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Implications of alternative metrics to account for non-CO_2 GHG emissions

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Economic and policy implications of alternative metrics to account for emissions of non-CO_2 greenhouse gases

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Executive Summary

Multi-gas mitigation strategies can achieve long-term stabilisation targets at lower costs than emission reductions of CO_2 only, and provide greater flexibility as they allow emissions trading between different gases not only internationally but also domestically. To achieve this tradability, multi-gas mitigation strategies require metrics that compare the emissions of different greenhouse gases through a common unit. Global Warming Potentials (GWPs) with a 100-year time horizon are the most widely applied metric, including in reporting and accounting of national greenhouse gas emissions inventories under the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol. However, GWPs are not the only scientifically plausible way of comparing the effects of the emission of different greenhouse gases. A number of well-known short-comings have been identified prompting a discussion internationally and domestically whether GWPs should be maintained or updated, or replaced with an alternative metric in international climate change agreements.

The Global Temperature Change Potential (GTP) is an alternative bio-physical metric that has gained the most traction in discussions about alternative metrics to date. Both GWPs and GTPs compare the warming effect from a pulse emission of a non-CO_2 gas with that from a pulse emissions of CO_2. The GWP measures the integrated radiative forcing caused by emissions, whereas the GTP compares the resulting warming for a specific future point in time. The future point in time at which GTPs are evaluated can be either a fixed time horizon into the future (fixed GTPs), or a specific future year, implying that the time horizon and hence weight assigned to non-CO_2 gases changes over time (time-dependent GTPs). Fixed GTPs typically assign lesser weight to short-lived gases such as CH_4 than GWPs; time-dependent GTPs that use the year 2100 as target year assign less weight to CH_4 initially but would assign increasingly greater weight to CH_4 than GWPs in the second half of the 21st century as the target year is being approached.

Our study had three inter-linked broad objectives, namely to:

- Provide a consistent quantification of exchange rates for CH_4 and N_2O, and their uncertainties, under GWPs and fixed and time-dependent GTPs, including future changes under a variety of assumptions
- Determine the cost-effectiveness globally of different metrics to achieve a variety of long-term stabilisation targets and under a range of assumptions regarding mitigation potential and policy choices, with a particular focus on agriculture
- Evaluate the potential economic implications on New Zealand from different metrics for a subset of scenarios, taking global changes into account.

Quantification of alternative metrics and their uncertainties

Our analysis gives similar results as other studies regarding the exchange rates for CH_4 and N_2O relative to CO_2 under different metrics and time horizons. We provide a comprehensive evaluation of uncertainties of these exchange rates based on current scientific understanding. Uncertainties of fixed 100-year GTPs are about twice as large as uncertainties of 100-year GWPs, which could make adoption of GTPs challenging and increases the risk of future changes as science progresses. We also evaluated the currently foreseeable changes in GWPs under a range of alternative scenarios for the 21st century to support current discussions in the UNFCCC about a possible updating of the exchange rates currently used. We found that under most scenarios, the weight placed on CH_4 would increase over the 21st century and be about 10-20% greater by 2100 than at present. While this change is non-negligible, it is much smaller than the change that would result from a policy decision to change time horizons or adopt an altogether different metric such as GTPs.

GWP values could also change in ways that are more difficult to foresee, either from rapid changes in atmospheric chemistry affecting the lifetime of CH_4, or from additional processes and feedbacks that are not currently included in the definition of the GWP of

CH_4 as employed by the IPCC. Most of these processes currently identified would tend to increase the GWP of CH_4, but their quantification is as yet only tentative.

Global cost-effectiveness of alternative metrics

We used the global integrated assessment model MESSAGE to explore the differences in global mitigation costs if alternative metrics (fixed 100-year GWPs and fixed-and time-dependent GTPs) were used to determine the most cost-effective multi-gas mitigation strategies at the global level. We evaluated costs for a range of alternative additional assumptions, namely differences in:

- Radiative forcing targets in the year 2100 (450 and 550ppm CO_2-eq)
- Assumptions about the future evolution of agricultural mitigation potential
- Policy choices with regard to the treatment of agriculture (i.e. their inclusion or temporary or permanent exclusion from any mitigation obligations).

