Motu

Cows, Sheep and Science: A Scientific Perspective on Biological Emissions from Agriculture

Michele Hollis, Cecile de Klein, Dave Frame, Mike Harvey, Martin Manning, Andy Reisinger, Suzi Kerr, and Anna Robinson

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Author contact details
Michele Hollis

withonelmichele@gmail.com

Suzi Kerr

Motu Economic and Public Policy Research

suzi.kerr@motu.org.nz

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Disclaimer
Any opinions expressed and all errors and omissions are the authors' responsibility.

Motu Economic and Public Policy Research

PO Box 24390	info@motu.org.nz	+64 4 9394250
Wellington	www.motu.org.nz	
New Zealand		

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Abstract

Biological emissions from agriculture (methane and nitrous oxide) make up almost half New Zealand's total greenhouse gas emissions, so their importance relative to carbon dioxide is of particular policy interest. Motu Economic and Public Policy Research brought together a group of New Zealand climate change and agriculture specialists to respond to questions posed by the Parliamentary Commissioner for the Environment on the science.

The paper finds that the overriding need to reduce carbon dioxide emissions is scientifically uncontentious. For the climate to stabilise, net carbon dioxide emissions must ultimately be cut to zero. There is debate about whether, when and how much action to take on other gases.

Some scientists advocate a comprehensive multi-gas approach, arguing that will be more cost-effective. It may already be too late to limit warming to two degrees without mitigating agricultural greenhouse gases. Others advocate a focus on carbon dioxide or on all long-lived gases (including nitrous oxide), with concerted mitigation of methane (a short-lived gas) only once carbon dioxide emissions are falling sustainably towards zero.

There is support for 'easy wins' on all gases, but it is unclear how easy it is for New Zealand to reduce total nitrous oxide and methane emissions while maintaining production. The report summarises current and emerging options, and discusses methods to calculate methane and nitrous oxide emissions at the paddock, farm, regional and national scale.

Finally, the report considers metrics used for comparison between gases, focusing on Global Warming Potential (GWP) and Global Temperture change Potential (GTP). The authors reached a consensus that the 'right' value depends on the policy goal and could change substantially over time; and if the main policy goal is to cost-effectively limit global average warming to two degrees above pre-industrial levels, then the value of methane should be less than the GWP100 value of 28 until global carbon dioxide emissions have begun to decline steadily towards zero. There is no agreement beyond this on the best value to use; the arguments reflect judgments about politics, economics, and the intersection of policy and science.

JEL codes

Q52, Q54, Q58, R14

Keywords

Agriculture, emissions, science

Summary haiku

The science is clear.

When debating emissions

Consider your goals.

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1 Executive Summary

This paper was commissioned by the Parliamentary Commissioner for the Environment in the context of the Commissioner's investigation into the merits of an 'all-gases, all-sectors' Emissions Trading Scheme. Motu brought together a group of New Zealand climate change and agriculture specialists to respond to five specific questions, and their corollaries, posed by the Commissioner.

1.1 What is the current state of understanding of the climate impacts of each greenhouse gas (CH_4, N_2O, CO_2)? Where is there consensus and divergence?

There has been a robust scientific understanding of the climate impacts of each of the greenhouse gases (GHGs) in question for many decades.

Nitrous oxide (N_2O) and carbon dioxide (CO_2) are both long-lived gases. N_2O has an atmospheric lifetime of about 120 years, whereas CO_2 can remain in the atmosphere for centuries to millennia. Tonne for tonne, however, N_2O is a much more powerful greenhouse gas than CO_2.

Methane (CH_4) is a short-lived gas with an atmospheric lifetime of about 12 years. Despite its short lifetime, CH_4 is also a more powerful greenhouse gas tonne for tonne than CO_2.

Carbon dioxide is the largest single contributor to human-induced climate change, however, because of the high volume of CO_2 emissions and its long lifetime.

Estimates of the relative potency of the different gases are updated from time to time. This is not evidence of diverging scientific opinion, but simply reflects the fact that increasing amounts of GHGs in the atmosphere change the radiative efficiency of these gases. In addition, evidence about additional indirect warming effects and about the natural processes by which GHGs are removed from the atmosphere is increasing with on-going research, which can result in revisions to the exact numbers.

1.2 Putting aside feasibility, which greenhouse gases should be the central focus of short-, medium- and long-term mitigation efforts? Why?

The overriding need to reduce carbon dioxide emissions is scientifically uncontentious. There is a strong, direct relationship between cumulative emissions of CO_2 and global warming; ultimately, net CO_2 emissions have to decline to zero for the climate to stabilise. In this sense, therefore, CO_2 must always be the "central" focus of mitigation efforts in the short, medium and long term.

Since N_2O is also a long-lived gas, it should also, feasibility aside, decline to zero. There are (in principle) ways to take more CO_2 out of the atmosphere than is being put in by human activities. This could enable some N_2O emissions to continue if that was deemed desirable, compensated for by a net global removal of CO_2 from the atmosphere.

By contrast, emissions of CH_4 and other short-lived climate forcers do *not* have to decline to zero for the climate to stabilise; they only have to stop increasing.

The debate over the desirability and urgency of CH_4 mitigation turns on whether, and in what circumstances, effort should be put into mitigating CH_4 emissions *in addition* to mitigating emissions of long-lived greenhouse gases.

On one side, advocates of a comprehensive multi-gas approach point to the cost-effectiveness of this approach, as it would allow CO_2 emissions to be reduced to zero just a little more slowly, so the same maximum (peak) warming could be achieved as under a CO_2-only strategy but the net cost of mitigation would be lower. In addition, recent studies suggest that without mitigation of agricultural non-CO_2 gases, CO_2 emissions would have had to peak already or in the very near future to leave a reasonable chance of not exceeding the current internationally agreed target of a maximum 2°C warming above pre-industrial levels.

On the other side, advocates of a focus on long-lived gases, or exclusively on CO_2, argue that putting effort into short-lived gases misses the point that every emission of CO_2 today matters for the ultimate peak temperature. They argue for a “peak CO_2 first” approach, where concerted action on short-lived gases starts only once it is clear that CO_2 emissions are trending downwards. They express concern that CO_2 mitigation promises to be difficult and costly enough without adding extra costs to the economy by trying to address other gases as well.

These differences are about how to apply generally agreed scientific and economic understanding to policy. They are not about the science itself. The drivers for the two ‘sides’ reflect different assessments of political and economic conditions.

1.3 Considering issues of feasibility, how much emphasis should be placed on mitigation of agricultural non-CO_2 gases? Why?

New Zealand farmers have already made substantial efficiency gains that have constrained the rise in total agricultural GHG emissions. There may be scope for more consistent implementation of current best practice on farms, and there are some new options on the horizon, but total agricultural emissions are projected to continue to rise in the short to medium term because of planned production increases.

To achieve overall reductions in agricultural GHG emissions would take some or all of the following:

- Constraining total production at current levels while increasing efficiency gains
- Future scientific and technological breakthroughs
- Shifts in production (i.e., away from ruminant animals).

1.4 How are methane and nitrous oxide emissions from the agriculture sector calculated, and how accurate are such calculations?

Current methods for measuring emissions of CH_4 and N_2O at the level of individual animals or paddock scale are resource intensive and subject to considerable uncertainty. It would not be feasible to use these methods as tools to directly estimate and monitor farm-level emissions across the country.

The only on-farm calculator widely in use in New Zealand is the nutrient budget model OVERSEER® (Overseer), which has a mixed reputation within the farming community. Overseer was not designed for GHG accounting, but it does capture many key pieces of information. It does not currently consider the different soil conditions or microclimates within a farm, which can be crucial for N_2O emissions. In general, Overseer is better used to track changes over time (trends), rather than for specific numerical estimates.

On a broader scale, New Zealand's National Inventory of GHGs includes estimates of agricultural GHG emissions. These are based on agricultural statistics of total production and average productivity per animal. Basic biological equations and agricultural statistics are then used to relate production per animal to feed intake. Estimated feed intake, in turn, is used to estimate methane emissions per animal and total nitrogen excreted. The estimated total nitrogen excreted is used to estimate nitrous oxide emissions as a percentage of total nitrogen excreted or applied in the form of nitrogen fertilisers. While these equations are simple, and miss differences between farms, they are based on an increasing number and diversity of empirical measurements, and are considered broadly robust at the regional and national level.

1.5 What methods are used to determine CO_2 equivalencies for other greenhouse gases? Where is there consensus and divergence on how best to do this?

There are numerous metrics available to calculate an 'exchange rate' between GHGs. Metrics typically use CO_2 as the benchmark and compare other gases to it. The two most common metrics are:

- *Global Warming Potential (GWP)* – used, with a time horizon of 100 years, as the standard metric in IPCC Assessments and under the UNFCCC. GWP measures the cumulative warming effect of the emission of 1 kg of a GHG over a given time period relative to the cumulative warming effect of 1 kg of CO_2 over the same period. The current best estimate of GWP100 for methane is 28.
- *Global Temperature change Potential (GTP)* – increasingly discussed as an alternative. GTP measures the global temperature change at a given point in the future due to the emission of 1 kg of a GHG relative to the temperature change at the same future point due to 1 kg of CO_2. The current best estimate of GTP100 for methane is 4. This is lower than for GWP100 because most of the warming effect of methane occurs in the first three decades after

emission, not in 100 years' time, whereas GWP100 calculates the gases' cumulative effect over the first 100 years.

To be most efficient, the metric chosen needs to be the best proxy for the aims of global climate change policy, such as limiting total temperature change (focus on the peak temperature) and/or limiting the rate of temperature change (focus on the temperature path) and/or limiting overall damages from climate change. Both the merits of the metrics themselves and the policy goals are vigorously debated by some New Zealand climate scientists, but the distinction between metrics and goals is often fuzzy.

Nonetheless, there is consensus that:

- the right value depends on the policy goal and could change substantially over time; and
- if the main policy goal is to cost-effectively limit global average warming to 2 degrees above pre-industrial levels, then the value of CH_4 should be less than the GWP100 value of 28 until global CO_2 emissions have begun to decline steadily towards zero.

How much less? As noted above, the arguments reflect judgments about politics, economics and the intersection of policy and science.

One argument goes that if the goal is to limit warming to about 2 degrees *at lowest global economic costs*, CH_4 must be regarded as having a value of *at least* 10 relative to CO_2 today. This argument is based on the fact the GTP100 of CH_4 is more than 10 when climate-carbon cycle feedbacks are included, and the assessment that 100 years is an extremely generous time horizon for limiting warming to near 2 degrees and would also cater for moderately higher levels of warming such as 2.5 and possibly even 3 degrees.

Another strand of debate is the current GTP100 value of 4 for CH_4 (excluding climate-carbon cycle feedbacks) may be more appropriate for today, given that the current priority must be to reduce CO_2 emissions. Potential revisions to metrics – which may be appropriate in the event that progress is made on CO_2 – could be conducted periodically alongside other potential revisions to targets, reviews of progress, etc.

With regard to New Zealand's economic self-interest, it is by no means clear which metric is best.

2 Introduction

This paper was commissioned by the Parliamentary Commissioner for the Environment (PCE) to answer a series of questions about the science of agricultural greenhouse gases: methane (CH_4) and nitrous oxide (N_2O). These questions have arisen during the Commissioner's investigation into the merits of an "all-gases, all-sectors" Emissions Trading Scheme and how agricultural greenhouse gases should be treated as part of New Zealand's climate change policy. The questions are:

1. What is the current state of understanding of the climate impacts of each greenhouse gas (CH_4, N_2O, CO_2)? Where is there consensus and divergence?
2. Putting aside feasibility, which greenhouse gases should be the central focus of short-, medium- and long-term mitigation efforts? Why?
3. Considering issues of feasibility, how much emphasis should be placed on mitigation of agricultural non-CO_2 gases? Why?
4. How are methane and nitrous oxide emissions from the agriculture sector calculated, and how accurate are such calculations?
5. What methods are used to determine CO_2 equivalencies for other greenhouse gases? Where is there consensus and divergence on how best to do this?

