Agriculture emissions and warming in Aotearoa New Zealand to 2050: Insights from the science

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Funded by Beef + Lamb NZ, Dairy NZ, Federated Farmers

Executive Summary

This working paper discusses the concept of net zero emissions and what it means in the context of the warming from methane. Aotearoa New Zealand has set targets of achieving net zero emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O) by 2050 and to reduce biogenic methane (CH_4) emissions by 10% by 2030 and 24-47% by 2050. This paper assesses the methane targets to 2050 under the Climate Change Response (Zero Carbon) Amendment Act of 2019 (CCRA) in Aotearoa New Zealand and provides analysis of what these targets, if achieved, would mean for the New Zealand economy's overall contribution to global warming. The purpose of this paper is to facilitate discussion among the public, government, and Climate Change Commission on the role of agricultural methane in New Zealand's mitigation strategy.

The scientific context is the very different manner by which methane, as a short-lived climate pollutant, affects global temperatures relative to the cumulative pollutants carbon dioxide and nitrous oxide. This science is very well understood. To stop carbon dioxide and nitrous oxide emissions from causing additional global warming, it is necessary to reduce the ongoing rate of emissions of these gases to net zero. Much smaller reductions, in the range of 10-30% over 30 years depending on prior methane emissions and ongoing emissions elsewhere, would stop methane emissions from causing additional global warming. Faster reductions in methane emissions can compensate for additional warming caused by other gases, while any increase in methane emissions has a disproportionately large additional warming impact. This very different response to methane emission reductions results from methane's relatively short, 12-year, lifetime and the fact that atmospheric methane concentrations are already elevated as a consequence of past and ongoing emissions.

A discussion of sectoral responsibilities to meet New Zealand's climate goals could be informed by contributions from respective sectors to past and ongoing global warming; to future additional warming under different scenarios; and the capacity of different sectors to reduce emissions. The decision on how much weight, if any, to give these three factors is a political one: the purpose of this report is simply to inform the first two.

Our analysis found that a 47% reduction in methane emissions by 2050, following a 10% reduction in methane emissions between 2020 and 2030, combined with linear reductions to net zero in CO_2 and N_2O emissions from 2020 to 2050, would see methane reductions essentially offsetting all future additional warming by CO_2 and N_2O emissions, bringing New Zealand's economy-wide cumulative warming back to 2022 levels by 2050. In this pathway, New Zealand causes net zero warming between 2022 and 2050 as the additional warming after 2022 is

reversed by 2050. This is because the "cooling" impact of ambitious emission reductions in the agriculture and waste sectors compensates for ongoing additional warming caused by energy and transport emissions over this period. This compensation for the warming impact of fossil-based emissions by mitigation in the agriculture sector raises concerns of fairness and equity, considering the cumulative nature of CO_2 and N_2O emissions. Such concerns cannot be addressed solely through a scientific analysis of the impact of emissions, but would also need to account, inter alia, with the social, economic and other environmental impacts of emission reduction measures in different sectors.

Our analysis also found that a 24% reduction in methane emissions by 2050 combined with linear reductions to net zero in CO_2 and N_2O to net zero by 2050 from 2020 would see New Zealand achieve net zero additional warming as an economy between 2027 and 2050, assuming the rest of the world pursues current policies up to that time. Faster emission reductions would be required by New Zealand to achieve net zero additional economy-wide warming by 2050 if the rest of the world reduces emissions faster because New Zealand's emissions would then have a slightly larger absolute impact.

In both cases, New Zealand's total contribution to global warming would peak in the mid- to late-2030s thanks to the combination of CO_2, N_2O and methane reductions. Many developed countries have pledged to achieve net zero by 2050 at the latest. In countries where CO_2 is the dominant contributor to warming, which is the majority, this implies their total contribution to global warming peaks around 2050.

Reductions in all three gases are essential to achieve this peak in the 2030s, and varying the rate of methane reductions after 2030 has little impact on the level and timing of this peak assuming CO_2 and N_2O decline to net zero by 2050 as planned. Faster methane reductions after 2030 primarily affect the rate at which New Zealand's emissions contribute to reduce New Zealand's contribution to additional global warming ("additional cooling") in the 2040s and beyond.

Using a range of climate mitigation pathways for the rest of the world (i.e. depending on how quickly other countries reduce their emissions), we found that reductions in agricultural methane in the range of 15-27% between 2020 and 2050 would see agricultural methane in New Zealand alone contribute net zero additional warming relative to a 2020 baseline (i.e. no additional methane-induced warming from 2020 from the agricultural sector). We also assessed the mitigation potential of decreases in emissions across all greenhouse gases in the agriculture sector. If each gas were to be addressed separately, long-lived gases (CO_2 and N_2O) would both have to achieve negative emissions to counteract its additional warming since 2020, whereas methane would only require a relatively small (15-27%) cut.

Additionally, it is necessary to consider New Zealand's role as an agricultural exporter and as an efficient producer of food (Wirsenius et al. 2020). If methane targets are met by reducing agricultural output, this would increase pressure to convert land elsewhere in the world to make up for the lost production. Therefore, interventions should consider this opportunity cost of land, which places value on land that is already in agricultural production. In other words, if New Zealand reduces output, there would be more pressure to convert land elsewhere, and global emissions may not be reduced. Hence interventions should consider whether or not global methane emissions would decline as a result of declines in New Zealand's emissions.

Agricultural methane reductions beyond what is needed to eliminate further additional methane-induced warming can counterbalance the additional warming due to other gases and sectors, or compensate for agricultural methane's contribution to warming prior to 2020. However, the costs and impacts of this approach need to be adequately assessed, especially as compared to the costs and impacts of long-lived gas emissions reductions. Cost-benefit comparisons of different measures need to consider their impact on additional warming: treating methane as CO_2-equivalent using GWP_{100} (for example, under an ETS) can be misleading because it does not reflect the actual warming impact of either ongoing methane emissions or methane reductions.

This report finds that aggregate emissions using GWP_{100} provide a poor indicator of contributions to the achievement of a global temperature goal. Contributions to warming (either computed explicitly with a climate model or based on aggregate emissions using GWP*) are more directly relevant to the long-term temperature goal of the Paris Agreement, but nevertheless, a broad range of methane emission reduction targets are still consistent with different assumptions about the allocation of shares of future warming.

The decision to set a separate national target for methane emissions, informed by the impact of different gases on global temperature, rather than a target for aggregate emissions using GWP_{100}, is strongly supported by all available science and should be reflected in implementation measures. In this regard, Aotearoa New Zealand can and should provide an example of science-based climate policy for countries with significant agricultural methane emissions from livestock or rice production.

1 Background

Under the United Nations Framework Convention on Climate Change (UNFCCC) emissions accounting systems, agriculture in Aotearoa New Zealand accounts for 50% of national greenhouse gas emissions, with about half of the country's land area being used for agriculture according to the Food and Agriculture Organisation (FAO) (NZ MFE 2022). With the establishment of the NZ Zero Carbon Act in 2019, which sets forth an ambitious strategy for reducing national emissions, the extent to which agriculture is responsible for contributing to this strategy has been called into question. This is due to the fact that a large proportion of NZ's agricultural emissions are from ruminant methane, a short-lived climate pollutant (SLCP), which only persists in the atmosphere for around 12 years as opposed to the millennial timescale of carbon dioxide.

Developments in greenhouse gas accounting have shown that metrics that account for this short-lived property of methane can be used to more accurately predict the impact of today's emissions on future temperatures. This report uses modelling of national contribution to warming by industrial sector to explore the implications of targets set under NZ's Zero Carbon Act for the path forward for agriculture in Aotearoa New Zealand.

1.1 Explanation of Greenhouse Gas Metrics

Anthropogenic greenhouse gas (GHG) emissions drive increased average global temperature by altering the energy balance of the atmosphere (Houghton 2001). The 1997 Kyoto Protocol standardized national emissions reporting by applying the Global Warming Potential (GWP) metric over a 100-year time horizon so that greenhouse gases with different physical properties could be combined under a common unit (UNFCCC 1997). GWP values are calculated as the radiative forcing of a pulse of a non-CO_2 GHG over a designated time horizon relative to that of a pulse of carbon dioxide (Lashof and Ahuja 1990). The resulting values are thus dependent on the selected time horizon, which are most typically reported over 100 or 20 years with vastly different results for gases with lifetimes that are less than the time horizon of the metric.

Concerns regarding the use of GWP date back to the first IPCC Assessment Report in 1990, citing uncertainty in the calculations (IPCC, 1992). Calculating GWP over 100 years distorts the near-term impacts of short-lived GHGs (namely, methane). Conversely, reporting the 20-year GWP may incentivize the reduction of methane at the expense of carbon dioxide mitigation, when the quantities of both greenhouse gases must decrease (Climate Analytics 2017).

Other metrics have attempted to address these issues. The Global Temperature Change Potential (GTP) converts radiative forcing of a non-CO_2 GHG into the effect on global average temperature at a specific time horizon for a pulse or sustained emission relative to that of carbon dioxide (Keith P. Shine et al. 2005; K. P Shine et al. 2007). Proponents of GTP argue that it is a more policy-relevant metric due to its connection to temperature targets (Abernethy and Jackson 2022). However, the GTP constants are still strongly dependent on the selected time-horizon and thus the arbitrariness that arises from that choice.