Consistent with theoretical expectations, we find that global aggregated net present value mitigation costs are greater under fixed 100-year GTPs by 5-20%, whereas costs are lower under time-dependent GTPs (for the target year 2100) by 4-5%, relative to costs under GWPs for the same levels of total radiative forcing in 2100.

These cost differences arise not primarily from differences in mitigation activities by sectors that emit non-CO_2 gases, but from differences in CO_2 mitigation costs from the energy sector. This is because less pressure to reduce CH_4 emissions requires greater efforts to reduce CO_2 emissions, resulting in greater urgency to upgrade or replace carbon-intensive energy infrastructure investments and hence greater costs. These costs from energy mitigation outweigh globally the mitigation cost savings in other sectors. Time-dependent GTPs reduce overall mitigation costs because the much greater emphasis on CH_4 mitigation in the second half of the 21st century results in a rapid reduction in CH_4 concentrations towards 2100, which allows a small delay in CO_2 emissions reductions early in the 21st century, which reduces aggregated net present value energy system mitigation costs.

Time-dependent GTPs reduce only aggregated net present value mitigation costs, but they lead to greater GDP losses in 2100 than under GWPs. This is due to much greater costs of non-CO_2 mitigation late in the 21st century, which is discounted in a net present value analysis. These increasing GDP losses raise questions about the feasibility and robustness of implementing time-dependent GTPs in practice. If time-dependent GTPs were adopted initially but then abandoned after a few decades, this would either raise mitigation costs again or jeopardise achievement of the agreed long-term target.

Even though differences in aggregated global net present value costs under alternative metrics are non-negligible, they are smaller than cost differences associated with alternative assumptions about agricultural mitigation potential, and much smaller than cost differences arising from alternative long-term stabilisation targets. Improving agricultural mitigation potential could reduce total global mitigation costs by about 20-25%, while relaxing the stabilisation target from 450 to 550ppm CO_2-eq would lower mitigation costs by more than 50%.

The benefits from enhancing agricultural mitigation potential and ensuring the widespread implementation of mitigation options would accrue to all countries, because the largest gain would arise from reduced stringency of CO_2 mitigation and hence carbon prices and mitigation costs in the energy sector. Conversely, if agriculture were excluded globally from any mitigation obligations (e.g. due to concerns about food security), this would increase total global mitigation costs by between about 15 to 50%. The cost increase is mostly due to higher carbon prices and energy sector mitigation costs to achieve the same long-term stabilisation targets. Excluding agriculture only until 2050 would result in smaller cost increases of between zero and 10%, depending on assumptions about improvements in agriculture mitigation potential.

Economic implications of alternative metrics for New Zealand

New Zealand is affected by alternative metrics directly and indirectly. The direct consequence of alternative metrics is that alternative weights are placed on CO_2 and non-CO_2 emissions. Indirect consequences of alternative metrics consist predominantly in differences in global carbon prices (assuming full participation in an international emissions trading regime), and changes in commodity prices arising from global mitigation actions or inactions for agricultural emissions.

We assumed that New Zealand would take responsibility for net emissions reduction targets of -15% by 2020 and -50% in 2050 relative to gross emissions in 1990, but that absolute emissions and emissions reductions would be calculated either by 100-year GWP or by 100-year GTP metrics. The 100-year GTP metric would reduce the overall national liabilities to meet such economy-wide emissions targets, but these benefits are partly or in some cases fully offset by changes in carbon and commodity prices.

If agriculture is priced globally, then using Global Temperature Change Potentials (GTP) instead of Global Warming Potentials (GWP) would not benefit New Zealand economically, as the lower emissions liability resulting from the GTP metric for New Zealand would be offset by smaller increases in commodity prices as agricultural production costs would be lowered globally. In all those scenarios, New Zealand receives a net economic benefit from mitigation actions compared to business-as-usual.