To compile this report, Motu brought together a group of New Zealand climate change and agriculture scientists and industry representatives, and worked with them to develop a response to the Parliamentary Commissioner's questions. The process is detailed in Appendix One.

This report aims to distinguish science from matters of competing values, interests, or assessments of how various national and international actors might behave.

Agriculture is the largest contributing sector to New Zealand's greenhouse gas (GHG) emissions, with agricultural CH_4 and N_2O making up 48% of total emissions in 2013; the second largest sector, at 39%, was energy (MfE, 2015a,b). Attempts to compare CH_4 and N_2O with the most important GHG produced by human activity, CO_2, are a matter of comparing apples and oranges.

Issues such as the basis for comparison and the relative priority to be put on mitigating different gases could have significant implications for New Zealand and/or individual farmers. These decisions are not scientific ones. Rather, they require the transparent application of scientific understanding to clearly articulated policy goals.

Climate change is a global issue, but when it comes to the feasibility of mitigation of agricultural GHGs, this paper focuses on New Zealand conditions, especially pastoral farming. In this area, New Zealand has an active research and development programme. Here, science can make a difference.

3 Climate impacts: gas by gas

The PCE has asked,

> "What is the current state of understanding of the climate impacts of each greenhouse gas (CH4, N2O, CO2)? Where is there consensus and divergence?"

3.1 What drives the climate impacts of greenhouse gases?

The term "climate impacts" usually refers to the consequences of climate change for natural and human systems, such as more frequent severe droughts.

All GHGs warm the atmosphere. They absorb infrared radiation produced when sunlight is reflected by the Earth's surface and they hold this heat energy in the atmosphere. The contribution of any particular GHG to "climate impacts" depends on:

- How effective the gas is at trapping heat energy (its radiative efficiency)
- How long the gas remains in the atmosphere (its longevity – during which time it continues to trap heat)
- How the gas is removed from the atmosphere (e.g., whether it produces other GHGs as it breaks down)
- How much of the gas there is in the atmosphere (its atmospheric concentration, which is the product of how much is emitted and how long it remains there).

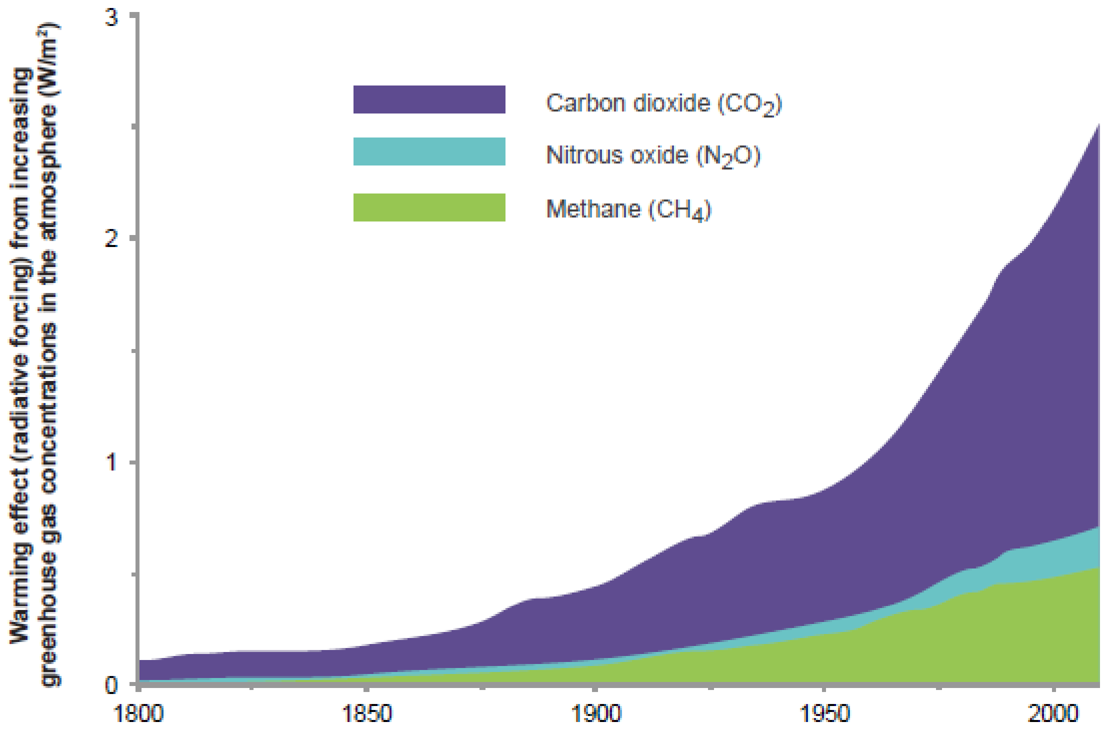
Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), in that order, have made the greatest contribution to the increased energy in the Earth system since 1750. (Stocker *et al*, 2013: 676)

> "Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years."(IPCC, 2014: 16)

Water vapour is the most abundant GHG, but its concentration is almost entirely determined by atmospheric temperatures and hence the concentrations of other GHGs, particularly CO_2. This was recognised by Svante Arrhenius in the 19th century, although scientists today understand the relationship between greenhouse gases and Earth's average temperature in much more detail.[1]

[1] In 2010, for example, Lacis et al showed that if the other major GHGs, CO2, CH4 and N2O, were removed entirely from the atmosphere then the resulting initial drop in temperature would lead to a rapid and continuing decrease in water vapour and the global average temperature would drop below -15°C in ten years.

Figure 1: Combined warming effect from increasing CH_4, N_2O and CO_2 concentrations



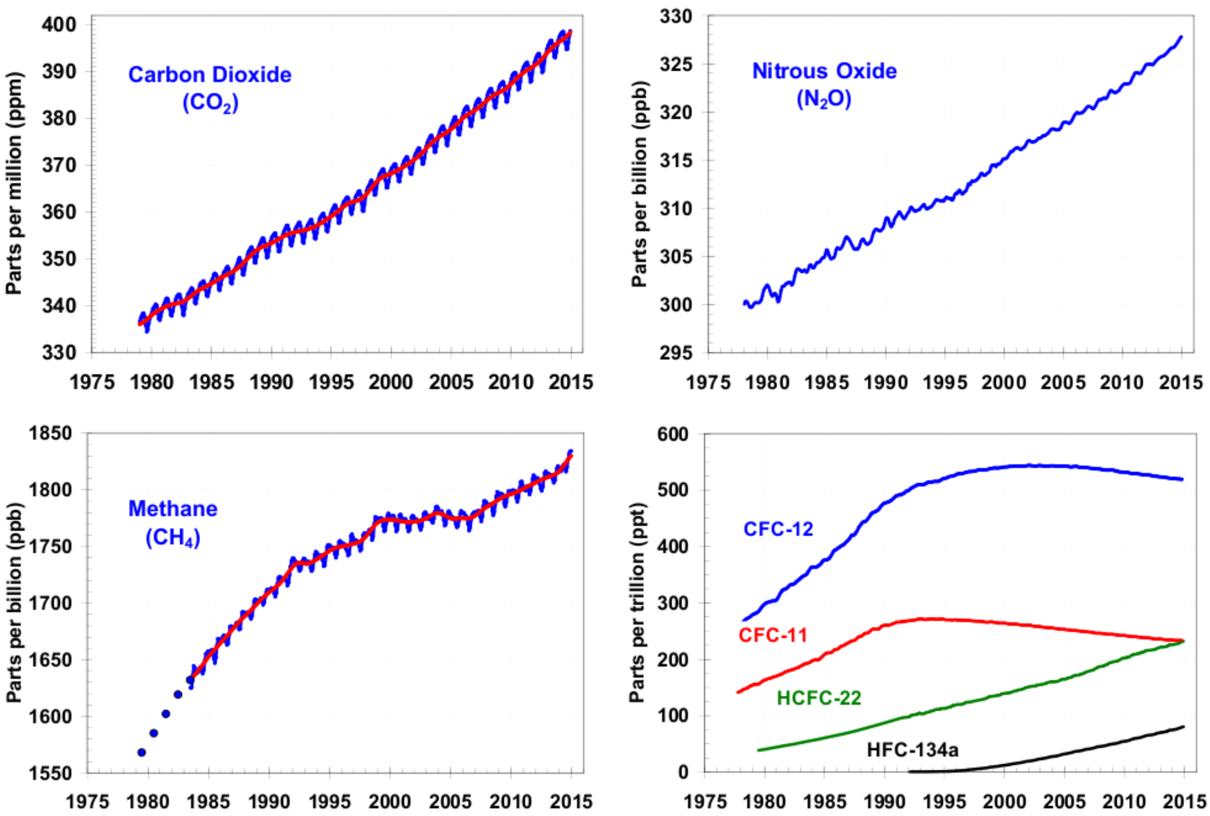
Contributions to the total warming effect on the global climate from methane, nitrous oxide and carbon dioxide from 1800 to 2010. Source: emissions from Meinshausen et al., 2011, Climatic Change 109(1-2), 213-241 and climate model calculations.

In simple terms, a "radiative forcing" is a change imposed on the energy balance of the Earth system (Hansen *et al*, 1997: 6834). The radiative properties of CO_2, CH_4 and N_2O are well known. There has been a robust scientific understanding of their properties in the atmosphere for many decades. Since 1995, reports by the Intergovernmental Panel on Climate Change (IPCC) have consistently expressed "very high confidence" in the radiative forcing mechanisms of these greenhouse gases (Myhre *et al*, 2013: 695).

Other climate forcers include changes in aerosols, the albedo effect, solar irradiance and volcanic eruptions.

Greenhouse gases have very different lifetimes in the atmosphere and are removed from the atmosphere in very different ways. We discuss this gas-by-gas below.

Figure 2: Recent trends in global average concentrations of some greenhouse gases



Source: http://www.esrl.noaa.gov/gmd/aggi/aggi.html

3.2 Carbon dioxide

3.2.1 How much carbon dioxide is there in the atmosphere?

Carbon dioxide is the largest single contributor to global warming relative to pre-industrial temperatures, both in terms of its cumulative concentration in the atmosphere and in terms of the volume of emissions (Stocker *et al*, 2013: 56).

Since pre-industrial times, the concentration of CO_2 in the atmosphere has increased by approximately 142%, to an estimated 396 parts per million in 2013 (WMO, 2014).

3.2.2 What is the trend?

As indicates, the global average concentrations of CO_2 continue to rise. Since 2000, CO_2 concentrations have been increasing by about 2 parts per million per year (Stocker *et al*, 2013: 50).

3.2.3 Where is the extra carbon dioxide coming from?

The main sources of anthropogenic CO_2 globally are fossil fuel burning, deforestation and cement production (in that order).

Carbon dioxide constituted 42.7% of New Zealand's emissions in 2013; the energy sector is the main emitter of CO_2, notably road transport and electricity generation (MfE, 2015a,b).

3.2.4 How long does carbon dioxide stay in the atmosphere?

Carbon dioxide has a very long atmospheric lifetime.[2] In a recent multi-model analysis, a pulse emission of CO_2 showed a rapid decline in the first few decades then "a millennium-scale tail" (Joos *et al*, 2013: 2793).

Allen sums up the implication of this:

> "there is no sustainable CO_2 emission level: global temperatures will continue to rise until net CO_2 emissions are reduced close to zero, with peak temperatures largely determined by cumulative CO_2 emissions up to that time." (Allen, 2015: 9)

If CO_2 emissions dropped by 50%, the concentration of CO_2 in the atmosphere would not drop permanently but, over time, would continue to rise at about half the rate of before the emissions drop.