Research in emissions accounting metrics identify the short-lived properties of GHGs like methane as responsible for the distorted incentives that come with conventional metrics. This is because the amount of global warming caused by short-lived GHGs is largely driven by their annual emissions rate (i.e. the flow into the atmosphere of that gas). This contrasts with long lived GHGs like CO_2, as their contribution to global warming is dependent on the total cumulative emissions since pre-industrialisation (i.e. the stock of the gas in the atmosphere). GWP* is a 'flow-based' metric, which looks at the rate-of-change of short-lived GHG emissions, which contrasts with GWP and GTP which are both 'stock-based' (M. R. Allen et al. 2018; Smith, Cain, and Allen 2021).

GWP* has been shown to more accurately model the relationship between historical emissions and historical temperature change due to this consideration of flow. Table 1 below expands on the differences between long- and short-lived greenhouse gases. This distinction is further illustrated by Figure 1.

Table 1: How long-lived and short-lived greenhouse gases affect the climate differently

Long-lived: carbon dioxide and nitrous oxide	**Short-lived: methane**
Eliminating emissions maintains contribution to global warming at a steady level (the temperature change caused by CO_2 plateaus)	Eliminating emissions leads to temperature declining from a peak, as contribution to global warming is driven by methane emissions rate (temperature change caused by methane declines until nearly all past warming has been reversed)
A constant rate of emissions leads to increased levels of global warming year-on-year (temperature change caused by CO_2 increases)	A constant rate of methane emissions maintains a constant level of warming relative to the base year, to first order. Including second order effects based on the present day and near future, temperature will increase slowly, as the climate is slowly responding to past increases in methane emissions (temperature change caused by methane increases slowly)
Reducing emissions slows the rate of increase of global warming (temperature change caused by CO_2 increases)	Reducing emissions can maintain methane's contribution to global warming at a constant level, if reductions are approximately 3% over 10 years. Reducing emissions faster than this can reduce global warming from methane. (temperature change caused by methane stable or declines)

Considering the Paris Agreement's goal to limit warming to well below 2 degrees, using a metric that measures the contribution of each gas to warming relative to that threshold would constitute a helpful policy tool. However, the use of conventional stock-based metrics (GWP_{100}) is somewhat entrenched in national and global emissions accounting schemes, although the Paris Agreement does allow the use of additional metrics. An alternative way of achieving a similar goal is to report GHGs separately and set separate targets alongside their GWP conversions (M. R. Allen et al. 2022). This would allow tracking of an entity's contribution to warming in addition to progress towards targets set using aggregate stock-based metrics.

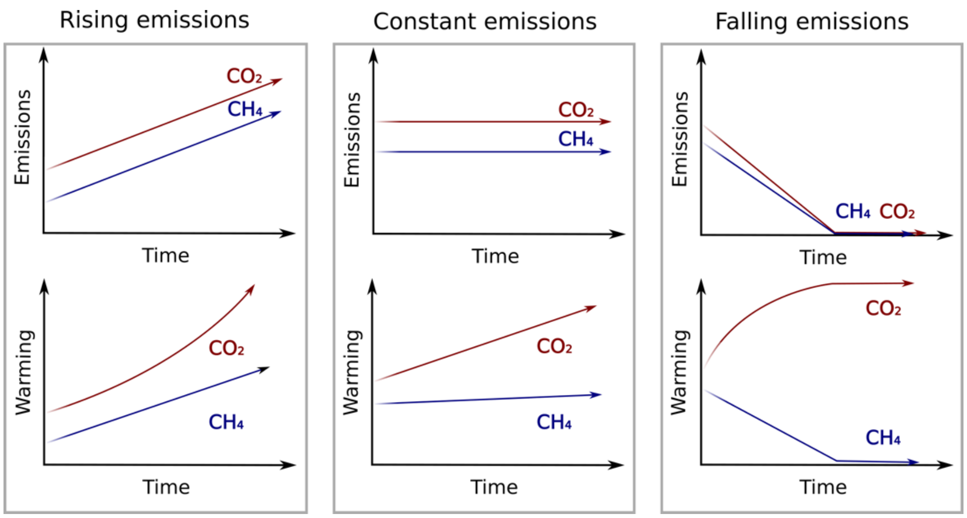

Figure 1: Figure from (M. Allen et al. 2022) showing the difference between the contribution to warming of methane and carbon dioxide under different emissions scenarios

1.2 Fossil versus biogenic methane and the carbon cycle

Due to the agricultural focus of this study, we must consider agriculture's role in the carbon cycle, as well as how the carbon in methane from the agricultural sector is distinct from that of carbon in fossil methane.

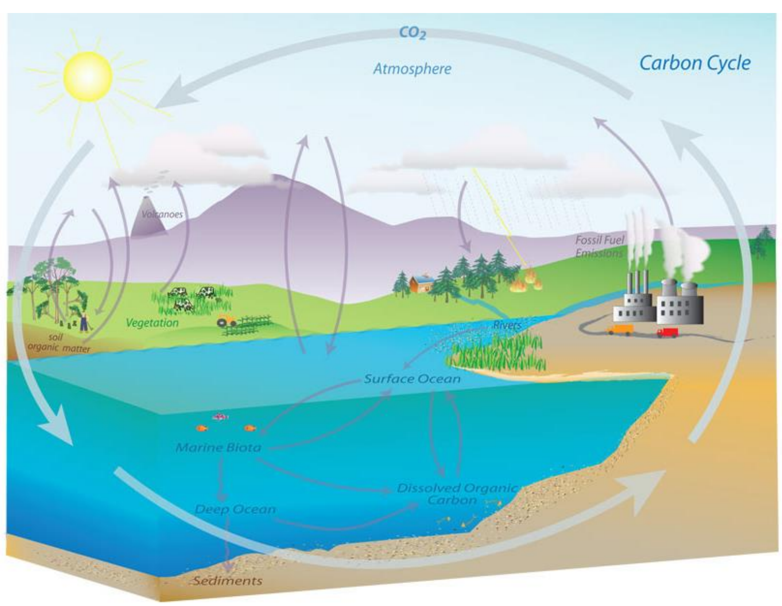

Figure 2: Simplified diagram of the carbon cycle https://www.noaa.gov/education/resource-collections/climate/carbon-cycle

The diagram of the carbon cycle (Figure 2) shows how carbon flows between the atmosphere, biosphere, ocean system, and earth's crust. These components of the carbon cycle occur on different timescales. Combustion of fossil fuels involves carbon that has been stored on a millennial timescale, whereas flows in and out of the biosphere occur on an annual or decadal timescale. It has been argued that this distinction must also be made when it comes to methane from fossil sources (i.e. natural gas) and biogenic sources (i.e. combustion of organic matter or enteric methane fermentation from livestock) (CLEAR 2020).

Approximately 12 years after methane is emitted into the atmosphere (on average), it oxidizes to form carbon dioxide and water. This carbon dioxide contributes to warming at a much lower level of radiative forcing than methane, but persists for centuries. For biogenic sources of methane, the carbon in the methane comes from atmospheric CO_2, and decays back to atmospheric CO_2. For fossil sources of methane, the carbon comes from fossil reserves, but is then added to the atmospheric stock of CO_2 once the methane has decayed. Thus, the contribution to warming for biogenic methane is marginally lower than that of fossil methane. This is accounted for in values for GWPs of methane, which are calculated for biogenic and fossil sources separately. For example, the IPCC AR6 value of GWP_{100} for fossil methane is 30, and for biogenic methane it is 27 (IPCC 2021b).

1.3 The Paris Agreement and Net Zero

Article 2 of the Paris Agreement states that countries must work to limit the "increase in temperatures to well below 2 degrees above pre-industrial limits and pursu[e] efforts to limit the temperature to 1.5 degrees." Article 4 states that in order to achieve the long-term temperature goal set out in Article 2, the world must "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century," though the exact meaning of 'balance' is left undefined (UNFCCC 2015).

Balancing emissions and removals of carbon dioxide is possible because there are both anthropogenic sources and anthropogenic sinks of CO_2. However, the dissipation of methane from the atmosphere happens naturally on a decadal timescale. Terms like 'carbon neutral' or 'climate neutral' are possible definitions for 'balance.' Carbon neutrality means that all carbon emissions are balanced by removals, but does not include methane and nitrous oxide. Climate neutrality is similar to net-zero in that a company's actions have no net effect on the climate system, although definitions of what this means vary. Climate neutrality is defined in the AR6 glossary as "Concept of a state in which human activities result in no net effect on the climate system" (IPCC 2021a). If "effect" is interpreted as "additional global warming" this would correspond to a state of net zero warming-equivalent emissions such as calculated by GWP*, but other interpretation of "net effect" are possible. Noting these ambiguities, AR6 made limited use of the term climate neutrality.

Net zero GHG emissions is defined as a state in which greenhouse gases into the atmosphere are balanced by removals out of the atmosphere over a specified period (IPCC 2018; 2021a). This balance is defined using a metric of equivalence. As described in the previous section, measuring progress towards net-zero using a stock-based metric does not account for the fact that methane does not necessarily have to reach zero in order to reach balanced atmospheric levels. Likewise, stock-based metrics undervalue the significant temperature impact of increased rates of methane emissions.