If a significant additional agricultural abatement technology for emissions of methane from enteric fermentation were to be developed, then New Zealand would also derive greater economic benefits from this technology if agricultural non-CO_2 emissions are priced according to the GWP rather than the GTP metric.

These two results are for scenarios where agriculture is exposed to the price of emissions globally. Two alternative scenarios are possible at the other end: either one could assume that countries remain nominally responsible for agricultural emissions but chose to exempt agriculture from stringent mitigation requirements through domestic policy choices (as at present for countries in Annex I of the UNCCC), or that agriculture emissions are removed from any obligations by international agreement.

New Zealand economic welfare is higher if New Zealand is liable for its agricultural emissions (coupled with a relatively lower carbon price, high commodity prices and global participation), than if agriculture were excluded globally and New Zealand has to face a higher carbon price coupled with lower commodity prices. This finding holds irrespective of the choice of GHG exchange metric for other non-CO_2 gases, although it is marginally stronger under the GWP metric than under the GTP metric. The strength of the finding also varies directly with the price on emissions.

The worst result for New Zealand arises if all countries are liable for agricultural non-CO_2 emissions, but other countries choose to shelter them from a carbon price, because this reduces the increase in world agricultural commodity prices from which New Zealand would be a net beneficiary. The negative implications are significantly greater in 2050 than in 2020. GTP metrics would marginally increase costs to New Zealand in 2020, but would reduce them compared to costs under the GWP metric by about 20% in 2050 (from -5.6% to -4.5% drop in RNGDI relative to business-as-usual).

As a very broad summary, whether New Zealand benefits from a switch from GWPs to GTPs depends heavily on other policy assumptions. If New Zealand stands to gain from global climate policy, GTPs would reduce those gains. If New Zealand stands to lose from climate policy, GTPs would temper those losses. Overall, the choice of greenhouse gas exchange metrics has a much smaller economic effect on New Zealand than the question whether other countries impose stringent mitigation requirements on their agricultural non-CO_2 emissions, especially under higher greenhouse gas prices. These conclusions might be modified under real-world policy scenarios that consider partial participation of sectors and regions in a global mitigation regime and lack of foresight by individual actors, but the analysis of such scenarios must be left to future study.

1. Introduction

Human-induced climate change is caused by the emission of a range of different greenhouse gases and aerosols. Carbon dioxide (CO_2) is the dominant anthropogenic greenhouse gas, but emissions of methane (CH_4) and nitrous oxide (N_2O) also contribute substantially to human-induced climatic warming (Forster et al. 2007).

Mitigation strategies that focus on reducing emissions of a suite of greenhouse gases can achieve long-term climate stabilisation targets at lower costs than strategies that focus on emission reductions of CO_2 only (Rao and Riahi 2006; Reilly et al. 2002; van Vuuren et al. 2007; van Vuuren et al. 2006a). Costs can be reduced further by allowing flexibility when and where individual gases are reduced and thus allow countries and individual stakeholders to pursue their own optimal mitigation strategies within overall aggregate emissions targets or allowances.

For these reasons, a flexible 'basket' approach to reporting emissions is used under the United Nations Framework Convention on Climate Change (UNFCCC) and in setting country-specific emissions reduction targets under the Kyoto Protocol (UNFCCC 2009d, c). This 'basket' approach sets aggregate emissions targets for a group of greenhouse gases but allows the flexibility of emissions trading between different gases internationally (through emissions trading, Joint Implementation and the Clean Development Mechanism) as well as domestically between industries through emissions trading schemes such as the NZ-ETS (NZ 2009a). The EU-ETS is currently not including non-CO_2 gases but could do so in future (Smith et al. 2000).