3.2.5 How does carbon dioxide get removed from the atmosphere?

Large amounts of carbon are continually exchanged between the atmosphere and the oceans, the atmosphere and the biosphere. In photosynthesis, plants and algae use the sun's energy to convert CO_2 and water into carbohydrates and oxygen. In the oceans, CO_2 dissolves in water. But CO_2 is also released from plants, animals and the oceans back into the atmosphere. The net removal of CO_2 from the atmosphere comes from the fact that the amounts of CO_2 absorbed into the oceans and biosphere are currently slightly larger than the amounts going back into the atmosphere.

These net removal processes for CO_2 operate on a wide range of different timescales: in much of the biosphere it takes up to a year before afforestation is absorbing more of a 'pulse' of carbon than it releases each year, but overall the biosphere is removing CO_2 from the atmosphere because deforestation is decreasing and afforestation is increasing globally (fewer trees are being cut down and more trees are being planted). It takes about seven years for the uptake of CO_2 into the surface oceans to be about the same as the amount of CO_2 released back into the atmosphere from the surface oceans, and this timeframe is affected by exchange of water into the deep oceans. There are also much longer time scales (up to millennia) in play for transfers into different forms of soil carbon, and fluxes into rivers and the ocean.[3]

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2 An atmospheric lifetime is defined as the time it takes for a pulse of a GHG to be reduced to 37% of its initial amount. A GHG does not decay evenly over time. For example, in the first 12 years, about 60% of a pulse of CH4 will be destroyed; it takes about another 40 years to remove most of the rest.

3 For time scales longer than about 20 years, transport into the intermediate-depth and then deeper oceans by ocean circulation, as well as by deposition of shell and foraminifera, becomes the dominant factor and this is sensitive to potential changes in ocean circulation processes. At present, water in the deeper parts of the Pacific Ocean contains carbon that has been out of contact with the atmosphere for 500–1000 years. Models of ocean circulation suggest climate change will lead to less mixing into the deeper oceans and so the long-term component of the CO2 removal processes gets even slower. On longer time scales again, much of the carbon going into the deep ocean is eventually

Recent estimates have calculated that roughly 48% of all the carbon released as CO_2 from fossil fuel burning, cement manufacture and land-use changes over the decade 2002–2011 remained in the atmosphere by the end of the decade. Of the remainder, approximately 28% was absorbed by plants and 26% was absorbed by the oceans (Le Quere *et al*, 2013).

3.2.6 Other effects of increased carbon dioxide

The emission of increasing amounts of CO_2 is also causing ocean acidification, with potentially serious consequences for marine ecosystems and food sources. The IPCC's 5th Assessment Report stated "with high confidence" that the pH of the oceans has decreased by about 0.1 since the beginning of the industrial era as a result of the oceans absorbing anthropogenic CO_2 (Stocker *et al*, 2013: 69). In terms of significance for New Zealand, it should be noted that this country's Exclusive Economic Zone is one of the world's largest (over 4 million square kilometres).

3.3 Methane

3.3.1 How much methane is there in the atmosphere?

Since pre-industrial times, the concentration of CH_4 in the atmosphere has increased by approximately 253%, to an estimated 1824 parts per billion in 2013 (WMO, 2014).

3.3.2 What is the trend?

The growth of CH_4 in the atmosphere has been variable: CH_4 concentrations were more or less stable for about a decade in the 1990s but started to grow again in 2007. This is illustrated in Figure 2 above. "The exact drivers of this renewed growth are still debated." (Stocker *et al*, 2013: 52) There are known reasons why CH_4 emissions vary naturally from year to year, however, especially through the effect of the climate on CH_4 release from wetlands.

3.3.3 Where is the extra methane coming from?

Globally, 40% of anthropogenic CH_4 emissions come from agriculture (mainly livestock, but also rice paddies), 30% from fossil fuel production and use (for example, natural gas leaks), 20% from landfill and waste management, and 10% from biomass burning. In New Zealand, CH_4 emissions are predominantly from livestock (79.9% in 2013; MfE, 2015b: 35).

3.3.4 How strong is methane as a greenhouse gas?

Methane is a strong GHG – on a per-weight basis, an emission of CH_4 is 84 times as potent as an emission of CO_2 over the first 20 years after the emission, and 28 times as potent over the first 100 years after the emission. The declining potency of CH_4 over time relative to CO_2 is due to the fact that CH_4 decays much more quickly than CO_2 in the atmosphere. These figures do not

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recycled back to the surface by ocean chemistry and transport processes, but there is some 'permanent' removal of CO2 due to formation of ocean sediments occurring on timescales from 5,000 years to 35,000 years and longer.

include the warming from CO_2 that is produced as CH_4 decays in the atmosphere or the feedback effects from CH_4 emissions on the lifetime of CO_2 that is already in the atmosphere. Methane on its own is responsible for roughly one-fifth of the warming effect from human activities since 1750 (NZAGRC, 2012a).

3.3.5 How long does methane stay in the atmosphere?

Methane is generally quoted as having an atmospheric lifetime of about 12 years, which means that about 60% of a single pulse of CH_4 will be gone from the atmosphere within 12 years, and much of the rest will have disappeared within 50 years. The peak warming effect from a pulse of methane occurs within the first decade after emission, and most of the total warming from that pulse happens within the first 30 years.

So, if CH_4 emissions dropped by 50% and were then held constant, the concentration of CH_4 in the atmosphere would drop rapidly and flatten out within decades, bringing radiative forcing (and hence warming) down with it.

3.3.6 How is methane removed from the atmosphere?

By far the most important way in which CH_4 is removed from the atmosphere is by chemical reactions that take place in the troposphere. The hydroxyl radical (OH) is central to these processes.[4] The OH radical is produced by the action of ultraviolet light on water vapour and, through a series of chemical reactions, it transforms CH_4 into various water-soluble molecules that are washed out of the atmosphere as rain or snow. There is also some uptake of CH_4 by bacteria in soils and in some parts of the ocean, and there is some removal by chemical reactions in the stratosphere.[5]

The breakdown of CH_4 produces other GHGs, including CO_2, carbon monoxide, tropospheric ozone and stratospheric water vapour. These by-products cause significant additional warming (Stocker *et al*, 2013: 56): as Table 1 indicates, the production of other GHGs during the breakdown of CH_4 is estimated to have contributed more than a third of the total warming from CH_4 emissions during the industrial era (to 2011). Tropospheric ozone is also hazardous to human and animal health and reduces the productivity of crops (Allen, 2015: 9).

For agricultural methane, however, the CO_2 molecule produced as a result of the breakdown of CH_4 simply replaces the CO_2 molecule that was originally stored in grass and eaten by a ruminant animal. The warming effect of this ‘recycled’ CO_2 is not included in the metric calculation that CH_4 is 28 times more powerful than CO_2 over 100 years. Thus, farmers are not ‘penalised’ for CO_2 from agricultural methane.

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[4] The hydroxyl radical is also pivotal to the atmospheric oxidation of other GHGs, such as HFCs, which, as ozone-depleting substances, may overtake in importance the CFCs and HCFCs that are being phased out under the Montreal Protocol on Ozone Depleting Substances.

5 Each of these removal processes is expected to change over time, and OH removal had been expected to become less effective as atmospheric CH4 concentrations rise. Thus far, OH has proved remarkably resilient but scientists continue to monitor OH levels with concern.

It is sometimes claimed that agricultural CH_4 is not a concern because livestock farming essentially recycles carbon (from the atmosphere into grass, from grass into livestock, and from livestock back into the atmosphere through respiration, enteric fermentation, dung and decay of livestock products). This belief does not account for the fact that some of the carbon consumed by livestock is transformed into CH_4 in the animal's rumen. Since CH_4 is a much more powerful GHG than CO_2, albeit a short-lived one, the farming of ruminant animals has a significant global warming effect. Reducing the emissions of any GHG makes a real difference.

3.4 Nitrous oxide

3.4.1 How much nitrous oxide is in the atmosphere?

Since pre-industrial times, the concentration of N_2O in the atmosphere has increased by approximately 121%, to an estimated 325.9 parts per billion in 2013 (WMO, 2014).

3.4.2 What is the trend?

As illustrates, the global average concentration of N_2O continues to rise and is now approaching 330 parts per billion.

3.4.3 How strong is nitrous oxide as a greenhouse gas?

Tonne for tonne, N_2O is a much more powerful GHG than CO_2 – over 100 years an emission of 1 kg N_2O traps 265 times more heat in the atmosphere than the emission of 1 kg of CO_2 – but there is much less of it in the atmosphere. (The atmospheric concentration of CO_2 is approaching 400 parts per million – more than 1000 times greater.)

3.4.4 How long does nitrous oxide stay in the atmosphere?

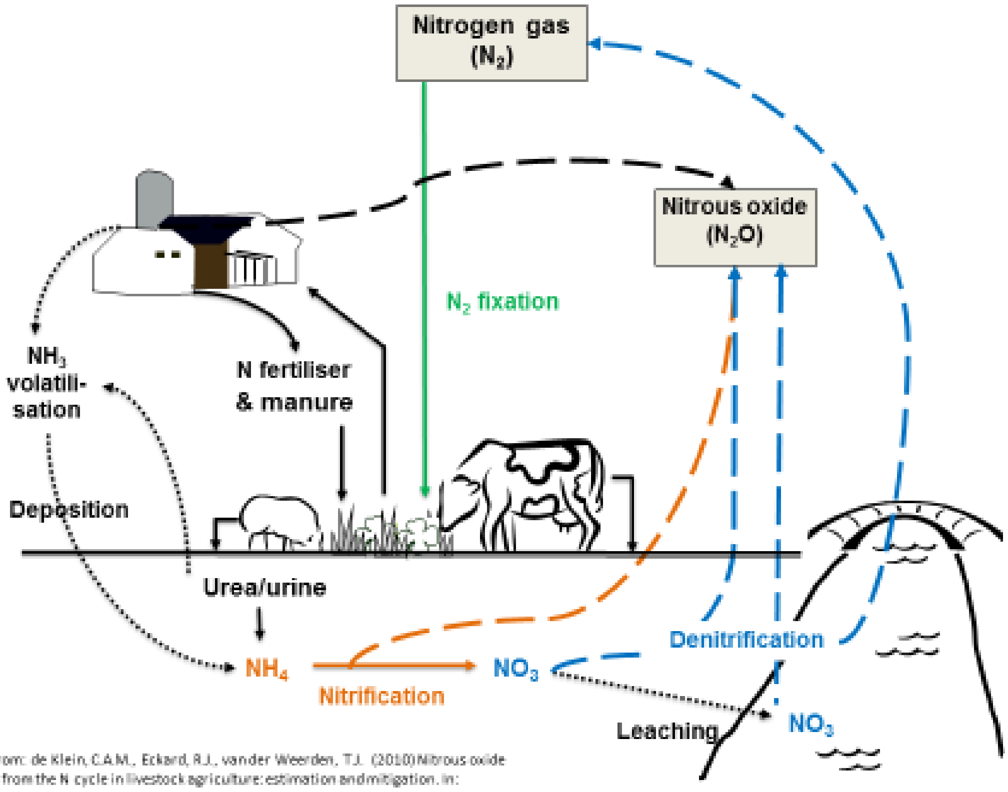
With an atmospheric lifetime of 120 years, N_2O is a long-lived gas.

3.4.5 Where is the extra nitrous oxide coming from?

Globally, most N_2O emissions come from agricultural soils, including the use of nitrogen fertilisers, with additional sources from some industrial processes. Almost all of New Zealand's N_2O emissions come from agricultural soils, specifically the breakdown of patches of animal urine on paddocks and from the application of nitrogen fertiliser. The production of arable crops also results in the emission of N_2O, but this is less of an issue in New Zealand than N_2O from pastoral agriculture.