It is well-known that global warming is most strongly correlated with cumulative carbon emissions (Matthews et al. 2009; Zickfeld et al. 2009). Therefore, reaching net-zero carbon is the primary determinant in whether emissions are balanced. In other words, reducing methane in lieu of reducing carbon does not address the issue of cumulative greenhouse gases. Because Article 4.1 references the temperature limit in Article 2, any definition of balance that is not guaranteed to achieve the temperature goal would create an inconsistency between the two articles. Thus, this paper analyses the impact of emissions with regards to their impact on the balance of greenhouse gases in the atmosphere and their impact on future temperatures.

1.4 Incorporating the cost of using land

Human material demands for land-based products such as food, feed, and fiber are major drivers of deforestation as well as the emissions from land use change, both historical and current. The 2019 World Resources Report: Creating a Sustainable Food Future highlights the need to include the carbon cost of using land for human purposes, also called the Carbon Opportunity Cost (COC) (Searchinger et al. 2019). This metric can be thought of as either the foregone sequestration due to human appropriation of land, or the average carbon cost to produce the next unit of a product globally. Products that require a large amount of land per kilogram of protein such as red meat and dairy have higher COCs. As demonstrated in a recent report applying this accounting framework to Danish agriculture, including the COC in national emissions calculations incentivizes more efficient production of food in order to alleviate pressure to deforest for food production elsewhere (Searchinger et al. 2021).

A recent report for the New Zealand Commissioner for the Environment estimates how much forestry would be required to offset warming from agricultural methane, and the area required was astoundingly high (PCE 2022). If this land area dedicated to forestry comes at the expense of agricultural output by taking land out of production, resulting in reduced output of milk and meat, this could drive land clearing elsewhere to meet demand. It is therefore important to consider these knock-on effects when developing a land sector strategy. The goals of agricultural mitigation decision-making should focus on how to produce more food on less land while reducing greenhouse gas impacts. One way to incorporate this concept into farm-level emissions accounting would be to set and track intensity targets for both land and emissions per kilogram of protein (see section 1.7 for further detail). Global food demands are projected to significantly increase between now and 2050, so in order to prevent conversion of natural ecosystems, existing productive land must become even more productive (Searchinger et al. 2021).

1.5 International agriculture and emissions policies

In the wake of the Paris Agreement and its temperature limits, countries and companies alike have set net-zero targets, and some have laid out plans for how they intend to achieve them.

However, the Zero Carbon Act puts forward that biogenic methane should have a separate target due to its decadal lifetime (Ministry for the Environment 2019). This is based on previous research and IPCC scenarios that found that biogenic methane does not need to reach net-zero in the same way that is required of carbon dioxide to halt the increase in global average temperature (Rogelj et al. 2018).

The UK, for example, passed the Climate Change Act in 2008, which mandates national net-zero emissions by 2050 relative to 1990. However, their land use policies do not necessarily indicate the separation of GHGs in target setting (Committee on Climate Change 2020). Their proposed interventions instead focus on planting trees and sequestering carbon in agricultural soils, both of which have dubious additional climate benefits due to the competition for land use (Ranganathan et al. 2020).

Meanwhile, the European Union's 'Fit for 55' plan, which requires a reduction of GHGs of 55% by 2030, makes no mention of reducing agricultural emissions at all (European Council 2023). However, some countries within the EU have published their own strategies. For example, Ireland's 2021 Climate Action Plan outlines a plan to reduce agricultural emissions by 30% by 2030, though their plan does not set separate targets by GHG (Government of Ireland 2021). It's important to note that Ireland has a simultaneous target to increase their dairy herd, milk output, and land dedicated to agriculture, a strategy that may conflict with their emissions reduction targets (McDonnell 2020). Overall, it appears that very few countries, if any, have set a biogenic methane target aside from New Zealand. For example, India has 23% of world milk production and intends to increase its production by 6% per annum. India's current carbon footprint per litre of milk is around 3 times that of New Zealand. A recent report (Mazzetto, Falconer, and Ledgard 2022) ranked New Zealand is the most efficient producer of fat and protein corrected milk (FPCM) – 46 percent less than the average of the countries studied.

Beyond national emissions targets, the Global Methane Pledge run by the Climate and Clean Air Coalition is an agreement by signatories to collectively work together to reduce anthropogenic emissions by 30% by 2030 relative to 2020 levels. While this global pledge is not specific to biogenic methane, over one hundred countries have signed, implying that nuanced discourse on short-lived pollutants is happening around the world.

1.6 National emissions targets and emissions intensity targets

New Zealand's national emissions targets were written into law in 2019. The emissions target set out mandates net-zero GHGs by 2050, with the exception of biogenic methane, which must be reduced by 10% relative to 2017 levels by 2030 and by 24-47% relative to 2017 levels by 2050.

The targets were derived from the IPCC Special Report on 1.5 degrees, which acknowledged that methane behaves differentially in the atmosphere than long-lived GHGs and there should be separate targets for methane (IPCC 2018).

It was specifically noted in that report that these ranges should not be used directly by countries for their targets: “These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements.” (IPCC 2018, Figure SPM3.b caption). Additionally, the New Zealand national emissions targets do not include the Carbon Opportunity Cost of land, meaning that any leakage from lost food production that might result from meeting the biogenic methane target would not be captured. As the SR1.5 emphasises, the most important point for meeting Paris Agreement goals is the impact of national policies on global emissions, so policies that simply displace emissions from country to country have limited impact.

Using conventional Global Warming Potential over a 100-year time horizon, agriculture is responsible for nearly half of New Zealand’s national annual CO_2-equivalent emissions, with the largest contribution coming from methane from livestock. However, agriculture is currently not responsible for half of the nation’s contribution to annual warming when we take into account methane’s shorter residence time in the atmosphere relative to carbon dioxide. This mismatch could lead to inadvertent biases if GWP_{100} is solely used to determine mitigation policy and hence modelling how emissions affect global warming is useful (Reisinger and Clark 2018). Their paper showed that agriculture caused about 10-12% of global CO_2-e (GWP_{100}) emissions in 2010, but modelling showed that direct livestock emissions of non-CO_2 GHGs led to 19% of the global warming at that time, rising to 23% if CO_2 from pasture conversions were included. The reason for the discrepancy is that global agricultural methane emissions had increased substantially over preceding decades, and conventional CO_2-e (GWP_{100}) understates the impact of these increases. This report will assess the contribution to warming of the New Zealand agriculture sector relative to other sectors, and the impact that would result from the percent reduction targets for biogenic methane.

While national emissions accounting remains a common approach, there is an ongoing discussion regarding the use of intensity metrics either instead of or in addition to gross emissions within a national boundary. Intensity metrics measure the emissions per unit of output (meat, milk, etc.). These values incentivise reduction of emissions without sacrificing the production of food. While national gross emissions targets are important, they can result in the “offshoring” of production emissions and land use if the incentivised strategy is to reduce agricultural production within the national boundary just to import it from somewhere else. This analysis addresses the contribution to warming and emissions reductions at a national scale, but as mitigation decisions are made, the impact should also be assessed from the perspective of the global emissions intensity to avoid perverse outcomes.

2. Contribution to warming of New Zealand agriculture

In this section, we analyse the contribution of different sectors and different greenhouse gases to global warming at present and in the future for different scenarios. The methods and models used are described in more detail in Appendix 1.

2.1 Sectoral contributions to global warming

Emissions of methane, carbon dioxide and nitrous oxide for each sector of the economy are shown in Figure 3 since 1990, showing that agriculture dominates methane and nitrous oxide, and energy dominates carbon dioxide emissions. These national inventory emissions, combined with a historical emissions dataset back to 1850 are used to drive a simple climate model, FaIR (Leach et al., 2021 and see Appendix 1 for methodology).

Figure 4 shows the contributions to global warming of each sector of New Zealand's economy since 1850. Methane is the dominant contributor to global warming when evaluated relative to this baseline, causing nearly 60% of New Zealand's contribution to global warming since 1850. Consideration of a pre-industrial baseline demonstrates the influence of the choice of base year on the results, but although the issue of "historical responsibility" is frequently raised in international climate discussions, high historical emitters such as the European Union have consistently opposed it being used to inform discussions of emission reduction targets. As such, contributions to additional warming since 1990, arguably the earliest date of an emerging international consensus on the climate issue, are more relevant.

New Zealand contributions to global warming by gas and sector since 1990 are shown in Figure 5, revealing that in the recent past, energy has caused considerably more global warming than agriculture. This demonstrates that when you choose a different baseline year to consider additional warming since, this can change which sector will have contributed the most to global warming. Table 2 shows the proportion that each sector contributes to global warming between 1990 and 2020, with energy contributing the largest proportion (54%) and agriculture second at 37% based on this model. (Methane was responsible for 16% and nitrous oxide 20% of the 37% contribution to warming from agriculture over this period.)

When aggregating GHG emissions to CO_2-e using the AR5 value of 28 for GWP100, agriculture represents 51% of the total CO_2-e emissions in 2020, giving it the largest sectoral emitter and which is a far greater proportion than its 37% contribution to additional warming since 1990.