The basket approach provides flexibility but crucially requires metrics that help determine the relative value of reducing emissions of one gas compared to another within any given year or short-term commitment period. Just as international currency markets require exchange rates between different currencies, so emissions trading schemes require exchange rates between different gases. However, the requirement to have a simple single 'number' at any given point in time that provides such an 'exchange rate' is in stark contrast to the very different physical and chemical properties of different greenhouse gases (in particular, very different lifetimes in the atmosphere ranging from a few years to many thousands of years) and their very different abatement potentials and contributions to greenhouse gas emissions in different sectors and countries.

This contrast between policy requirements and bio-physical and economic properties of different gases lies at the heart of the difficulties around selecting appropriate metrics to compare emissions of different greenhouse gases in the UNFCCC context.

1.1 Global Warming Potentials (GWPs) as dominant metric

Global Warming Potentials (GWPs) with a 100-year time horizon are the most widely applied metric to compare emissions. They are used in reporting and accounting of national greenhouse gas emissions inventories under the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, with numeric values as given in the IPCC's Second Assessment Report (Lashof and Ahuja 1990; Schimel et al. 1996 (in IPCC 1996); UNFCCC 2009d, c).[1]

GWPs are the ratio between the integrated radiative forcing (warming effect) resulting from a pulse emission of a unit weight of a given gas and the integrated radiative forcing resulting from a pulse emission of the same unit weight of CO_2. Based on the latest IPCC assessment (Forster et al. 2007), using the 100-year GWP, the emission of one kg of CH_4 has the same integrated warming effect over 100 years as 25 kg of CO_2. Based on the same approach, the emission of 1 kg of N_2O has the same 100-year integrated

[1] These numbers have since been updated in the IPCC Fourth Assessment Report (Forster et al., 2007), which produced somewhat different numbers owing to revision of some key processes for individual gases (see Table 1). However, these revised numbers have not yet been used to update reporting and accounting rules under the UNFCCC.

warming effect as 298 kg of CO_2. These 'exchange rates' between gases determine their relative contribution to overall emissions targets and the economic value in reducing their emissions to meet overall targets.

GWPs have the advantage that their definition is relatively simple and their calculation is transparent and generally does not require highly complex models. However, GWPs make two key, yet arbitrary, assumptions regarding:

- ***The physical quantity of concern:*** GWPs assume that the *integrated radiative forcing* arising from a pulse emission is the most relevant way of comparing the climatic consequences of greenhouse gas emissions, and
- ***The time horizon:*** 100-year GWPs as used in the UNFCCC and its Kyoto Protocol integrate the warming effect following a pulse emission over 100 years; that is, they weigh the warming effect equally each year for the next 100 years but then ignore all warming that may occur beyond the next 100 years.

Even though GWPs were initially intended only as illustrative of how one *might* compare emissions of different greenhouse gases (IPCC 1990), 100-year GWPs have become the de facto norm for comparing emissions in virtually all climate policy, reporting, carbon footprinting and awareness raising contexts.

The importance of the time horizon is demonstrated in Figure 1.1, which shows the radiative forcing caused by emission of 1 kg CH_4 and 25 kg CO_2 in a given year for the subsequent 100 years. CH_4 has a much higher radiative efficiency but a much shorter atmospheric lifetime than CO_2. Averaged over 100 years, the integrated warming effect of 1 kg CH_4 is identical to that of 25 kg CO_2, but if a shorter time horizon were used, the emission of CH_4 would be valued more than 25 times that of CO_2 (owing to its much greater absorption of infrared radiation per unit mass increase in the atmosphere), whereas if a longer time horizon were used, CH_4 would be valued much less because CH_4 has mostly disappeared after about 50 years, while CO_2 remains in the atmosphere for much longer (more than 20% of an emission of CO_2 remain in the atmosphere for thousands of years (IPCC 2007a; Solomon et al. 2009).