There are principally two naturally occurring soil microbial processes at work: nitrification and denitrification. Nitrification is the oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) with N_2O as a by-product. Denitrification, generally accepted as the main source of N_2O from grazed pastoral soils, is the reduction of nitrate (NO_3^-) to nitrogen gas (N_2), with N_2O being produced along the way (de Klein *et al*, 2008). Both these processes are illustrated in Figure 3.

Figure 3: The nitrogen cycle



Adapted from: de Klein, C.A.M., Eckard, R.J., van der Weerden, T.J. (2010) Nitrous oxide emissions from the N cycle in livestock agriculture: estimation and mitigation. In: *Nitrous Oxide and Climate Change* (Ed. K.A. Smith) Earthscan Publications. Pp 107-142

3.4.6 How is nitrous oxide removed from the atmosphere?

For N_2O, the removal from the atmosphere is predominantly through the action of solar radiation on the chemistry of the stratosphere, although soil and biological processes remove some as well.

3.4.7 Other effects of nitrous oxide

Action on N_2O emissions often has co-benefits for reducing nitrate leaching to waterways and vice versa.

Carbon dioxide and CH_4 increase stratospheric ozone, whereas N_2O depletes it. As the Montreal Protocol successfully phases out other ozone-depleting substances, these GHGs may determine how quickly and to what levels the ozone layer recovers again later this century.

3.5 Comparison of gases

Table 1 below compares some features of the three gases in question. The cumulative effect of past emissions shows the combined warming effect of: the amount emitted, the relative potency of the gas tonne for tonne, and how long the gas remains in the atmosphere.

Table 1: Comparison of GHGs

Name	**Chemical formula**	**Atmospheric lifetime**	**Cumulative effect of past emissions, 2011 (in watts per square metre)**	**Global emissions, 2011 (in millions of tonnes)**	**Other non-warming effects**
Carbon dioxide	CO_2	Centuries to millennia	1.7 W/m^2	38,000 Mt	Ocean acidification
Nitrous oxide	N_2O	120 years	0.17 W/m^2	7 Mt	Stratospheric ozone depletion
Methane	CH_4	12 years	0.64 W/m^2 (direct) 1.0 W/m^2 (total, includes indirect effects)	330 Mt	Increase tropospheric ozone

Source: Adapted from Allen, 2015: 10 and Myhre et al, 2013.

As discussed above (Section 3.3.6), when CH_4 is broken down in the atmosphere, it produces substances that themselves warm the planet, especially ozone in the troposphere and water vapour in the stratosphere. In Table 1, the "total" includes some of the more well-established indirect effects.

There is increasing recognition that emissions of non-CO_2 gases also influence the lifetime of CO_2 in the atmosphere (known as "climate-carbon cycle coupling"). The latest IPCC report provides estimates for the warming effect from CH_4 if this indirect warming were included: in that case, over 100 years, emitting 1 kg of CH_4 would cause 34 times the warming of 1 kg of CO_2. The corresponding figure without climate-carbon cycle coupling is 28 times. The basic mechanisms behind this indirect warming effect are well understood but there are relatively large uncertainties regarding its exact magnitude (Myhre *et al*, 2013).

Estimates of the relative potency of the different gases are updated from time to time. This is not evidence of diverging scientific opinion, but simply reflects the fact that increasing amounts of GHGs in the atmosphere change the radiative efficiency of these gases. In addition, evidence about additional indirect warming effects and about the natural processes by which GHGs are removed from the atmosphere is increasing with on-going research, which can result in revisions to the exact numbers.

4 Which gas(es) should be the priority for mitigation?

The PCE has asked

> "Putting aside feasibility, which greenhouse gases should be the central focus of short, medium and long-term mitigation efforts? Why?"

For the purposes of this report, we define feasibility as the existence of technically viable options for mitigation. How far and how fast people (individually and collectively) take mitigation action also depends on social, cultural, economic and political factors, which are beyond the scope of this report; for instance, measures may be technically feasible but not financially viable or politically palatable.

4.1 Fundamental importance of carbon dioxide

The overriding need to reduce CO_2 emissions is scientifically uncontentious. There is a strong, direct relationship between cumulative emissions of CO_2 and global warming, so in order to limit the warming, we must limit the cumulative emissions of CO_2; ultimately CO_2 emissions must decline to zero for the climate to stabilise. In this sense, therefore, CO_2 must always be the "central" focus of mitigation efforts in the short, medium and long term.

If the international community wants to limit warming at any level, then the close relationship between cumulative emissions of CO_2 and overall levels of warming suggests that a CO_2-first focus is the place to start since any delay in emission reductions would require an even more rapid reduction later to achieve the same climate outcome. There is, however, debate about whether CO_2 should be the sole focus.

A key part of this debate hinges on the different behaviour of long-lived versus short-lived GHGs in the atmosphere. If the world capped emissions of CO_2 and N_2O at current levels, the atmospheric concentration of these gases – and their warming effect – would keep increasing for hundreds to thousands of years. To stabilise the climate, it is necessary to reduce the overall (net) emissions of long-lived climate forcers to zero. By contrast, emissions of short-lived climate forcers do *not* have to decline to zero; they only have to stop increasing. If the world caps emissions of CH_4 at current levels, the atmospheric concentration of CH_4 – and its effect on global temperature – would stabilise over the course of a few decades. To put it another way, short-lived climate forcers have a temporary effect on the Earth's energy balance on a time-scale of years to decades, while CO_2 emissions effectively cause a permanent change.

Table 2: Comparison between long-lived and short-lived GHGs: response to change in emissions

Change in emissions	Change in concentration as a result	
	Long-lived GHGs (CO2, N2O)	**Short-lived GHGs (CH4)**
Continue to increase emissions	Increase	Increase
Stabilise emissions (i.e., keep emitting but at a steady rate, no increase)	N_2O: increase for c. 100 years CO_2: increase continues for 100s of years	CH_4: increase for c. 10 years then stable
Decrease emissions	Increase, or stable, depending on scale of emissions reductions	Decrease, or stable, depending on scale of emissions reductions
Eliminate (i.e., net zero emissions)	N_2O: decline to pre-industrial levels in several centuries CO_2: effectively never return to pre-industrial levels over 1000s of years (IPCC, 2013b: FAQ12.3)	CH_4: decline to pre-industrial levels in about 50 years
Negative emissions (i.e., remove more than is emitted)	CO_2: technically feasible, could reduce CO_2 concentrations to pre-industrial levels if required N_2O: not currently technically feasible	CH_4: not currently technically feasible

Note that while it is necessary to reduce the overall (net) emissions of long-lived climate forcers to zero, this does not mean that emissions of every long-lived GHG individually must be eliminated. There are already ways to take more CO_2 out of the atmosphere than is put in (e.g., reforestation, increasing soil carbon, bioenergy combined with industrial carbon capture and storage), and this could enable some N_2O emissions to continue if that was deemed desirable or necessary.

Note, too, that even though, at minimum, short-lived GHG emissions must stabilise, it may still make sense to cut these emissions below current levels, as this would reduce overall warming.

The debate over short-lived climate forcers turns on whether, and in what circumstances, effort should be put into mitigating CH_4 *in addition* to mitigating the long-lived greenhouse gases.

On one side, advocates of a comprehensive multi-gas approach point to the cost-effectiveness of this approach, as it would allow CO_2 emissions to be reduced to zero just a little more slowly while achieving the same outcome in terms of peak warming. Recent work by Reisinger *et al* (2015) suggests that without mitigation of agricultural non-CO_2 gases, CO_2 emissions would have had to peak already or in the very near future to have a reasonable chance of warming not exceeding 2°C. Current international agreements follow a multi-gas approach.

On the other side, advocates of a focus on long-lived gases, or exclusively on CO_2, argue that CO_2 mitigation promises to be difficult and costly enough without adding extra costs to the economy overall by trying to address other gases as well. They express concern that putting effort into short-lived gases misses the point that every emission of CO_2 today matters for the ultimate peak temperature. One leading voice on this side of the debate puts it:

> "to meet the goals of the UNFCCC, policies are required to ensure that global CO_2 emissions are contained within a cumulative budget consistent with limiting warming to a safe level. These policies must be independent of, and in addition to, any multi-gas emission goals. In effect, this implies a 'peak CO_2 first' strategy: the need to limit cumulative CO_2 emissions would over-ride most opportunities to offset CO_2 reductions against SLCP [short-lived climate pollutant] measures until global CO_2 emissions are falling fast enough that there is a realistic prospect of meeting the cumulative budget. As soon as those conditions are met (for example, when CO_2 emissions are projected to reach zero before global temperatures reach 2°C), SLCP emission reductions will become a crucial priority to limit peak warming." (Allen, 2015: 22. Emphasis added.)

These differences are about how to apply generally agreed scientific understanding to policy. They are not about the science itself. The drivers for the two 'sides' reflect different assessments of political and economic conditions.

Table 3: Which GHGs should be the focus of mitigation efforts?

GHG mitigation focus	**Arguments for**	**Arguments against**
Focus exclusively on CO_2	Reflects reality that CO_2 is the primary problem. Clear message easy to communicate. Single focus reduces potential for perverse policy outcomes. A 2°C target has no basis in science and/or 2°C is unrealistic as a target – better to exceed 2°C a little but keep the clear focus on the main source of long-term warming.	Fewer options available to achieve same temperature target. Much greater costs due to the requirement to reduce CO_2 more rapidly. It may already be too late to meet a 2°C target by focusing only on CO_2.
Focus on long-lived gases, CO_2 and N_2O (ignore short-lived climate forcers)	Provides countries with more flexibility about their options for how to limit warming than a CO_2-only focus. A 2°C target has no basis in science and/or 2°C is unrealistic as a target – better to exceed 2°C a little but keep the clear focus on the main source of long-term warming.	Fewer options available to achieve same temperature target than a comprehensive approach. Greater costs than if short-lived climate forcers also included. It may already be too late to meet a 2°C target by focusing only on CO_2 and N_2O.
Take a comprehensive multi-gas approach, including short-lived climate forcers	Likely to be cheaper and easier to achieve same temperature target. Encourages development of options to address other gases that may prove useful closer to peak temperature.	Waters down the message that CO_2 mitigation is the most crucial. Potential for perverse policy outcomes, e.g., excessive focus on short-lived climate forcers.

4.1.1 The 2°C target:

Under most scenarios, GHG emissions have to start declining within the next 15 years in order to reach a target of limiting global warming to no more than 2°C above pre-industrial levels[6]. The longer the delay now, the more difficult global mitigation efforts are likely to be. If concerted global efforts to reduce GHG emissions do not result in declining global CO_2 emissions within 15 years or so (roughly 2030),

> "it will require substantially higher rates of emissions reductions from 2030 to 2050; a much more rapid scale-up of low-carbon energy over this period; a larger reliance on CDR [carbon dioxide removal[7]] in the long term; and higher transitional and long-term economic impacts." (IPCC, 2014: 24)8

The science is clear that the higher the global mean surface temperature is allowed to go, the more severe the overall impacts, but there is no basis in science to regard 2°C as a threshold in itself. In the main, climate impacts are not likely to increase in severity in a gradual, uniform (linear) manner. The severity of impacts may increase exponentially and/or by step-changes when biological or human systems cross thresholds where they cannot cope any more. Thus, it is not clear how much worse things will be if the global temperatures were to peak at, say, 2.1°C.

