by practical, economic, social and environmental considerations, and we have tried to evaluate the key issues for each option. Table 2 presents a summary of our assessment, using a traffic-light evaluation of barriers and risks to adoption for each option. The options have been ordered by the confidence that each option will be available in principle (although this confidence can be modified depending on its assumed efficacy and the scale at which it would be used).

For several mitigation approaches that address N_2O, issues related to water quality and nutrient discharges will be strong and in some cases even primary drivers for their adoption; this includes reduced nitrogen fertiliser use and application of nitrification and urease inhibitors but potentially also dairy de-intensification, low-emissions feeds and breeding. The extent to which water quality acts as driver for uptake of GHG mitigation options will vary strongly between catchments, and as a result, their impact on national emissions may be more limited.

The ability to adopt mitigation options is also highly variable among farmers and farm types. Important factors include the level of management intensity, with dairy systems generally having more mitigation options available (but also important differences between high- and low-input dairy systems; certified organic systems occupy a particular niche and are more restricted in the mitigation options they can use). Important differences also arise from farmer skills, access to skilled labour, relevant information and enough skilled advisors, finance through banks, ability and willingness to take risks, and the extent to which markets dictate farm practices. This makes any assumption about adoption rates and their use in modelling a challenging task, with a wide range of likely outcomes. Individual farms may find some options impossible to adopt even though it is considered possible in general for this farm type, and vice versa.

Overall, regardless of the specific direction taken, further changes in farm systems will be required to achieve efficient mitigation. This will mean farmers will need to adapt as both the impacts of climate change and climate and other relevant policies become a reality, and global markets respond to both. Investment into extension will be required to assist farmers with the system change that some of the mitigation options would imply, as well as investment into monitoring tools to ensure that positive actions by farmers can be counted. Farmers, export marketing companies and government will need to work together within a broader engagement process towards this future, including regulatory requirements. We hope that this report provides a useful stepping stone on the path toward a broad, collective understanding of the potential and scope of future mitigation options.

Table 2: Summary of confidence that mitigation options will exist in-principle, risks and barriers to their uptake, and potential range of annual emission reductions under low and high efficacy and adoption rates by 2030, relative to total agricultural GHG emissions. Significant co-benefits with non-climate policy are flagged where they occur.

Mitigation option	confidence	mitigation (low)	mitigation (high)	cost/benefit	market	environmental	system-fit	universality	monitoring
Breeding low-CH_4 sheep	VH	0.0%	0.3%						
Urease inhibitors	VH	< 0.2% *							
Performance: Dairy	VH	1.1%							
Performance: Beef	VH	approx. 0.7% *							
Performance: Sheep	VH	0.3%							
Manure: bio-digesters	VH	0.1%							
Once-A-Day milking	VH	0.3%	1.0%				Co-benefit		
Individual trees: dairy farms	VH	3.5%				Co-benefits			
Small-scale plantings on sheep & beef farms	VH	3.3%				Co-benefits			
CH_4 inhibitor: twice-a-day in-shed feeding (dairy)	H	0.3%	2.4%						
Low-emission feeds (dairy): existing forages	H	1.5%	2.3%						
Low-emission feeds (S & B): existing forages	H	0.5%	0.7%						
Reduced N fertiliser use	H	0.2%	0.2%			Co-benefit			
Breeding low-CH_4 cattle	H	0.0%	0.2%						
Dairy de-intensification	H	1.3%							
Nitrification inhibitors: DCD	H	0.2% **	1.0% **			Co-benefit			
Nitrification inhibitors: novel	H	0.2% **	1.0% **			Co-benefit			
Manure: spreading	H	< 0.2% *				Co-benefits			
Manure: restricted grazing	H	< 0.4% *				Co-benefits			
CH_4 inhibitor: slow-release (all systems)	M-H	0.7%	4.7%						
Breeding low-MUN cattle	L-M	***				Co-benefit			
CH_4 vaccine	L	2.1%	6.4%						
Low-emission feeds (dairy): GM ryegrass	L	0.0%	0.0%						

Legend: colour coding is used to illustrate our assessment as follows (mitigation outcome refers to the reduction of total biological GHG emissions from agriculture that would be achieved under assumptions of high efficacy/uptake and low efficacy/uptake, respectively).

Confidence rating	Mitigation outcome	Risk rating
Very high (VH)	> 4.0%	high risk
High (H)	1.0-4.0%	medium risk
Medium (M)	0.2-1.0%	low risk
Low (L)	< 0.2%	no risk identified

Notes:

* the option was not modelled but a maximum value inferred from basic assumptions (see text for details)

** the modelled value excludes application on beef farms since the inventory cannot represent this at present

*** the option was not quantified at all, given missing current evidence to estimate future impact

Further reading

The documents listed below are examples of the broader evidence base that underpins the expert assessment presented in this report, and can provide useful entry points for further reading.

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