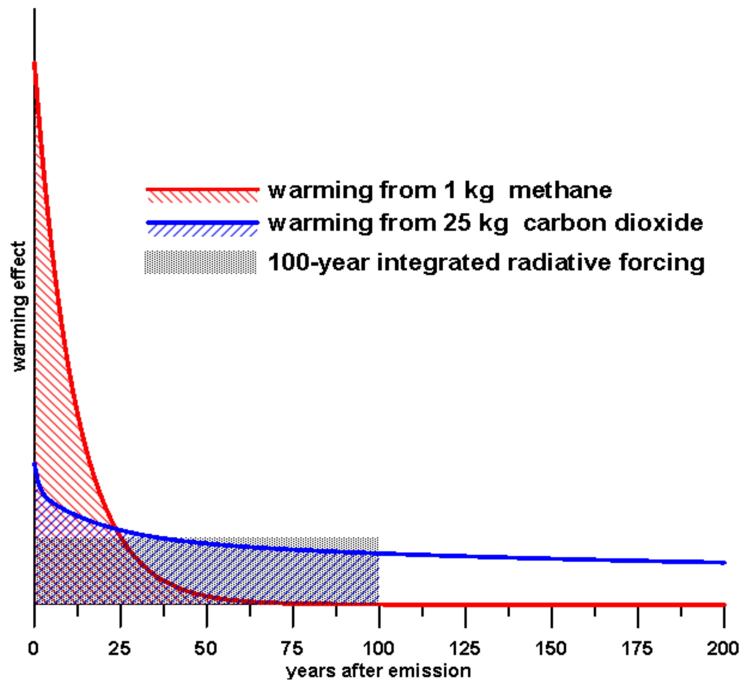


Figure 1.1. Comparison of the warming effect of the emission of 1 kg CH_4 and 25 kg CO_2 for the subsequent 200 years (Forster et al. 2007). Integrated over 100 years, the integrated radiative forcing (warming effects) are the same, but the different behaviour over time implies that different time horizons would change the comparison and hence the measure of equality.

Reducing current CH_4 emissions would therefore primarily lower the near-term rate of human-induced warming over the next few decades but would have little effect on long-term warming (unless those emissions reductions are sustained indefinitely). By contrast, reducing current CO_2 emissions would only have a limited effect on near-term warming rates but would lower warming over timescales of several decades to millennia (IPCC 2007a, 2009). However, the sustained level of global CH_4 emissions has an important influence on the total cumulative CO_2 emissions that are consistent with long-term stabilisation targets (Cox and Jeffery 2010; Meinshausen et al. 2009). Sustained reductions of CH_4 emissions would increase the allowable cumulative CO_2 emissions; vice versa, if CH_4 emissions remain at a permanently higher level, this would require more rapid emissions reductions of CO_2 and would reduce the total cumulative CO_2 emissions consistent with long-term stabilisation targets.

There is no independent scientific theory that can dictate which metric or time horizon is more appropriate for comparing greenhouse gases. For many natural ecosystems as well as human systems, slowing the rate of near-term change is critical to allow adaptation to gradual change to occur. On the other hand, many critical long-term impact such as melting of polar ice sheets and long-term sea level rise are driven more by long-term integrated warming rather than the near-term rate of change.

In addition the different lifetimes of CO_2 and CH_4 in the atmosphere imply a very different risk profile. Radiative forcing from CH_4 can be reversed more quickly if scientific research were to reveal that the world is heading for a major climatic catastrophe (by stopping CH_4 emissions), whereas stopping CO_2 emissions would do little to reduce radiative forcing, and CO_2 would have to be actively removed from the atmosphere (through large-scale emergency plantations, or through energy-intensive technical processes) to rapidly reduce radiative forcing (Boyd 2009; Broecker 2007; Dessler 2009; Marland and Obersteiner 2008; Read 2008). Furthermore, many CO_2-generating processes rely on long-lived capital infrastructure investments (e.g. power plants and pipelines) that give a higher risk of sunk costs should rapid re-adjustments of CO_2 emissions targets be required (IPCC 2007b), whereas adjustments to agricultural practices may be more flexible, even though they face their own sources of inertia.