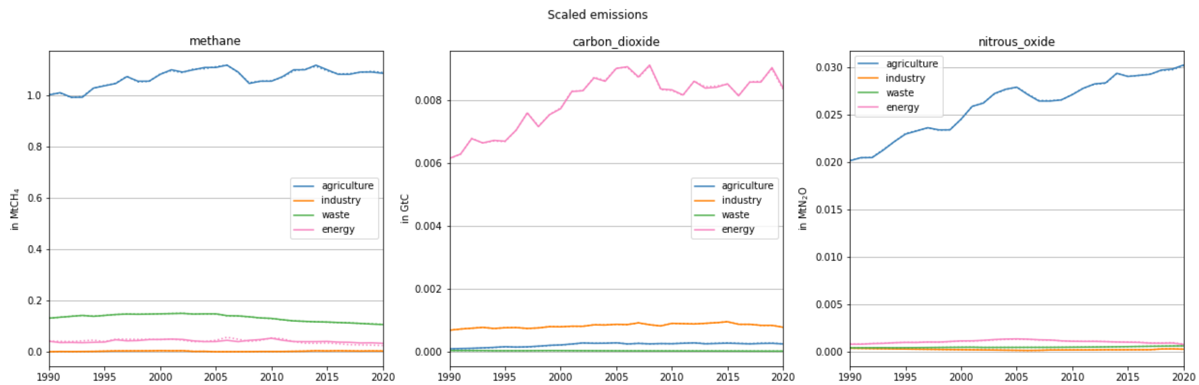

Figure 3: Emissions of CH_4, CO_2 and N_2O from agriculture in New Zealand

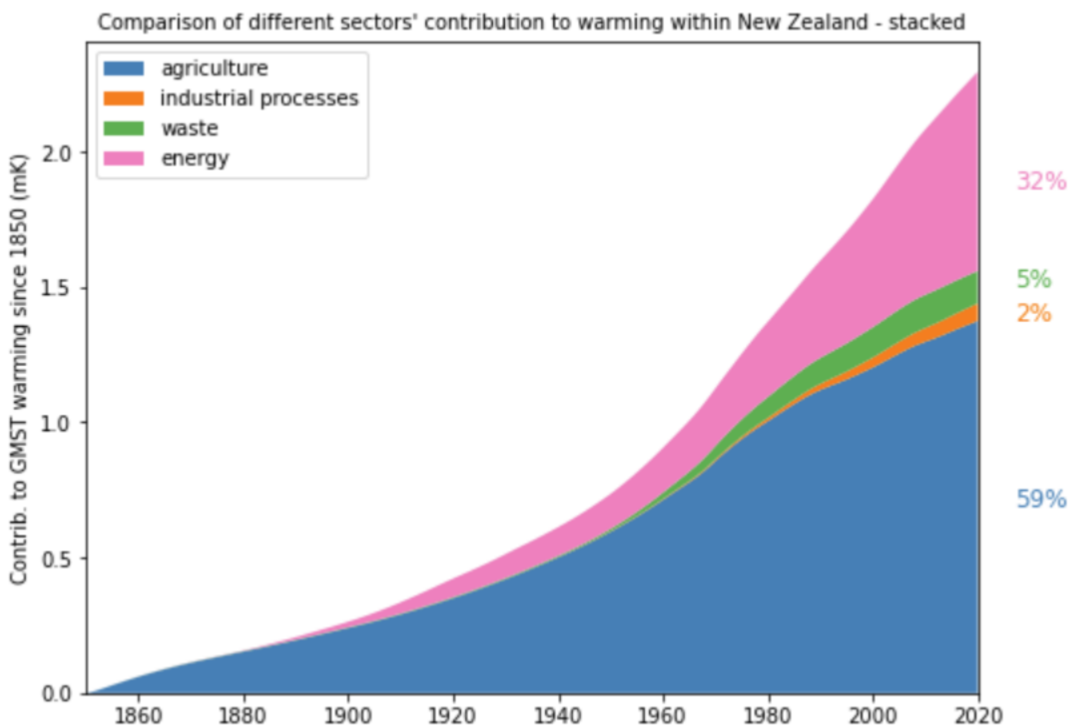

Figure 4: Contribution to additional global warming since 1850 from GHG emissions from each sector in the New Zealand economy. Emissions include CO_2, CH_4 and N_2O

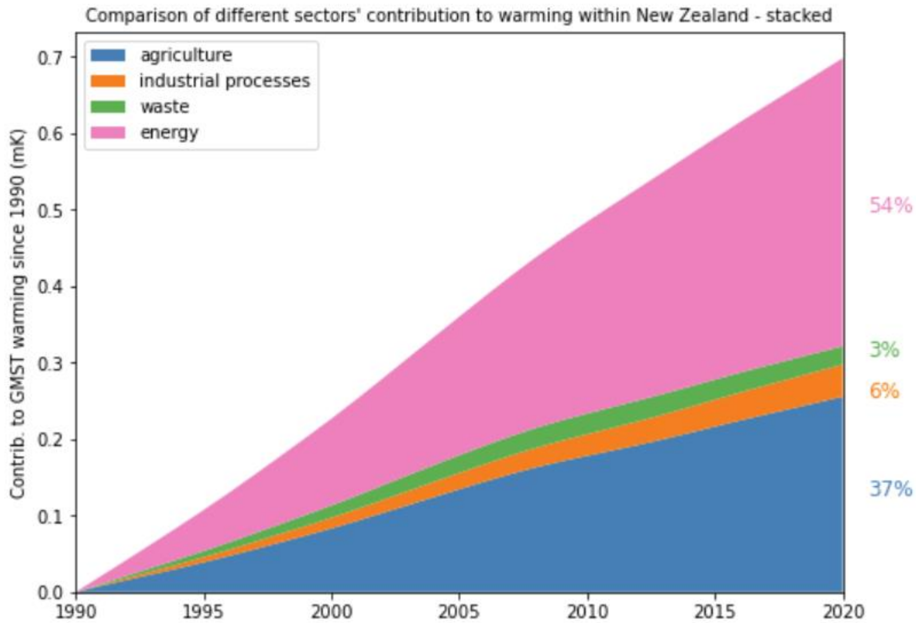

Figure 5: As figure 4, but with a baseline year of 1990.

Table 2: Contribution to additional warming by sector in New Zealand between 1990 and 2020

New Zealand Sector	Contribution to additional warming between 1990 and 2020
Agriculture	37%
Industrial Processes	6%
Waste	3%
Energy	54%

Next, we consider the contribution to warming from New Zealand's agricultural emissions in more detail. Virtually all greenhouse gas emissions in the agriculture sector are nitrous oxide and methane, with a small amount of carbon dioxide resulting from the use of fossil fuels for farm equipment. Nitrous oxide comes directly from manure management as well as direct and indirect emissions from applied nitrogen on fields. Methane also results from manure management as well as enteric fermentation of ruminants. Table 3 shows that, since 1990, methane is responsible for just over 40% of the warming from agriculture despite the fact that it is short-lived.

As methane is a short-lived pollutant, the rate at which its emissions increase temperature is largely driven by how rapidly methane emissions are increasing (M. R. Allen et al. 2018).

Between 1990 and around 2006, methane emissions were increasing; from 2006 onwards there is some variability, but the trend is relatively flat. This translates to a steeper gradient in the contribution to temperature from methane emissions (blue wedge in Figure 6) before 2006 and a reducing gradient thereafter.

For a few years around 2006, methane accounts for 50% of the warming from agriculture since 1990. From 2008 onwards, the proportion is less than half. For the other key agricultural GHG, N_2O, its long lifetime (over a century) means that the level of global warming it contributes over a period of several decades is largely driven by its cumulative emissions. Since 1990, New Zealand's emissions of N_2O have followed an increasing trend, and thus the amount of global warming from this gas continues to rise (green wedge in Figure 6). By 2015, N_2O contributes 50% of New Zealand agriculture's global warming since 1990, rising to 53% by 2020 (Table 3). Over time the proportion of global warming from agricultural CO_2 also increases, as it is long-lived and therefore has a cumulative effect on global warming. Appendix 2 provides a more detailed discussion of the differences in contribution to warming of long-lived and short-lived greenhouse gases in New Zealand and the significance of selecting a temporal boundary.