Proponents of an exclusive focus on long-lived GHGs (until it is clear that CO_2 emissions are approaching zero, or at least declining sustainably towards zero) sometimes argue:

- An early focus on CH_4 diverts attention and effort away from CO_2 and so makes it less likely that global temperatures will peak near 2°C. The sooner stringent mitigation action is taken on CO_2 the better.
- There is little sign of the concerted international and national action required to keep global warming under 2°C and a more effective strategy for limiting global warming is to get serious about CO_2 rather than act as if 2°C is going to be met.
- If CO_2 emissions are not going to drop to zero within the next 40-60 years (i.e., if the international community misses the 2°C target), action now on CH_4 makes no difference to the peak temperature. It is important to focus resources (money and political effort) where they will more likely bring the biggest benefit.
- In New Zealand, most action to mitigate N_2O emissions will constrain CH_4 emissions as well as improving water quality.

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6 "These scenarios are characterized by 40 to 70% global anthropogenic greenhouse gas emissions reductions by 2050 compared to 2010, and emissions levels near zero or below in 2100." (IPCC, 2014: 20)
7 Carbon dioxide removal techniques range from the restoration of natural carbon sinks through reforestation to novel geo-engineering solutions.
8 It should also be noted that temperature stabilisation (e.g., at 2ºC) is not the same as stabilisation of the Earth system. As a species, we have already committed the planet to future climate change as a consequence of the stock of anthropogenic CO2 in the atmosphere today. Many aspects of climate change, such as polar ice sheet melt and sea-level rise will continue for centuries, even if GHG emissions are stopped.

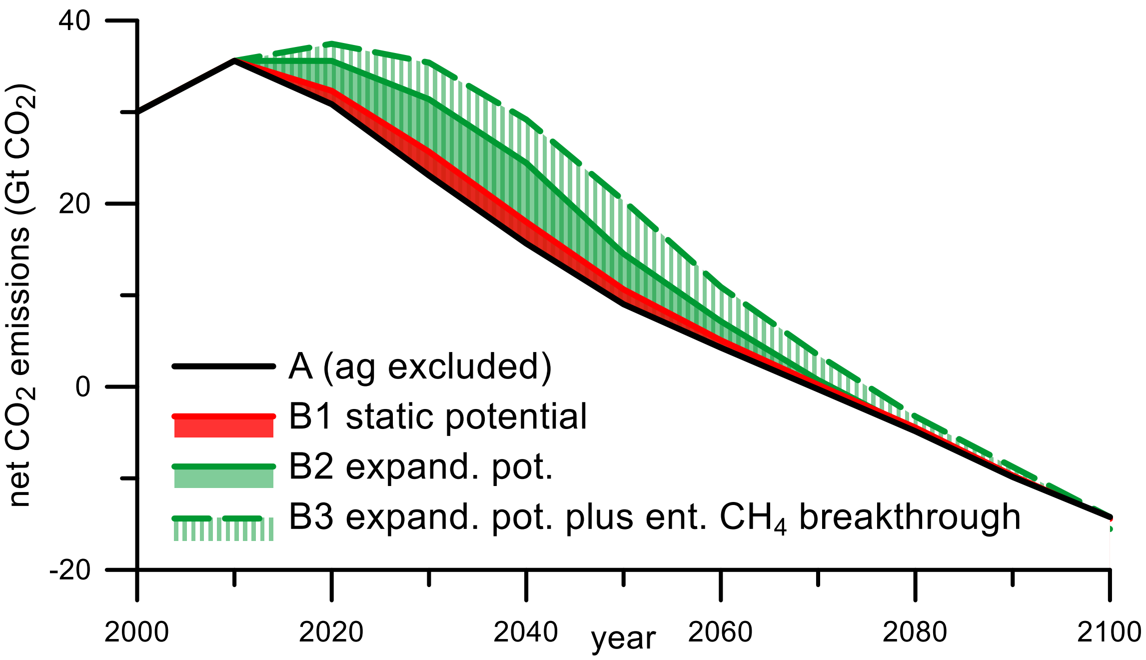
Proponents of a comprehensive approach sometimes argue:

- 2°C is the stated international goal at this time, so nations should look seriously at how to achieve it. A target is necessary because it enables policy to be based on cost-effectiveness and/or it focuses decisions.
- Agricultural non-CO_2 gases must be included in order to achieve 2°C; it may already be too late to achieve 2°C with CO_2 reductions only.
- Early CH_4 mitigation can at least delay *when* peak temperature is reached.
- Even if countries fail to achieve the 2°C target, reducing CH_4 emissions will mean that temperatures peak at a lower level than would otherwise have been achieved.
- Ambitious and sustained mitigation of CH_4 would allow the necessary decline of CO_2 emissions to occur just a few years more slowly (while achieving the same peak warming); this makes CO_2 mitigation more feasible and at lower cost.

The figure below, taken from Reisinger *et al* (2015), suggests that without mitigation of agricultural non-CO_2 gases, CO_2 emissions would have had to peak already or in the very near future to have a reasonable chance of not exceeding 2°C. Reisinger *et al* estimate that action on N_2O and CH_4 could allow a delay of up to 15 years in peak CO_2 emissions, subject to new technology for enteric fermentation.

Figure 4 shows when and by how much CO_2 emissions have to be reduced to achieve a 2°C target under various scenarios. Scenario A assumes no mitigation of agricultural non-CO_2 emissions. Scenario B1 assumes that efforts are made to reduce agricultural non-CO_2 emissions but that the potential to do so is limited and does not expand with time. Scenario B2 and B3 assume expanded potential for mitigation. B3 adds a cost-effective technological breakthrough that substantially reduces CH_4 emissions from livestock. All scenarios result in the same amount of radiative forcing in the year 2100; under the B scenarios CO_2 emissions do not have to be cut as soon to achieve the same result.

Figure 4: Modelled net CO_2 emissions, with varying levels of action on agricultural GHGs



4.1.2 Importance of the temperature path:

The arguments for and against early action on CH_4 are essentially the same whatever the ultimate temperature peak. (2°C is simply the currently accepted international goal.)

As noted above, early action on CH_4 can buy time for adaptation, by dampening near-term warming. The physical limit on the potential gains from mitigating CH_4 is about 10–15 years. This assumes that a concerted focus on CH_4 does not reduce action on CO_2, and some scientists express doubt about that. Assuming effective simultaneous action were taken on both gases, whether this would be a good use of resources depends on the cost-effectiveness of mitigation versus adaptation measures at the time.

In modelling by Rogelj *et al* (2014), the stringent CH_4 mitigation scenario reduces the average rate of temperate change per decade by about 20% between 2010 and 2030, and by about 25-40% between 2030 and 2050.[9]

As Allen points out there are two different goals here: action to limit peak warming (medium to long term); and action to dampen current climate change (short term). In both cases, CH_4 mitigation could play a role but it is important to be clear what that role is. Methane mitigation is not a reason to delay CO_2 mitigation: "Long-term climate change is overwhelmingly determined by cumulative CO_2 emissions, so the longer actual reductions in CO_2 emissions are postponed, the more difficult it becomes to limit long-term warming. The same rate of CO_2

9 The same study shows that CO2 mitigation can also dampen near-term warming: the stringent CO2 mitigation scenario reduces the average rate of temperature change per decade by more than 50% between 2030 and 2050 (Rogelj et al, 2014: 4).

emission reductions that would limit CO_2-induced warming to 3ºC if initiated now would only limit it to 4ºC if initiated after 15 more years of emissions growth at 2% per year." (Allen, 2015: 22)

Even if a judgment is made that policy should focus solely on limiting peak warming, and hence that CO_2 and N_2O are most important in the short term, policy makers must still consider research and development lead times, especially if it is deemed necessary in New Zealand to mitigate CH_4 without reducing total agricultural production.

4.1.3 Mitigation close to peak temperature:

Once it is clear that CO_2 emissions are approaching zero, mitigation of CH_4 can make a difference to what the peak temperature is.[10] How much difference? Estimates vary. Bowerman *et al* (2013) estimate about 0.2°C. Rogelj *et al* (2014) give a range of 0.3–0.7°C.

Hence, many scientists who doubt the value of significant early CH_4 mitigation, do advocate stringent CH_4 mitigation once CO_2 mitigation is well underway. There is no agreed definition of precisely when this action should kick in.

4.1.4 Case of an environmental tipping point:

If the world were to approach a major environmental tipping point, it would make sense to use CH_4 mitigation *on top of* action on long-lived gases in an attempt to avert the tipping point.[11]

Tonne for tonne, what would matter in such a situation is the short-term potency of each GHG; and CH_4 is much more potent than CO_2 over approximately the first 10 years. But at the extreme, the world would run out of CH_4 to abate. Action on short-lived climate forcers could postpone the tipping point; action on long-lived climate forcers must be taken to avoid it.

Note that we say action on short-lived climate forcers *could* postpone the tipping point because natural climate variability can have a large effect on global temperature in the short term. The obvious response is to build in a safety margin by reducing CO_2 emissions as soon as possible.

5 Feasibility of mitigating agricultural non-CO2 emissions

The PCE has asked

> "Considering issues of feasibility, how much emphasis should be placed on mitigation of agricultural non-CO_2 gases? Why?"

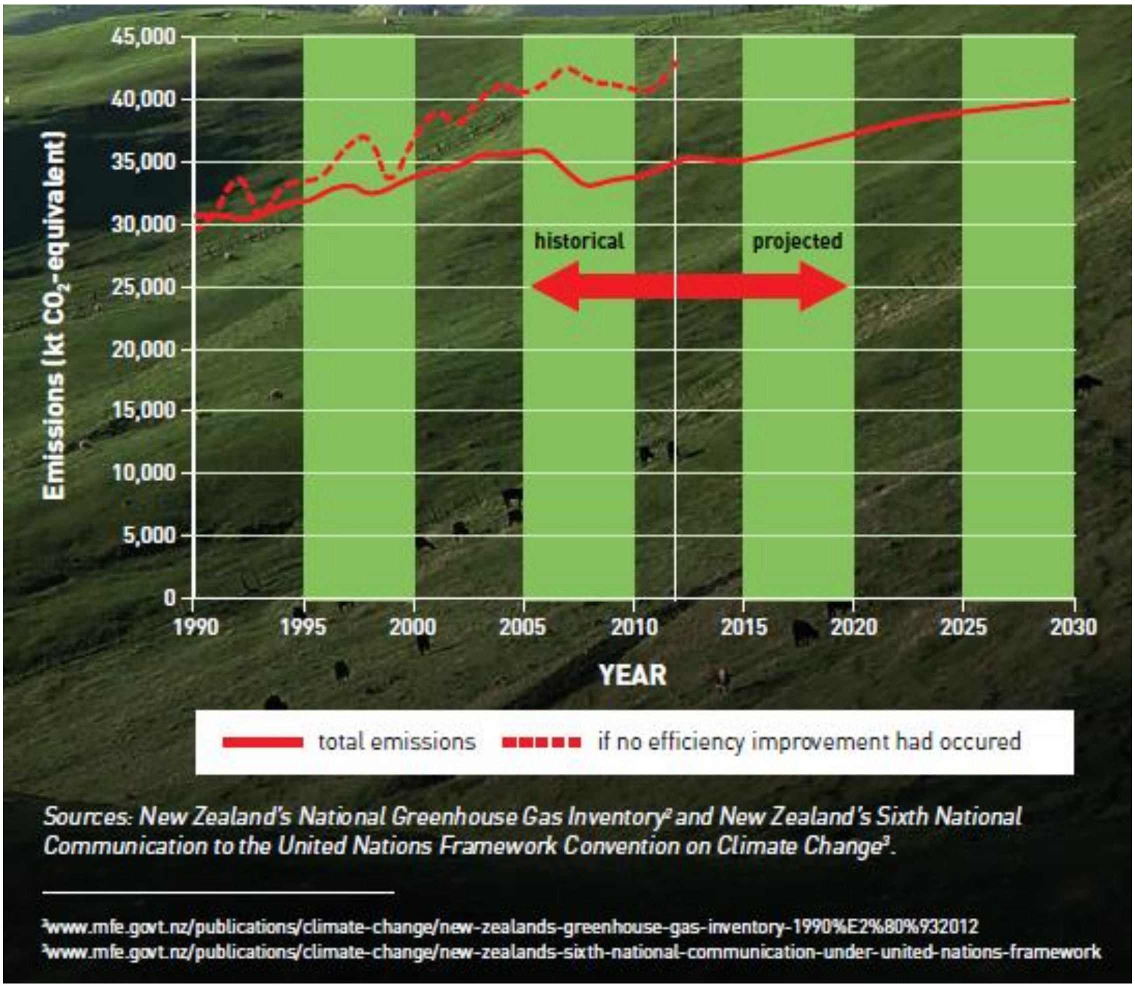
10 Mitigating other short-lived climate pollutants, especially HFCs, near the peak could have additional positive benefits, but it is worth noting that key emission sources of black carbon (soot) would be phased out already by CO2 mitigation (Rogelj et al, 2014: 1).