The choice of the 'appropriate' metric for comparing different gases is therefore inevitably a value judgement that reflects socio-economic, cultural and political preferences and attitudes to risk as well as assumptions about technological mitigation potential, and the socio-economic consequences of mitigation in various sectors and national economies (see sections 4 and 5). Scientific, technical and economic considerations can and must inform policy choices with regard to metrics, but they cannot determine them without explicit policy guidance on what objectives mitigation strategies are seeking to achieve (IPCC 2009).

The choice of metrics is of obvious importance to countries that have a large share of non-CO_2 emissions in their national greenhouse gas inventories and face binding emissions constraints for the basket of greenhouse gases. New Zealand has by far the largest share of non-CO_2 emissions of all industrialised (Annex-I) countries that face binding emissions targets under the Kyoto Protocol, owing to the large role of agricultural activities in its national economy, the high percentage of renewable electricity generation and limited heavy industry. Future emissions targets that require much more stringent emissions reductions by 2020 and beyond from developed countries could therefore have a large impact on the relative weight that is accorded in New Zealand to the need to reduce emissions from agriculture compared to emissions reductions of CO_2 from fossil fuels and emissions or removal of CO_2 through forestry activities (afforestation and deforestation).

Based on standard 100-year GWPs, agriculture was responsible for about 46% of New Zealand's total emissions in 2008, but if different time horizons or altogether different metrics were used, this proportion could increase or decrease due to the different weight assigned to the relatively short-lived greenhouse gas CH_4 compared to the very long-lived greenhouse gas CO_2. Figure 1.2 shows the emissions contributions from different sectors in New Zealand using 20-, 100- and 500-year GWPs as examples, using 2008 emissions. The figure shows that if a 20-year time horizon were used, agriculture would represent 62% of New Zealand's total emissions and constitute by far the largest emissions sector. By contrast, if 500-year GWPs were used, agriculture would represent only about 26% of total emissions due to the lower weight assigned to CH_4 emissions and its relative importance would be comparable to transport emissions (27%) and less than stationary energy emissions (37%).

However, none of the metrics that have received serious scientific or economic attention in the scientific literature would alter the fact that New Zealand has by far the highest proportion of agricultural emissions of any developed country that currently faces binding economy-wide emissions targets under the Kyoto Protocol.

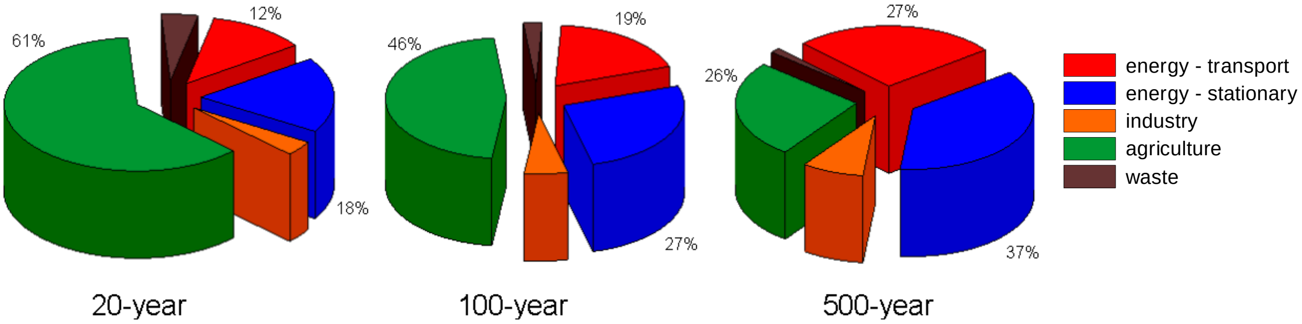


Figure 1.2. Relative contribution of different sectors to total New Zealand greenhouse gas emissions, using GWPs with different time horizons (20, 100 and 500 years). Percentage contributions to total emissions are shown for agriculture, transport and stationary energy. GWP values are from IPCC (1996), emissions data are for the year 2008 based on UNFCCC National Greenhouse Gas Inventory database (submissions from 2010).