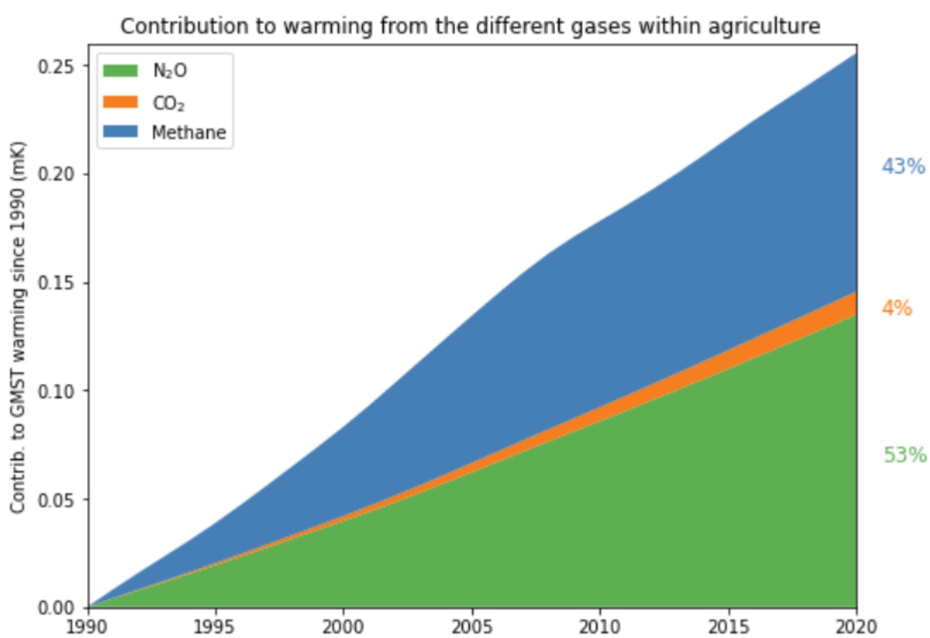

Figure 6: Contribution to additional warming since 1990 of CH_4, CO_2 and N_2O emissions from agriculture in New Zealand, based on the FaIR model.

Table 3: Contribution to additional warming in 2020 since 1990 for the agriculture sector by greenhouse gas

Gas	Contribution to additional warming in 2020 since 1990 within agriculture
CH_4	43%
CO_2	4%
N_2O	53%

Combining the information in Tables 2 and 3, agricultural methane emissions have therefore contributed approximately 16% (43% of agriculture's 37% contribution) of additional warming caused by all economic activity in New Zealand over the period 1990 to 2020.

3. Contribution to warming under New Zealand's Zero Carbon Act

New Zealand's Zero Carbon Act (ZCA) requires that, by 2050, all long-lived greenhouse gases reach net-zero, and biogenic methane reduces by 24-47% relative to 2017 levels, with a 10% reduction by 2030. The question of whether or not this target is aligned with the 1.5 degree Paris Agreement threshold, or indeed whether this target represents a fair distribution of responsibility across New Zealand's sectors, is not possible to answer solely based on physical science. The most universally-relevant target would be to simply say that all countries and industries have a responsibility to minimize their contribution to warming as much as possible. There is no scientifically agreed-upon method of disaggregating the responsibility further, and the level of mitigation of each country essentially depends on the actions taken by all others. However, we can look objectively at the impact that this target has on New Zealand's contribution to warming. We can then try to understand what actions are necessary to meet the target, and who should be responsible for implementation and supporting the transition.

It is useful to note that the methane reduction targets are gross, while the targets for the long-lived gases are net and rely on offsetting to be achieved.

Figure 7 shows the additional warming impact over time since 2020 if emissions are reduced linearly in line with the ZCA target, with the solid lines for methane and total warming representing 24% reduction for methane and the dotted lines representing 47%. This graph shows that New Zealand would achieve peak warming or "net zero additional warming" as an economy in the 2030s. The deeper methane cuts allow the country to effectively reverse all New Zealand's additional warming that has occurred since 2022.

In other words, reducing emissions in line with the more ambitious target would come close to the entire country achieving zero additional contribution to warming by mid-century relative to 2022, but would stop just shy of meeting that goal.

An important discussion is whether the policy priority should be limiting New Zealand's peak contribution to warming, or contribution to warming by 2050. The figures show that, if we assume that CO_2 and nitrous oxide are indeed reduced to net zero by 2050, the main impact of greater rates of methane reductions after 2030 is to achieve 'additional cooling' after New Zealand's overall contribution to warming peaks.

While the additional warming since 2020 from long lived gases will remain constant after they have reached net-zero emissions, New Zealand agriculture's methane emissions represents a mitigation opportunity for 'additional cooling' to counter the long-lived gases' 'additional warming'. In summary, the ZCA emissions cuts would lead to CO_2 and N_2O generating some additional warming between now and 2050, as their declining emissions over this time period cause additional warming (Table 1 and Figure 1).

One might interpret this result in such a way that New Zealand's agricultural emissions have the potential to be the deciding factor in whether or not the country achieves zero additional contribution to warming (see Figure 8 for additional warming from each sector). Assuming that every other sector pursues mitigation strategies that are as ambitious as possible to reach net-zero emissions, the New Zealand government should invest in mitigation of the agricultural sector as well, noting that it is the only sector with substantial potential to achieve additional cooling. However, the reduction of agricultural methane emissions should not come at the expense of food production. A recent report on mitigation in the Danish land sector projects that demand for food will grow significantly between 2010 and 2050 (Searchinger et al. 2021). The logic therefore follows that, on a global average, every hectare of productive agricultural land must produce significantly more food in order to avoid the conversion of natural ecosystems for agriculture elsewhere. The technologies required to reduce agricultural emissions, particularly methane, without impacting yields, are still very much nascent.

As the figures below demonstrate, the reduction of agricultural methane is an integral part of minimizing contribution to warming and therefore avoiding 1.5 degrees of warming globally. Thus, measures to reduce methane emissions intensities, e.g. enteric methane inhibitors, genetics, health improvements, etc. would be a substantial contribution to minimizing warming and protecting food security globally.

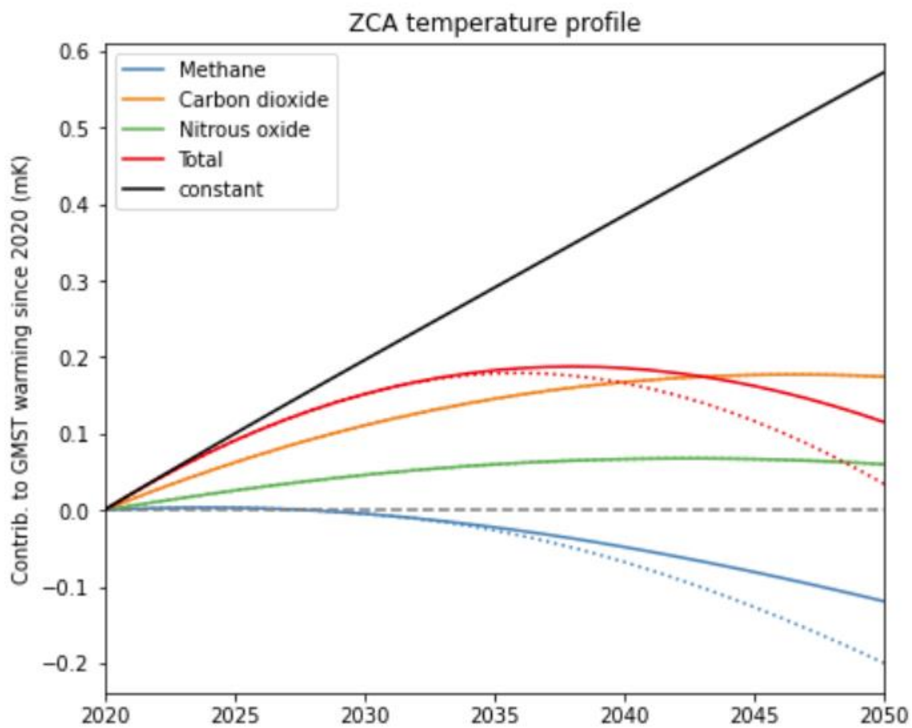

Figure 7: Additional warming since 2020 for ZCA emissions strategy (red)compared with potential additional warming that would occur if emissions continued at present-day levels (black). Solid lines for methane show a 24% reduction by 2050; dotted lines a 47% reduction by 2050. The background scenario used is SSP-245, a current policies scenario. The additional warming would be different under other background scenarios as this will affect the radiative efficiency of each gas.

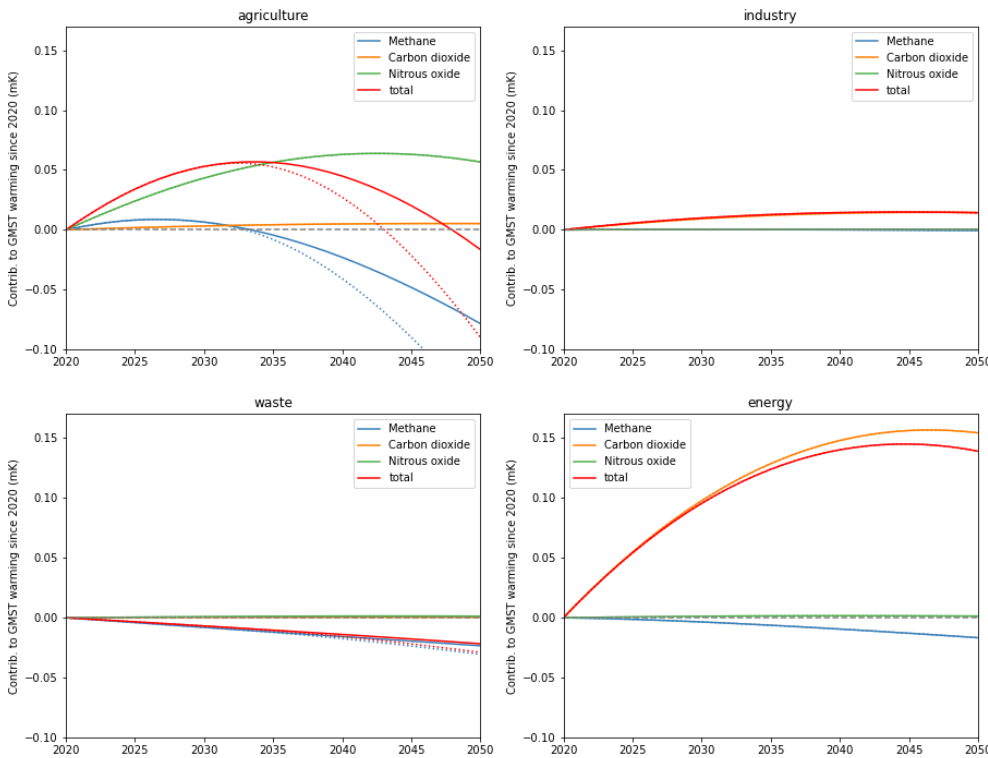

Figure 8: Additional warming under the ZCA broken down by greenhouse gas for agriculture (top left), industry (top right), waste (bottom left), and energy (bottom right)