11 This discussion assumes, of course, that the timing of an environmental tipping point could be predicted, and that those predictions are heeded.

New Zealand has already successfully reduced agricultural emissions intensity: on average, GHG emissions on-farm per unit of meat or milk produced have dropped by about 1% per year on average for at least the past 20 years. Improved animal genetics and management, combined with better grassland management and feeding practices, mean that farms are using resources much more efficiently to increase their outputs. Without these efficiency gains, New Zealand's total agricultural GHG emissions would have increased by about 40% since 1990, as illustrated in Figure 5.

As it is, however, the country's total agricultural GHG emissions have increased by about 15% since 1990 because total agricultural production has increased faster than the achieved efficiency gains. From another perspective, if farmers in New Zealand had maintained the same level of food production as they had in 1990, total emissions from the agriculture sector would now be about 20% below 1990 levels due to efficiency gains. This demonstrates that emissions reductions are feasible and do not necessarily conflict with food production, but it also shows that total emissions reflect a balance between population/economic growth and environmental objectives.

Figure 5: New Zealand's actual and projected agricultural GHG emissions, 1990–2030



Source: NZAGRC and PGgRc (2015b)

There may be scope for more consistent implementation of current best practice on farms that could further reduce emissions intensity. Further increases in milk production per cow, and increasing lambing percentages, would be expected to further decrease emissions intensity even under a business-as-usual approach over the next 10–20 years. However, there are a variety of estimates of how much more can be achieved by best practice alone.

There are also some options already available that could be used on some farms to limit total emissions growth (not just emissions intensity), notably: reducing stocking density combined with use of higher genetic merit animals, low-nitrogen feed, more targeted use of nitrogen fertiliser, improved manure management from housed animals, and maintaining carbon inputs to soils. Nitrification inhibitors have been shown to reduce emissions but are not currently an option owing to residue concerns. Urease inhibitors are technologically similar to nitrification inhibitors and residue-free on current evidence; they are being applied to about 200,000 hectares of pasture in New Zealand.

Despite the options above, total agricultural emissions are projected to continue to rise in the short to medium term due to planned increases in total production.

To turn this trend around would take some or all of the following:

- Constraining total production at current levels while increasing efficiency gains
- Future scientific and technological breakthroughs
- Shifts in production (i.e., away from ruminant animals).

The New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC) and Pastoral Greenhouse Gas Research Consortium (PGgRc) have summarised a suite of New Zealand-led research initiatives into agricultural GHG mitigation options (for full details, see NZAGRC and PGgRc 2015b). Some may become available within 2–5 years:

- Breeding low-emitting sheep and cattle
- Low-CH_4 feeds and feed additives
- Methane inhibitors
- Low-nitrogen feeds and enhanced plant growth at lower nitrogen levels
- Application of biochar to some pasture.

Longer term (more than 5 years from commercial reality), New Zealand scientists are working on:

- Methane vaccines
- Low emissions forages and active chemical compounds (e.g., natural nitrification inhibitors)
- Promoting plants and soil microbes that convert dung, urine and fertiliser into less harmful forms of nitrogen (rather than N_2O and nitrates)
- Enhancing soil carbon sinks.

Technical feasibility is only one part of the story; the rate and extent of adoption of new technologies, systems and techniques will have a significant effect on net emissions reductions.

If a technology could reduce emissions by 30% but it is used on only 10% of the national herd, total emissions would be reduced by only roughly 3%. Policy choices then arise about whether and how to create incentives for uptake of particular mitigation options.

Regardless of their position on how much focus should remain on CO_2 (Section 3 of this report), most scientists agree that 'easy wins' should be taken on all gases.

Internationally, the lower cost options for CH_4 mitigation tend to be in fossil CH_4, especially by plugging leaks from gas pipes. There is also considerable scope for efficiency gains that reduce the emissions intensity of agricultural production in many developing countries (without the need for new technologies).

However, it is clear that it is not currently 'easy' for New Zealand farmers to achieve net emissions reductions of non-CO_2 gases without reducing production or changing their product mix (away from ruminant animals). If farmers were to hold production steady at current levels, every efficiency gain would result in net emissions reductions, but opinion varies as to how much more can realistically be achieved; some suggest that current on-farm skill levels may put a ceiling on improvements while others expect the long-term trend of efficiency gains to continue.

There is no consensus amongst New Zealand scientists as to how much emphasis should be put on mitigation of agricultural non-CO_2 gases beyond continuing to improve emissions intensity, although it is recognised that there are substantial co-benefits for water quality of reducing leaching and nitrate runoff. The divergence of views reflects the arguments traversed in Section 4 of this report, which arise from differences about policy goals and processes, and how science is seen to interact with policy.

6 Calculation of agricultural greenhouse gases

The PCE has asked

> "How are methane and nitrous oxide emissions from the agriculture sector calculated, and how accurate are such calculations?"

6.1 Local measurements

Current methods for measuring emissions of CH_4 and N_2O at the level of individual animals or paddock scale are used, amongst other things, to verify the emissions factors employed in New Zealand's national GHG inventory (the "National Inventory"). The methods are resource intensive, and some are themselves subject to considerable uncertainty. It would not be feasible to use these methods as tools to directly estimate and monitor farm-level emissions across the country. (These methods are described in more detail at NZAGRC and PGgRc, 2015a.)

For CH_4, respiration chambers produce the most precise measurements but are labour and resource intensive, can be used only on a very limited number of animals, and cannot replicate 'real world' conditions. The sulphur hexafluoride tracer technique, in which an animal is fitted with a 'yoke' that samples its breath, allows animals to graze freely in a paddock, but is still labour intensive and is not as accurate as respiration chambers. Various portable accumulation chambers and 'hoods' are also under development.

For N_2O, soil chambers can directly measure N_2O from small plots (e.g., urine patch areas), but there is uncertainty associated with upscaling to larger areas. Soil chambers are relatively labour intensive and a very large number of chambers would be required to measure paddock-scale N_2O emissions. Measuring emissions from a farm as a whole is not feasible with soil chambers.

At the paddock scale, scientists are also using micro-meteorological techniques to calculate the amount of CH_4 or N_2O generated by all the livestock in a paddock. These can be useful to check whether it would be reasonable to upscale the measurements from individual animals or small plots to represent emissions of the total number of animals and the total area of a farm. Micro-meteorological measurements are labour intensive, highly technical and very difficult to make with a great deal of precision – there are many variables at play and the gas fluxes that the techniques are trying to measure are, individually, small.

6.2 National-level estimates

From experiments, especially those using respiration chambers, it is clear that there is a strong relationship between the amount of food an animal eats (for most of the pastoral diets of New Zealand animals) and the amount of CH_4 it emits. These empirical data underlie the emissions factors used in the National Inventory to turn estimates of the total dry matter intake into estimates of the amount of CH_4 emitted. The total dry matter intake is then also combined with the nitrogen content of the feed to estimate the amount of nitrogen excreted by animals, and the percentage of this nitrogen that is then released to the atmosphere as N_2O.

The National Inventory is a tool for monitoring trends in absolute emissions and emissions intensity at a national scale. It generally does a very good job with trends, and a less good job (i.e. has significant uncertainties) with absolute numbers. The equations underlying the National Inventory are simple and miss differences between farms, but are considered broadly robust at the aggregate regional and national level.

As mentioned above, the emissions factors used in the National Inventory are based on measurements in experimental studies that are each associated with a level of uncertainty. However, the quality of so-called "activity data", i.e., the information used to estimate input variables such as the number of animals, animal production levels, fertiliser, etc., is also an important factor determining the uncertainty of the GHG estimates.

In the most recently released figures for New Zealand's National Inventory, the uncertainty in net emissions (including the land-use, land-use change and forestry sector) for the 2013 calendar year is ±11.2%. The uncertainty in the trend in net emissions since 1990 is ±12.3%. (MfE, 2015b: 23).

More specifically for agriculture, the overall uncertainty of the 2013 inventory figure for enteric CH_4 emissions (from dairy and non-dairy cattle, sheep and minor livestock populations such as goats, horses and swine), expressed as a 95% confidence interval, is ±16% (MfE, 2015b: 147). For CH_4 from manure management, New Zealand assumes the IPCC default uncertainty values of ±20% and ±30% depending on the methodology used in the calculations (MfE, 2015b: 158). For N_2O emissions from agricultural soils, using a 95% confidence interval, uncertainties in the annual emissions figure have been assessed as +74% and -42%, but "*the uncertainty in the trend is much lower than the uncertainty for an annual estimate*" (MfE, 2015b: 176).

The National Inventory undergoes annual independent international expert review. Improvements and refinements of the basic equations that relate feed consumption to CH_4 emissions, and nitrogen excretions to N_2O emissions, supported by targeted measurements, can result in changes in emissions factors over time. Where emissions factors change, this is applied to the entire time series of emissions back to 1990 to ensure consistent accounting of changes over time.

At a regional and national scale, atmospheric inversion methods can estimate the spatial distribution of CO_2 and non-CO_2 emissions. This technique uses continuous measurement of atmospheric gas concentrations at selected sites and combines it with computer modelling. It can pick up natural fluxes of gas that are not accounted for in national inventories, and may be used as a 'top-down' comparison with the 'bottom-up' national inventory. This method is still subject to considerable uncertainty: typically in the range of ± 35% for work done to date in New Zealand.

6.3 Farm-scale calculator

The only on-farm calculator widely in use in New Zealand is the nutrient budget model OVERSEER® (Overseer). Initially a nutrient budgeting tool, Overseer was not designed to estimate farm-level GHG emissions but can be used for that purpose. It relies on combining GHG emissions factors specified in the National Inventory with data about the farm itself. The quality of these farm input data is at least as important as the quality of the emissions factors and will vary.

Overseer has a mixed reputation within the farming community, especially in catchments where it has been used as a regulatory tool. There are complaints that the software is not user-friendly, although the Overseer budget is usually completed by trained consultants rather than by farmers themselves. Farmers' familiarity with Overseer may make it advantageous to use for GHG accounting and using it would avoid farmers having to deal with a second tool or model.[12]

For CH_4, Overseer combines data about the farm (e.g., herd size, herd population characteristics, milk and meat production), uses the Australian feeding standard methodology to estimate the total dry matter intake per animal class, then applies the relevant emissions factor (determined by New Zealand-based research trials) to this dry matter intake to estimate CH_4 emissions from enteric fermentation and from dung.

For N_2O, the estimate of total dry matter intake is also pivotal, and is combined with the nitrogen content of this dry matter to estimate the amount of nitrogen excreted on pasture as urine or dung, or in the dairy shed as effluent. In addition, the amount of nitrogen fertiliser used is important. Each of these four sources of nitrogen (urine, dung, effluent and fertiliser) have different emissions factors, determined by largely New Zealand-based field trials, used to estimate the total amount of 'direct' N_2O emitted from a farm. Overseer also calculates the so-called 'indirect' N_2O emissions associated with nitrate leaching and ammonia volatilisation.