1.2 Criticisms of GWPs and alternative proposals

The widespread and often unquestioned use of 100-year GWPs and their implicit assumptions in climate policy, carbon footprinting and reporting schemes has been criticised by the science community (physical scientists as well as economists) on several grounds (see O'Neill 2003; Shine 2009; Tanaka et al. 2010 for useful summaries of such criticisms). Those criticisms generally fall into four broad categories:

1) The arbitrariness of the chosen climate indicator (radiative forcing) to measure the climatic effect of emissions that mitigation strategies seek to avoid
2) The arbitrariness of the time horizon of 100 years and the fact that damages occurring after this time horizon are effectively ignored
3) Scientific uncertainties and limitations arising from the particular definition of GWPs and the processes that are included in its calculation, and the choice of CO_2 as the gas against which the warming effect of other gases is compared
4) The fact that the weight placed on emissions reductions of any gas does not take into account the economic and technological potential of reducing its emissions relative to the damage it causes, that they do not include the standard economic practice of discounting, and that they do not consider any ancillary environmental, social or economic benefits or costs of emissions reductions.

Scientists have attempted to address points 1 and 2 by proposing alternative bio-physically based metrics, often by choosing different indicators by which gases are compared and that are assumed to be more relevant to climate change impacts (e.g. the actual change in temperature, or estimates of the integrated damage caused through climate change following emissions of those gases), or by choosing or advocating different time horizons (20, 50, 100 and 500 years have been used most widely) (see Tanaka et al. 2010 for an overview of alternative metrics).

Criticisms around point 3 focus on the fact that GWPs as defined by the IPCC give only limited consideration to feedbacks that could affect the total radiative forcing and other physical or chemical changes in the atmosphere caused by emission of any particular gas. Recent studies suggest that including the interaction between CH_4 and short-lived reactive gases and aerosols could increase the 100-year GWP of CH_4 from 25 to more than 30 (Shindell et al. 2009); including carbon-cycle feedbacks resulting from emission of CH_4 would also increase its 100-year GWP to about 30 (Gillett and Matthews 2010); but considering the photochemical interaction between CH_4 and N_2O emissions would reduce the 100-yer GWP of N_2O (Prather and Hsu 2010).

A related criticism is that under the IPCC definition of GWPs the integrated radiative forcing from a pulse emission is evaluated for an atmosphere with constant background concentrations of all greenhouse gases. In practice though, the concentrations of all greenhouse gases can be expected to change over time, which would influence the additional radiative forcing caused by an emission. The IPCC definition has the advantage of being value-neutral (in that it does not assume any particular future trajectory in concentrations), but it is also one step removed from reality.

A further definitional problem is that GWPs are defined as the integrated radiative forcing of a target gas *relative to that of* CO_2. The change in CO_2 concentrations following a pulse emission of CO_2 is more complex than for many other greenhouse gases due to the complexity of the global carbon cycle and its coupling via climate-carbon cycle feedbacks to the climate system, and the very long time that a fraction of any carbon emission remains in the atmosphere. Using a different gas as a reference for GWPs with smaller uncertainties regarding its long-term behaviour in the atmosphere and associated warming effect would result in smaller uncertainties for GWPs that compare different non-CO_2 gases (e.g. the warming effect of N_2O relative to that of CH_4).

However, given that CO_2 is the dominant greenhouse gas in terms of current and projected future radiative forcing and therefore comparison of emissions of non-CO_2 gases with CO_2 is a key question for climate policy, the uncertainties associated with the lifetime and long-term behaviour of CO_2 cannot be avoided even if a different reference gas for GWPs were used.

Point 4 has been addressed by developing various metrics that explicitly take economic costs of reducing emissions of different gases into account and/or include economic discount rates in their evaluation of the climatic impacts of different gases, and/or by constructing models that determine the most cost-effective reductions of each gas for a given set of climate policy goals without relying on metrics to explicitly compare gases with each other (Johansson et al. 2006; Manne and Richels 2001; van Vuuren et al. 2006a). Most recent such studies have focused on *cost-effectiveness* of the trade-off between gases, i.e. finding the metric that delivers a prescribed stabilization outcome at least cost (see Johansson 2011 for a recent such study and detailed comparison with physical-based metrics). However, *cost-benefit* approaches that aim to find a metric that achieves the optimal balance between costs of mitigation and damages caused by climate change have also been developed (e.g. Hammitt et al. 1996).