4 Warming implications of different targets for 2050

4.1 Scenarios of equal additional warming

In this section, we consider the implications for global warming of different theoretical future emissions reductions for New Zealand, to gain insight into how much impact cutting each different gas has. In both of the following two examples, the same amount of additional warming has occurred in 2050 relative to 2020 from the long lived gases, and from methane.

Figure 9 shows an emissions pathway determined by the constraint that at 2050, the additional warming from each GHG relative to 2020 is zero. In other words, by 2050, the warming from each GHG is the same as it was in 2020. Methane reduces by 15% over the 2020 to 2050 period to generate this outcome, which is a lower level of reduction than stated in the Zero Carbon Act. CO_2 and N_2O emissions, on the other hand, must go net-negative halfway through the time period in order for the negative emissions to offset the emissions (and warming) in the first half of the period.

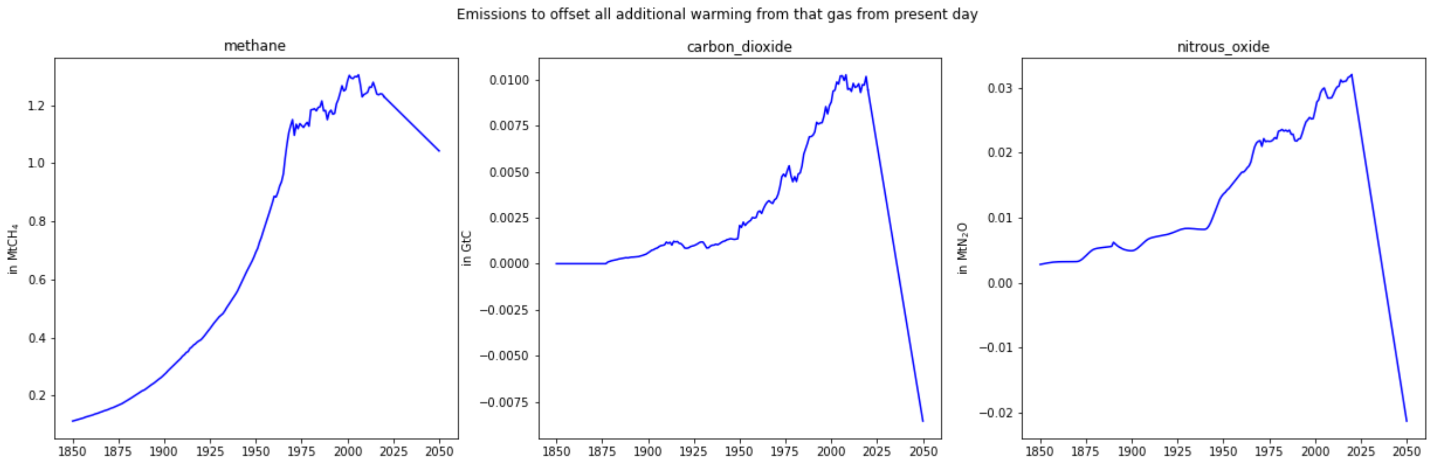

Figure 9: New Zealand's emissions of CH_4, CO_2 and N_2O in a scenario where the additional warming at 2050 relative to 2020 for each individual gas is zero

In the next experiment, we have considered first the warming impact of reducing CO_2 and N_2O emissions from New Zealand to zero by 2050, linearly. We have then calculated (method in Appendix 1) how New Zealand's methane emissions would need to change between 2020 and 2050 to give the same additional warming impact at 2050. As the CO_2 and N_2O emissions lead to additional warming over this period, this means that the CH_4 emissions would have to rise by 35% over this period to match the same level of additional warming. Figure 10 shows the additional warming since 2020 for this hypothetical scenario, where methane and long-lived gases (LLGs) reach the same level of additional warming at 2050. It is important to note that this experiment is purely theoretical and not a recommended course of action. Moreover, the trajectories are very different, with methane-induced warming under this scenario increasing monotonically while LLG-induced warming peaks and begins to decline. If the trends were to continue beyond 2050, the contribution to global warming from methane would exceed that from CO_2 and N_2O. This experiment only illustrates matching the warming at 2050.

These experiments demonstrate the differences between how long and short-lived gases affect temperature. Notably, reducing emissions of CO_2 and N_2O to zero does not eliminate the level of warming already caused by historical emissions. This is a key difference between methane and the LLGs, and why LLGs need to reach net-zero to stop additional global warming, whereas methane can be cut by a lesser fraction and lead to no additional warming – and possibly even additional cooling if emissions are cut by a large enough fraction.

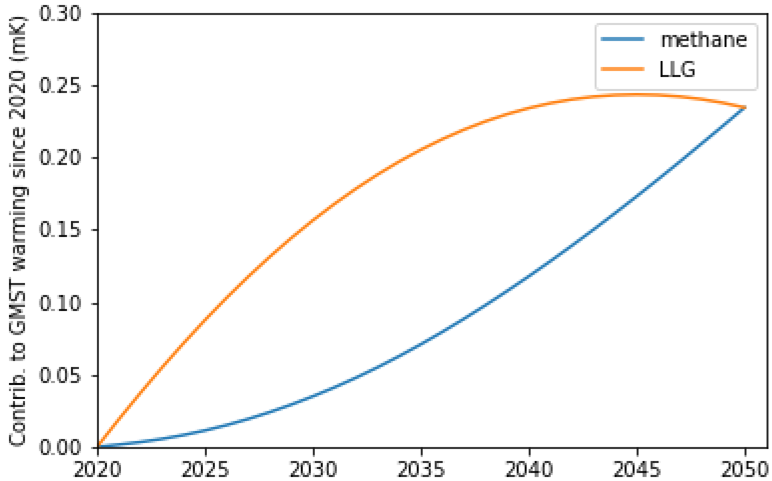

Figure 10: Additional warming since 2020 for the scenario where additional warming from methane is matched to be the same in 2050 as for long lived gases (LLG) which have linearly decreased to zero emissions in 2050 (for the whole New Zealand economy). This results in methane emissions rising by 35% between 2020 and 2050 in order to generate the same additional warming as the LLGs.

4.2 Reduction needed by the agriculture sector to eliminate additional warming

By assuming a linear decrease in methane emissions between 2020 and 2050, we found the percentage reduction in methane emissions that was required by 2050 to offset the warming from (a) agricultural methane emissions since 2020 and (b) all agricultural emissions since 2020 (i.e. CH_4, CO_2 and N_2O). This was calculated relative to two different background emissions scenarios: SSP-119 (a highly ambitious mitigation scenario) and SSP-245 (a moderate ambition scenario, see Appendix 1 for further details).

SSP-119 is a pathway to keeping global temperatures from rising 1.5 degrees above pre-industrial levels. SSP1 denotes the 'taking the green road narrative' and SSP-119 refers to a radiative forcing on 1.9 W/m^2 under SSP1. SSP-245 is a 'middle of the road' pathway (SSP2) to keeping global temperatures rise to less than 3 degrees above pre-industrial levels (4.5 W/m^2). SSP-245 can be thought of as the world continuing with business as usual without strengthening climate action, and therefore does not achieve the Paris Agreement goal of limiting warming to well below 2 degrees (Riahi et al. 2017; Meinshausen et al. 2020).

To provide context for these scenarios, if all countries that have made commitments under the Paris Agreement to reduce their emissions achieve their current targets it is estimated that this would keep global temperatures from rising 2.4 degrees above pre-industrial levels by the end of the century (Climate Action Tracker 2021).

To undo all the warming from New Zealand's agricultural CH_4 since 2020 by 2050, CH_4 would have to reduce by between 15-27% between 2020 and 2050, dependent on the background emissions scenario.

To undo all the warming from all agricultural emissions between 2020 and 2050, the CH_4 cuts would have to be between 29-40% (Table 4). It is useful to note that New Zealand already has a target to reduce nitrous oxide to net zero by 2050.