As for the national GHG inventory, Overseer provides reasonably robust estimates of GHG changes on a single farm over time (i.e., trends). There is more uncertainty about the specific numerical estimates. Furthermore, N_2O emissions are crucially dependent on soil moisture and within-farm differences in soil conditions may affect emissions. Overseer does not currently consider such within-farm soil or climatic differences. Table 4 outlines what GHG mitigation measures Overseer can currently reflect.

12 There are examples of models that have been developed elsewhere (e.g., Canada: the Holos model) with a more explicit focus on farm-scale GHG mitigation potential, including some ability to account for regional 'ecodistrict' differences due to climate and soils (Little et al, 2008).

Table 4: What action by farmers to limit GHG emissions can be taken into account by Overseer at present?

	Overseer can reflect these options currently open to farmers	**Overseer cannot reflect these options currently open to farmers**
Overall responses	Land-use change to non-ruminant production Reduced land use intensity – production per hectare, application of fertilisers, etc. Dietary changes (e.g., low nitrogen diet)	
CH4-specific	Productivity improvements per animal (e.g., fewer animals whilst maintaining or increasing total farm production) Manure management – e.g., covered anaerobic lagoons	
N2O -specific	Nitrogen inhibitors (on hold) Reduced nitrogen fertiliser use Grazing off poorly drained soils – onto another farm – in winter (need to be careful to account for animals elsewhere)[13] Feed pads.	Urease inhibitors[14] Management practices that use real-time information about soil moisture content to adjust grazing and/or fertiliser management to avoid pastures with high soil moisture content.

7 Greenhouse gas metrics

The PCE has asked:

> "What methods are used to determine CO2 equivalencies for other greenhouse gases? Where is there consensus and divergence on how best to do this?"

7.1 Why use metrics at all?

A metric is

> "a 'common currency' or 'exchange rate' that sets the relative value of reducing one greenhouse gas relative to another." (NZAGRC, 2012c: 2)

Internationally, metrics are needed to compare effort between countries. Multiple country targets are difficult to manage in negotiations, and there needs to be some basis for comparison between targets. Currently, under the United Nations Framework Convention on Climate Change

13 Overseer can reflect differences in soil types between farms, but not within a single farm, unless the user sets up the system so that each area within a single farm is treated as a mini-farm of its own.
14 AgResearch advises that it would be relatively easy to include Urease inhibitors within Overseer.

(UNFCCC), countries set a target for reductions in a consistently weighted basket of different GHGs, but even if targets were set for each gas there would still be an implicit weighting across gases when comparisons are made across countries.

Metrics are also needed if emissions of different gases are traded within an Emissions Trading Scheme domestically or across countries.

Metrics are a tool, and should be selected according to the policy goal(s). This is an extremely important point for decision makers, lest the metric is allowed to drive policy under a false cloak of objectivity rather than metrics being used to inform transparent judgments.

It is possible to use one metric for international comparisons and reporting and trading – mostly short-term decisions – but to perhaps employ a wider range of metrics for policy analysis and long-term investment decisions. There is no perfect metric, but nor is there any theoretical or scientific impediment to changing the metrics used as conditions change significantly in the future.

7.2 Commonly used metrics and their characteristics

Metrics typically use CO_2 as the benchmark and compare other gases to it. Because of its short life, CH_4 is much more sensitive to the choice of metric and time horizon than N_2O. By far, the two most common metrics are:

Global Warming Potential (GWP)

GWP is used, with a time horizon of 100 years, as the standard metric in IPCC Assessments and under the UNFCCC. It measures the cumulative warming effect of the emission of 1 kg of a GHG over a given time period relative to the cumulative warming effect of 1 kg of CO_2 over the same period.

Global Temperature change Potential (GTP)

GTP is increasingly discussed as an alternative to GWP. It measures the global temperature change at a given point in the future due to the emission of 1 kg of a GHG relative to the temperature change at the same future point due to 1 kg of CO_2.

7.2.1 Time horizons matter

The time horizon selected matters a great deal and reflects judgements about the relative importance of short-, medium- or long-term effects. This is illustrated by Table 5, which compares GHG values using GWP and GTP with 20 year and 100 year time horizons. Looking at the cumulative impact on the Earth's energy budget (GWP), over the next 20 years, 1 kilogram (kg) of CH_4 emitted today has about 84 times greater direct impact on the Earth's energy budget than 1 kg of CO_2, but if we consider the relative impact over 100 years, that kg of CH_4 has 28 times greater direct impact than 1 kg of CO_2. Looking at future warming effects (GTP), the warming resulting from the emission of 1 kg CH_4 today is still four times greater 100 years from now than the emission of 1 kg of CO_2; but the difference is much more marked if we only look 20 years into the future:

Table 5: Comparison of GWP and GTP for 20 and 100 year time horizons

GHG	**Lifetime (years)**	**GWP20**		**GWP100**		**GTP20**		**GTP100**	
CO_2	centuries to millennia	1	1	1	1	1	1	1	1
CH_4	12.4	84	86	28	34	67	70	4	11
N_2O	121.0	264	268	265	298	277	284	234	297

Source: Adapted from Stocker *et al*, 2013: 714.

Table 5 shows GWP and GTP without and with climate-carbon cycle coupling (left and right, respectively), so, for example, the current best estimate for CH_4 including the indirect effects of climate-carbon cycle coupling is 34 for GWP100 and 11 for GTP100. Values for CH_4 do not include CO_2 from CH_4 oxidation. Values shown here are for agricultural CH_4; values for fossil CH_4 are higher by 1 and 2 for the 20 and 100 year metrics, respectively.

The international community's currently agreed goal is to limit global warming specifically to 2°C. The timeframe for achieving this, on current projections, is some 40–70 years.

Given this timeframe, questions have been raised about the use of a 100-year time horizon.[15] Joos *et al* say the UNFCCC choice of this time horizon for GWP "lacks a scientific basis" (2013: 2795). Others, however, argue that 100 years is a good starting point for an integrated metric: 100 years is the longest time horizon used for infrastructure planning as well as representing one long human life or four generations in terms of economic productivity.

Critics of GTP100 note that there is nothing special about the particular year 2115.

Some scientists advocate the use of a dynamic metric (e.g., time-dependent GTP) – one that selects a fixed year in the future that comes closer with time. The chosen year is often the target year at which global temperatures would peak if mitigation efforts were successful. Time-dependent GTPs give an increasing weight to CH_4 emissions as the target year approaches.

Table 6 sets out the implications of a time-dependent GTP consistent with meeting the 2°C goal (Reisinger, 2014). It shows that mitigating 1 kg of CH_4 today is worth more than ten times the value of mitigating 1 kg of CO_2, because a fraction of the CH_4 emitted today affects the temperature in the target year (roughly 2070), but as the world approaches the target the value of mitigating CH_4 gets much greater because CH_4 emissions make a much bigger difference to the near-term temperature.

[15] Any metric that uses a fixed time horizon do not reflect the ongoing effect of long-lived greenhouse gases, especially CO_2, beyond that time horizon. In this sense, both GWP and GTP devalue the consequences of emissions we make now on future generations.

Table 6: Value of CH_4 under time-dependent GTP consistent with 2°C target

Year emitted	CH_4 value compared with CO_2
1990	5.3
2010	9.8
2050	81

7.2.2 Policy goals and metrics

The choice of metric depends not only on the time scale we are interested in, but on the policy goal(s) and assumptions about the scale and effectiveness of future global emissions mitigation. To be most efficient within a climate change context, the metric chosen needs to be the best proxy for the aims of global climate change policy, such as limiting total temperature change (focus on the peak/target) or limiting the rate of temperature change (focus on the path).

Table 7: Policy-relevant features of metrics compared

Features	**GWP100**	**GTP100**	**Time-dependent GTP**
Fit with a central focus on carbon dioxide?	Puts more weight on short-lived gases than GTP100, so tends to promote action spread across GHGs.	Puts much less weight on short-lived gases, so tends to promote focus on CO_2.	Puts less weight on short-lived gases now and more close to target, so tends to promote focus on CO_2 now.
Fit with a global peak temperature target?	Is not designed to fit with a temperature target but is a reasonable measure of the impact of emissions on peak warming if temperatures are expected to stabilise within the next 40 years.	In principle, aligns more directly with a global temperature target. But for a 2°C target, the appropriate time horizon would be about 55 years rather than 100 years.	Fits with peak temperature target if temperatures are on track to stabilise when expected. If it becomes clear that CO_2 emissions are not going to be eliminated in time to meet the 2°C target, the metric (target year) would need to be adjusted.
Fit with a goal of keeping the temperature path as low as possible?	Puts more weight on short-lived gases, and deals with cumulative effects.	Puts much less weight on short-lived gases; does not consider the temperature path but only a specific point of time in future.	Puts less weight on short-lived gases early on. Does not consider the temperature path but ramps up attention to short-lived gases over time
Uncertainty	Not as far along the cause–effect chain (considers the steps from emissions to concentration to radiative forcing), so less uncertainty.	Further along the cause–effect chain (considers the steps from emissions to concentration to radiative forcing to temperature), so greater uncertainty.	Further along the cause–effect chain (considers the steps from emissions to concentration to radiative forcing to temperature), so greater uncertainty. If aim is to match timing of peak temperatures, additional uncertainty about when this temperature peak might occur.
Complexity	Single value, although subject to revision.	Single value, although subject to revision.	Changing values, but the change is predictable. Still also subject to revision, including the timing of peak temperature (target year).

7.2.3 Uncertainty

All choices among metrics build in assumptions about future emissions. "The choice of metric represents, at some level, a bet on the success or failure of future climate mitigation policy." (Allen, 2015: 17)

The IPCC 5th Assessment Report points out that uncertainty increases with the time horizons used for both GWP and GTP. The uncertainty for CH_4 and N_2O at GWP100 can be as much as ±40%. In contrast, GTP has higher uncertainty, though greater policy relevance, because the metric has to predict a climate response (global temperature change). The further down the driver–response–impact chain a metric is, the more policy relevant but the less certain a metric becomes. (Myhre *et al*, 2013: 710)

It is also inevitable that metric values will change over time as the concentration of CO_2 in the atmosphere increases and as scientific understanding of atmospheric processes, especially indirect warming effects, becomes even more precise. Every IPCC Assessment has revised the GWP values, mainly due to revisions of estimated indirect warming effects, raising the relative weight of CH_4 each time (for GWP100: from 21 in 1995, to 25 in 2007, to 28 in 2013, and as much as 34 if climate-carbon cycle feedbacks are included).

Proponents of the time-dependent GTP argue that, from a policy perspective, unpredictable changes in a metric value (e.g., because of a revision of the scientific understanding) are likely to be more challenging than predictable changes associated with dynamic metrics.

7.2.4 Which metric is correct?

Because different metrics reflect different policy goals, and take account of different factors, no metric can be said to give 'the right answer' regardless of context: metrics can only be said to be more or less useful for a stated purpose. During the preparation of this report, we considered the question 'what is, roughly, the best value to use for methane versus carbon dioxide today?' It was not possible to reach an agreed figure, largely because there is no single policy objective, but there is consensus that:

- the right value depends on the policy goal and could change substantially over time; and
- if the main policy goal is to cost-effectively limit global average warming to 2 degrees above pre-industrial levels, then the value of CH_4 should be less than the GWP100 value of 28 until global CO_2 emissions have begun to decline steadily towards zero.

How much less? As noted above, the arguments reflect judgments about politics, economics and the intersection of policy and science.

One argument goes that if the goal is to limit warming to about 2 degrees *at lowest global economic costs*, CH_4 must be regarded as having a value of *at least* 10 relative to CO_2 today. This argument is based on the fact the GTP100 of CH_4 is more than 10 when climate-carbon cycle feedbacks are included, and the assessment that 100 years is an extremely generous time horizon for limiting warming to near 2 degrees and would also cater for moderately higher levels of warming such as 2.5 and possibly even 3 degrees.

Another strand of debate is the current GTP100 value of 4 for CH_4 (excluding climate-carbon cycle feedbacks) may be more appropriate for today, given that the current priority must be to reduce CO_2 emissions. Potential revisions to metrics – which may be appropriate in the event that progress is made on CO_2 – could be conducted periodically alongside other potential revisions to targets, reviews of progress, etc.

7.3 Other metrics

Although GWP and GTP are the most commonly discussed, there are numerous alternative metrics in the literature, including:

- Modifications of GWP and GTP to reflect the time lag between combustion and regrowth of biomass for energy
- Metrics for biophysical effects such as albedo changes
- Absolute Regional Temperature Potential, to estimate temperature responses in four latitude bands[16]
- Component-by-component or multi-basket approaches, that show how peak temperature is constrained by cumulative emissions for long-lived gases and emission rates for short-lived gases
- Metrics that add economic dimensions, such as Global Cost Potential and Cost-Effective Temperature Potential.

Amongst the plethora of competing metrics, the IPCC identified three topics that need to be addressed in future so that metrics can be useful to users and policy makers:

> "(1) which applications particular metrics are meant to serve;
>
> (2) how comprehensive metrics need to be in terms of indirect effects and feedbacks, and economic dimensions; and
>
> (3) how important it is to have simple and transparent metrics (given by analytical formulations) versus more complex model-based and thus model-dependent metrics." (IPCC, 2014)

In addition, none of the easily understandable climate metrics take into account the different effects that GHGs have on the Earth system, such as the effect of CO_2 on ocean acidification (Boucher, 2012: 59). All this suggests caution against an over-reliance on a single metric.

16 Neither GWP nor GTP acount for regional variations, such as whether climate impacts are likely to occur sooner and/or be more severe in one part of the world than another.

7.4 Implications of metric choice for New Zealand

Although it may be tempting to argue for a metric that appears to be in New Zealand's economic self-interest, it is by no means clear what this metric would be. Relevant factors here include the effect of the metric on the global carbon price and on incentives for reforestation and reduced deforestation, and which gases prove easier or harder to mitigate in future.

If New Zealand designed its policy approach to achieve the optimal goal for the globe, we would opt for the metric that is best for the world as a whole. We would then negotiate within this to get the best possible outcome for the country: the target for New Zealand may change under a different metric.

References

Allen, M. 2015. Short-Lived Promise? The Science and Policy of Short-Lived Climate Pollutants. Oxford: Oxford Martin School, University of Oxford.

Boucher, O. 2012. "Comparison of Physically- and Economically-based CO_2-equivalences for Methane," Earth System Dynamics, 3, pp. 49–61.

Bowerman, N. H.; Frame, D. J.: Huntingford, C.: Lowe, J. A.; Smith, S. M. and M. R. Allen. 2013. "The Role of Short-lived Climate Pollutants in Meeting Temperature Goals," Nature Climate Change, 3, pp. 1021-1024.

de Klein, C. A. M.; Pinares-patino, C.; and G. C. Waghorn. 2008. "Greenhouse Gas Emissions," in Environmental Impacts of Pasture-Based Farming, R. W. McDowell, Ed. Wallingford: CAB International.

Dorner, Z. and S. Kerr. 2015. Methane and Metrics: From global climate policy to the NZ farm. Wellington: Motu Working Paper.

IPCC (Intergovernmental Panel on Climate Change). 2013a. "Annex III: Glossary" in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, S. Planton, Ed. Cambridge and New York: Cambridge University Press, pp. 1447-1465.

IPCC (Intergovernmental Panel on Climate Change). 2013b. "Summary for Policymakers," in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press, pp. 3-29.

IPCC (Intergovernmental Panel on Climate Change). 2014. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC.

Joos, F.; Roth, R.; Peters, G.; Enting, I.; von Bloh, W.; Brovkin, V.; … and A. Weaver. 2013. "Carbon Dioxide and Climate Impulse Response Functions for the Computation of Greenhouse Gas Metrics: a," Atmospheric Chemistry and Physics, 13, pp. 2793–2825.

Le Quere, C.; Andres, R.; Boden, T.; Conway, T.; Houghton, R.; House, J.; … and N. Zeng. 2013. "The Global Carbon Budget 1959–2011," Earth System Science Data, 5, pp. 165–185.

Little, S. M.; Lindeman, J.; Maclean, K. and H. H. Janzen. 2008. *Holos – A Tool to Estimate and Reduce GHGs from Farms. Methodology and Algorithms for Version 1.1.x.* Ottawa: Agriculture & Agri-Food Canada.

MfE (Ministry for the Environment). 2015a. New Zealand's Greenhouse Gas Inventory 1990–2013 Snapshot. Available online at http://mfe.govt.nz/publications/climate-change/new-zealands-greenhouse-gas-inventory-1990%E2%80%932013-snapshot. Last accessed on 29 September 2015.

MfE (Ministry for the Environment). 2015b. New Zealand's Greenhouse Gas Inventory 1990–2013. Submitted to the United Nations Framework Convention on Climate Change 10th April 2015. Wellington: Ministry for the Environment.

Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; … and H. Zhang. 2013. "Anthropogenic and Natural Radiative Forcing," in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

NOAA (National Oceanic and Atmospheric Administration). n.d. A primer on pH. PMEL Carbon Program. Available online at http://pmel.noaa.gov/co2/story/A+primer+on+pH. Last accessed on 1 June 2015.

NZAGRC and PGgRc. 2015a. Reducing New Zealand's Agricultural Greenhouse Gases: How We Measure Emissions. Palmerston North and Wellington: New Zealand Agricultural Greenhouse Gas Research Centre and Pastoral Greenhouse Gas Research Consortium.

NZAGRC and PGgRc. 2015b. Reducing New Zealand's Agricultural Greenhouse Gases: What We Are Doing. Palmerston North and Wellington: New Zealand Agricultural Greenhouse Gas Research Centre and Pastoral Greenhouse Gas Research Consortium.

NZAGRC. 2012a. NZAGRC Factsheet 1: The Impact of Livestock Agriculture on Climate Change. Palmerston North: New Zealand Agricultural Greenhouse Gas Research Centre.

NZAGRC. 2012b. NZAGRC Factsheet 2: Impacts of Global Climate Change on New Zealand Agriculture. Palmerston North: New Zealand Agricultural Greeenhouse Gas Research Centre.

NZAGRC. 2012c. NZAGRC Factsheet 3: Economic and Policy Implications of Alternative GHG Metrics. Palmerston North: New Zealand Agricultural Greenhouse Gas Research Centre.

Reisinger, A. 2014. Implications of GHG Emission Metric for Agricultural Emission Trends and Target. Palmerston North: New Zealand Agricultural Greenhouse Gas Research Centre.

Reisinger, A.; Rogelj, J. and A.Daigneault. 2015. Interactions between agriculture non-CO_2 mitigation choices and fossil CO_2 emissions within integrated low-carbon pathways. Palmerston North: New Zealand Agricultural Greenhouse Gas Research Centre.

Rogelj, J.; Schaeffer, M.; Meinshausen, M.; Shindell, D. T.; Hare, W.; Klimont, Z.; … and H. J. Schellnhuber. 2014. "Disentangling the Effects of CO_2 and Short-lived Climate Forcer Mitigation," PNAS, 111:46, pp. 16325–16330.

Stocker, T.; Qin, D.; Plattner, G.-K.; Alexander, L.; Allen, S.; N. B.; … and U. Cubasch. 2013. "Technical Summary," in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

WMO (World Meteorological Organization). 2014. Greenhouse Gas Bulletin, No. 10. The State of Greenhouse Gases in the Atmosphere based on Global Observations through 2013. Available online at http://www.wmo.int/pages/prog/arep/gaw/ghg/documents/GHG_Bulletin_10_Nov2014_EN.pdf. Last accessed on 3 October 2015.

Appendix

How this report was compiled

This report has been developed with the assistance of a group of New Zealand scientists and others with expertise in agricultural greenhouse gases.

During the information-gathering phase, a range of people affiliated to the following organisations were interviewed: AgResearch; Dairy NZ; Federated Farmers; NZ Agricultural Greenhouse Gas Research Centre; NIWA; Victoria University of Wellington.

Motu then convened a meeting to discuss an initial draft of the report. This was attended by most of the interviewees, along with two staff from the Office of the Parliamentary Commissioner for the Environment.

Three further drafts of the report were circulated for further comment. Feedback on the science contained in this report was received from:

- Dr Cecile de Klein, Science Impact Leader Environment – Greenhouse Gases, AgResearch
- Dr David Frame, Professor of Climate Change & Director – NZ Climate Change Research Institute, Victoria University of Wellington
- Dr Mike Harvey, Principal Scientist – Atmosphere, NIWA
- Dr Martin Manning, Professor Emeritus – NZ Climate Change Research Institute, Victoria University of Wellington
- Dr Andy Reisinger, Deputy Director – NZ Agricultural Greenhouse Gas Research Centre
- One anonymous scientific reviewer

Glossary

Term (in order of appearance)	**Commonly understood definition**	**Source for more detail / technical specificity**
Radiative efficiency	How effective a gas is at trapping heat energy	
Radiative forcing	Net change in energy balance of the atmosphere due to emissions of greenhouse gases and other climate forcers (i.e., the product of radiative efficiency and atmospheric concentration).	Myhre *et al*, 2013: Section 8.1 *Radiative Forcing*
Climate forcers	Factors external to the natural climate system that 'force' or push the climate towards a new long-term state. These may either warm the planet (e.g., GHGs) or cool the planet (e.g., sulphate aerosols).	
Aerosols	Tiny particles in the air. Natural sources include volcanic eruptions, desert dust storms, sea spray, and wild fires. Human-related sources include rainforest burning for land clearance, and sulphate aerosols from fossil fuel combustion (e.g., for energy or transport).	IPCC, 2013a: 1448, *Aerosol*
Albedo	How much of the sun's energy is reflected back into space. "Snow-covered surfaces have a high albedo, the albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and cover changes."	IPCC, 2013a: 1448, *Albedo*
Troposphere	The lowest part of the Earth's atmosphere (roughly the first 10 kilometres up from the Earth's surface, although its depth varies with latitude – thinner near the poles; thicker near the Equator).	See, for example, http://earthobservatory.nasa.gov/Glossary
Stratosphere	The next section of the Earth's atmosphere above the troposphere (roughly 10–50 kilometres from the Earth's surface).	See, for example, http://earthobservatory.nasa.gov/Glossary
Climate stabilisation	The climate might be said to have "stabilised" when one or more specified parameters (e.g., global mean surface temperature, or atmospheric GHG concentration) have remained within a desired range over a long period.	Note, e.g., IPCC 2013b: 28 "*Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions.*"

Term (in order of appearance)	**Commonly understood definition**	**Source for more detail / technical specificity**
Short-lived climate forcers	Compounds whose effect on the climate occurs primarily within the first decade after their emission.	IPCC, 2013a: 1458, *Near-term climate forcers*
Emissions intensity	Emissions per unit of product (e.g., kilogram of milk solids) or of economic production (e.g., real GDP)	See, e.g., www.stats.govt.nz for official NZ statistics on *greenhouse gas intensity*.
Uncertainty	"A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour."	IPCC, 2013a: 1464, *Uncertainty*
Metric	"A 'common currency' or 'exchange rate' that sets the relative value of reducing one greenhouse gas relative to another."	NZAGRC, 2012c: 2

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