In the less ambitious scenario (SSP-245), there is a higher concentration of CH_4 in the atmosphere than the more ambitious scenario (SSP-119). As the radiative efficiency of CH_4 and N_2O is anti-correlated with its own atmospheric concentration (Reisinger, Meinshausen, and Manning 2011), each kg of CH_4 or N_2O emitted produces a smaller amount of warming in the less ambitious scenario. There is therefore a smaller amount of warming to offset using CH_4 cuts in SSP-245. Following this principle, the higher the background emissions scenario, the lower the percentage cuts would be, as the amount of warming generated from the same amount of emissions would be less.

Using GWP*, one would approximate 0.3% reductions per year (i.e. around 10% reduction between 2020 and 2050) to have no additional warming. However, there is an approximately 20-year lag after this cut is implemented before the temperature levels off, so there would be some additional warming between 2020 and 2040. Hence, if the scenario requires temperature to return to 2020 levels, a larger cut is required to do so, e.g. 15% in the SSP-245 background scenario, which is more similar to the background assumption for the standard GWP* equation (Smith et al., 2021) than SSP-119.

In the context of the ZCA targets, this model result means that a 24% reduction in CH_4 emissions by 2050 would offset all, or nearly all, of the additional warming from agricultural CH_4 emissions since 2020. A 47% reduction would offset more than all the additional warming from all agricultural emissions since 2020.

Table 4: Methane reduction relative to 2050 for various SSPs

	CH_4 reduction at 2050 relative to 2020 (%)	
Baseline emissions scenario	To offset warming from agricultural CH_4 since 2020	To offset warming from all agricultural emissions since 2020
SSP-119	27	40
SSP-245	15	29
SSP-370	8	23

4.3 Change in methane needed to be consistent with a target of limiting global warming to 1.5 degrees

It is important to note there is yet no agreed simple formula to determine individual country's responsibility and capability. It is also beyond the scope of this paper to provide commentary on which of the potential methods is most appropriate. However, some of the potential methods put forward for assessing country responsibility are impacted by the use of the GWP_{100} metric and would provide different results if a warming-based approach is used. In particular, emissions per capita is often put forward as a method of determining country responsibility. Any allocation of "fair shares" of mitigation contributions requires decisions on what is being allocated and the basis for the allocation.

National historical contributions to warming to date are generally much closer to national fractions of current consumption or GDP than fractions of the global population. This reflects the fact that, in general, resources are typically allocated in terms of ability to pay rather than on an equal per capita basis. There is no global resource that is allocated on an equal per capita basis, so allocating contributions to future emissions, total warming, or additional future warming, on an equal per capita basis would represent a significant policy innovation. Most scenarios indicate national contributions to future warming continue to reflect GDP more than population.

Whatever approach is used, a stock-based metric, like GWP_{100}, does not accurately reflect the relationship between a country's emissions and their contribution to additional warming. New Zealand's current percentage contribution to ongoing global warming and New Zealand's current percentage of global emissions aggregated using GWP_{100} differ by more than a factor of two, and the discrepancy would be even greater if emissions were aggregated using GWP_{20}. This demonstrates how misleading emissions aggregated using any standard metric can be in evaluating contributions towards achieving a global temperature goal. As stated in Reisinger and Clark (2018) "Evaluating the effects of direct livestock emissions on actual warming without relying on any simplifying GHG equivalence metric is therefore highly desirable to inform robust mitigation choices."

Figure 11 shows, purely as an illustration, that if CO_2 and nitrous oxide emissions were reduced linearly to net zero over 2020-2050, then limiting New Zealand's contribution to additional warming from 2015 to 0.065% of 0.4°C (i.e. a contribution to post-2015 warming consistent with reaching 1.5°C in 2050 and New Zealand's share of the global population, ignoring contributions to warming prior to 2015) would require methane emissions to be reduced by 27% over this same period. Although the allocation of responsibility for emission reductions according to historical contributions to warming has been extensively discussed in UNFCCC negotiations, there has been no consensus on either how historical responsibility should be calculated or how if at all, it should be taken into account in setting targets.

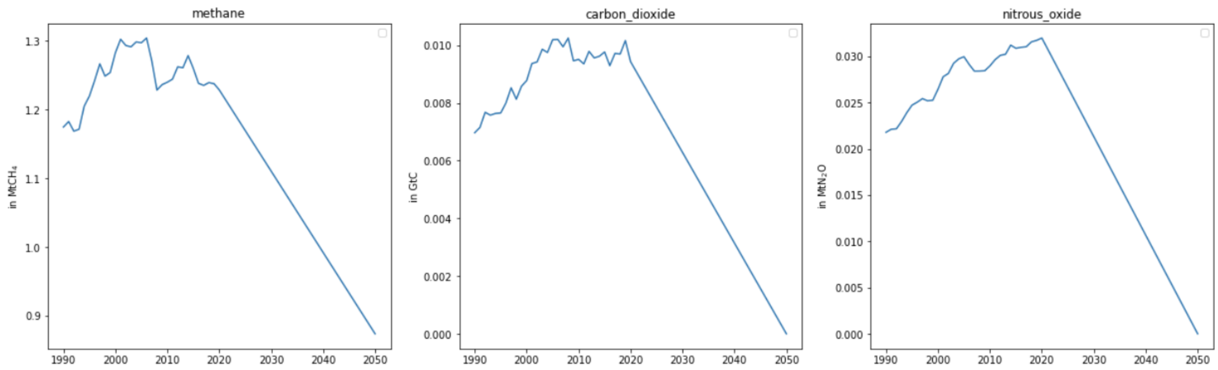

Figure 11: Emissions reductions under a 'fair-share per capita' scenario relative to 2015.

In summary, aggregate emissions using GWP_{100} provide a poor indicator of contributions to the achievement of a global temperature goal. Contributions to warming (or aggregate emissions using GWP*) are more directly relevant to the long-term temperature goal of the Paris Agreement, but nevertheless, a broad range of methane emission reduction targets are still consistent with different assumptions about the allocation of shares of future warming.

Appendix 1: Methods

For the emissions calculations, we employed two datasets; historical PRIMAP emissions data extending back to 1850 and New Zealand's Greenhouse Gas Inventory data spanning the years 1990 to 2020. Our preference was to use the official inventory data but due to its lack of historical data, we scaled the PRIMAP data from 1990 to 2020 to fit the inventory data. This was achieved by taking the ratio of the mean values of the inventory and PRIMAP data between 1990 and 2020, subsequently applying this ratio to the entirety of the PRIMAP dataset from 1850. Our analysis concentrated on the three primary greenhouse gases: methane, carbon dioxide and nitrous oxide. To accurately convert emissions profiles into warming, we used the emissions data in the gases' native units as inputs into a simple climate model called the Finite-Amplitude Impulse Response model (FAIR).

In order to calculate warming, we first established an emissions baseline. Shared Socioeconomic Pathways (SSPs) represent scenarios of projected socioeconomic shifts, each accompanied by a corresponding emissions trajectory. SSP-245 is a middle of the road mitigation scenario, perhaps representative of the current policy outlook, where warming in 2100 is around 2.8◦C (Meinshausen et al. 2020). We examined the temperature difference between the baseline emission (SSP-245) and the baseline emissions minus the emissions of interest, thereby determining the warming attributable to the specific emissions. To get the warming since a particular date, we subtracted the warming from that date (say 1990) from each term of the warming time series.

For the minimisation calculations, we varied a single parameter: the linear percentage decrease of methane by the year 2050, commencing in 2020. We employed Python's Nelder-Mead optimisation method to identify the methane percentage at which the emissions will reach a certain temperature goal.

Temporal boundary

This study primarily assesses New Zealand's contribution to warming since 1990 until the present, given the availability of emissions inventory data only since 1990. For the projections to 2050, we use a baseline year of 2020 as this is the most recent year in the inventory.

System boundary

The data used for this analysis includes all nationally reported agricultural emissions as outlined in New Zealand's National Inventory Report. This includes enteric methane, manure management, emissions from agricultural soils, field burning of agricultural residues, liming, and urea application.

Appendix 2: Mitigation potential of long and short-lived GHGs

Section 2 showed the extent to which different GHGs and sectors have contributed to additional global warming in recent years over and above the warming to the baseline year of 1990. In this Appendix, we will consider the potential of different GHGs and sectors for mitigation of global warming. As each GHG has a different lifetime in the atmosphere, the effects from past emissions persist for varying timeframes. This concept is referred to here as historical or 'maintained warming'. At any point, if GHG emissions are stopped entirely, the 'maintained warming' is the amount by which temperatures would fall as a result. As CO_2 and N_2O are long lived, stopping their emissions leads to only a small reduction, if any, in global temperatures, meaning the maintained warming from these long-lived gases is small. On the other hand, methane is short-lived, so stopping methane emissions would mean that the atmospheric methane levels would no longer be held up by ongoing methane emissions. Past emissions would be removed from the atmosphere though chemical reactions, and they would not be replaced with new emissions. Hence, the maintained warming for methane is much larger than for long lived gases.

In Figure 12 through Figure 15, the maintained warming is shown by the hatched areas as a negative value; in other words, the amount temperature would go down if the emissions of that sector or gas were halted since the baseline year. The change in temperature shown is relative to temperature in that baseline year, which is 1990 in the figures. Figure 12 shows the warming from each of New Zealand's economic sectors (agriculture, energy, industry and waste). The agricultural sector (blue in Figure 12) has the largest component of maintained warming, and hence provides the greatest potential for emissions cuts to cause cuts to global warming. Figure 13 through Figure 15 show the same data disaggregated by GHG. While the maintained warming is shown in Figure 12 as a negative value, another way to think of it is to equate to the amount of warming that is added to the system if you maintained emissions at 1990 levels compared to having no emissions from 1990 onwards. This is how maintained warming is shown in Figures 14 to 16. It is clear that methane (Figure 15) has the largest maintained warming.

These figures also show the 'additional warming' by the non-hatched areas. This is the amount of warming caused by emissions from each sector relative to the level of warming in 1990. From Figure 12, we see that while agriculture has the greatest potential impact on global warming from emissions cuts (blue hatched), the energy sector causes the greatest amount of additional warming (solid pink) between 1990 and 2020. It is clear from Figure 14 that CO_2 is the dominant gas from the energy sector, which has substantial level of additional warming, but negligible maintained warming.

The sum of maintained warming and additional warming has been termed the 'marginal warming' (Reisinger et al. 2021), as this quantity considers the difference between a future emission being released, or not being released (no-activity counterfactual). Figure 12 shows that New Zealand's emissions between 1990 and 2020 raised global temperatures by roughly an additional 0.7 thousandths of a degree. However, if New Zealand had emitted nothing at all in that period, temperatures would be nearly 0.8 thousandths of a degree cooler in 2020 relative to 1990. In other words, the difference in temperature in a scenario including or excluding New Zealand's emissions is 1.5 thousandths of a degree (i.e. New Zealand's marginal warming between 1990 and 2020).

The quantities of maintained versus additional warming depend entirely on the date used for the baseline. Figure 4 from Section 2 shows that for a baseline of the year 1850, at which point we would assume emissions are approximately zero, all warming is additional. Since pre-industrial times, more than half of New Zealand's contribution to warming comes from the agricultural sector.

Based on the definition of maintained warming, it might seem that warming due to carbon dioxide would only be additional. However, this is not the case for biogenic carbon. This notion of maintained and additional warming is conceptually aligned with the Carbon Opportunity Cost discussed previously. In the same way that constant methane "holds up" temperature, carbon from previous land clearing for agriculture persists in the atmosphere causing warming so long as that land remains in production. The opportunity cost of using land for agriculture is that the land is not used to store carbon as a natural ecosystem. In this way, warming from biogenic carbon emitted due to land clearing can also be thought of as maintained warming.

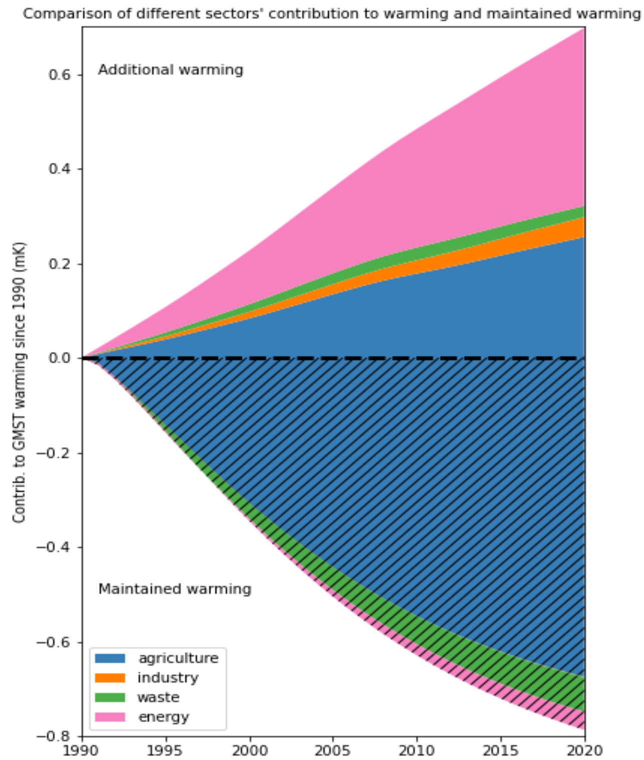

Figure 12: Additional warming from CH_4, CO_2 and N_2O emissions combined, relative to 1990 warming level (solid colours, shown with a positive sign convention), and maintained warming since 1990 (hatched areas, shown with a negative sign convention), shown by sector

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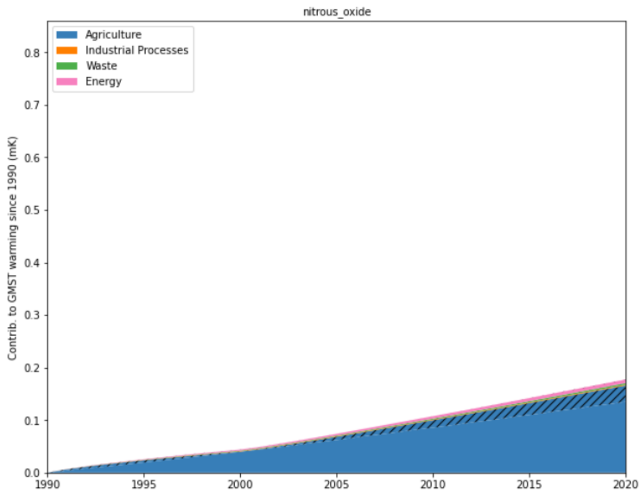

Figure 13:Additional (solid) and maintained (hatched) warming relative to 1990 from N_2O emissions. Here, both are shown with a positive sign convention, with the sum of the two representing the marginal warming.

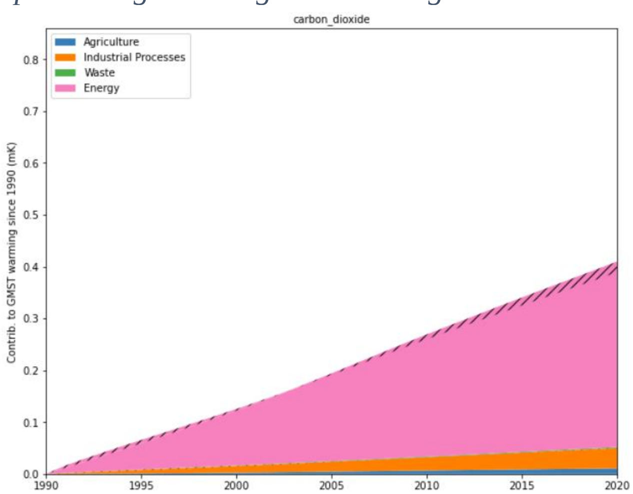

Figure 14: As Figure 9 for CO_2.

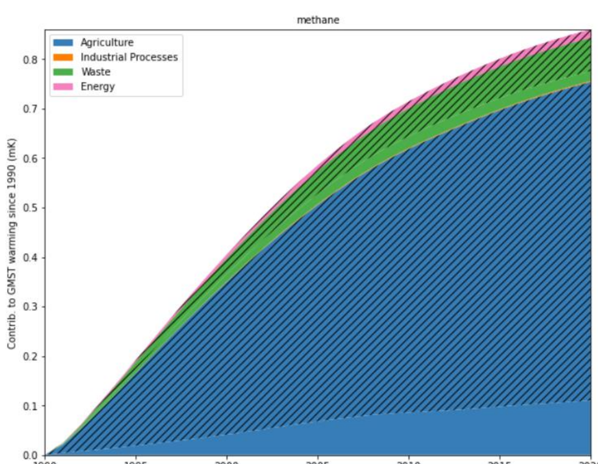

Figure 15: As Figure 9 for CH_4.

Figures 12 to 15 demonstrate that, while CO_2 from the energy sector is clearly responsible for a large proportion of the additional warming that has occurred since 1990, the large blue wedge of agriculture's maintained warming shows that the reduction of agricultural methane represents the greatest opportunity to reduce New Zealand's contribution to warming. Cutting emissions in the future will decrease the level of maintained warming (hatched) for any of the gases. However, because of CO_2 and N_2O's longer lifetimes, the maintained warming is relatively small. Its short lifetime means that CH_4's maintained warming is high, hence its high potential for reducing contributions to global warming.

Appendix 3: Glossary

Contribution to global warming from an emissions source (e.g. global emissions, emissions from a country, or a sector): This is calculated using a climate model by running the global model in a baseline simulation (Sim A) and running the model with the sector in question removed (Sim B). The magnitude of the difference between Sim A and B is the contribution to global warming from the source in question.

Additional warming: The warming from an emissions source (e.g. global emissions, emissions from a country, or a sector) relative to the same in a chosen base year.

Marginal warming: the warming from an emissions source relative to the absence of that emission. This is calculated using a climate model by running the global model in a baseline simulation (Sim A) and running the model with the sector in question removed for all times after the year you wish to start evaluating marginal warming from (Sim C). The magnitude of the difference between these is the marginal warming.

Net zero greenhouse gas emissions: Where emissions and removals of all GHGs sum to zero, with non-CO_2 GHGs scaled to CO_2-equivalent values using a climate emissions metric. GWP100 is commonly used for this.

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