The preference for *cost-effectiveness* over *cost-benefit* metrics arises largely from the difficulties of quantifying damage costs, which are difficult enough for just CO_2, let alone when having to be measured over multiple gases with different damage functions. Including the treatment of non-monetary damages and discounting damages to human lives adds yet more difficulty (Johansson 2011; Johansson and Hedenus 2009; Tanaka et al. 2010) and would likely limit their political acceptability.

Some scientists have argued, in some cases without referring explicitly to metrics, that greater emphasis on CH_4 reductions would bring large co-benefits and that climate policy should place much greater emphasis on CH_4 mitigation (see Cox and Jeffery 2010; Shindell et al. 2012; Weaver 2011 for recent such discussions). However, other scientists have also warned that reducing CO_2 emissions must remain the dominant concern because of its long lifetime and cumulative effect of emissions in the atmosphere (Lowe et al. 2009; Solomon et al. 2009). Another realization from recent studies is that the use of any single fixed metric is probably misguided, given the different lifetimes and hence temporal evolutions of greenhouse gas emissions and concentrations while the world aims to stabilize overall climate change over the 21st century. Stabilisation of radiative forcing at low level requires increasingly stringent emissions targets and constraints particularly on CO_2 emissions, given that a fraction of today's CO_2 emissions remain in the atmosphere for many thousands of years. This suggests that emissions of CO_2 in particular cannot be traded off indefinitely against emissions of shorter lived gases or aerosols, suggesting that any given 'exchange rate' between e.g. CH_4 and CO_2 may only be appropriate for a limited period of time but not for the entire 21st century (Berntsen et al. 2010; Manning and Reisinger 2011; Shine et al. 2007).

Out of the broad range of options and proposals for alternative metrics (Tanaka et al. 2010), the key alternative biophysical metric that has gained most traction in science and policy circles is the Global Temperature Change Potential (GTP) (Shine et al. 2007; Shine et al. 2005). The GTP compares emissions of greenhouse gases not by their integrated warming effect over a given period of time, but by the amount of warming that a pulse emission of a gas would cause at given time in future, compared to a pulse emission of CO_2. In other words, GTPs are point-based measures, compared to GWPs which integrate the warming effect of emissions over a given period of time.

As CH_4 has a much shorter lifetime in the atmosphere than CO_2, the weight assigned to CH_4 emissions under a 100-year GTP metric is much less than under a 100-year GWP metric, because almost all of the CH_4 would have disappeared after 50 years and hence warming 100-years into the future would be much less affected by emissions 100 years ago. Differences between GWPs and GTPs are much less for N_2O due to its longer lifetime, but different time horizons still matter particularly if time horizons of more than 100 years were chosen (see Table 1).

Table 1. Values for GWPs and GTPs for CH_4 and N_2O for different time horizons (based on Forster et al. 2007 in IPCC (2007); IPCC 1996; Reisinger et al. 2010, and unpublished data based on this study, see section 3). Values shown are medians across a range of climate models; values in square brackets indicate the 5-95% uncertainty range based on the model range (Reisinger et al. 2010).

	20-year horizon	**100-year horizon**	**500-year horizon**
CH_4			
GWP (IPCC 1996)	56	21	6.5
GWP (IPCC 2007)	72	25	7.6
GWP (Reisinger 2010)	72.3 [60.6–86.6]	25.0 [19.3–31.5]	6.5 [5.4–8.8]
GTP (Reisinger 2010)	49.7 [37.5–65.6]	6.9 [3.9–13.5]	0.7 [0.0–2.3]
N_2O			
GWP (IPCC 1995)	280	310	170
GWP (IPCC 2007)	289	298	153
GWP (this study)	294 [248–355]	303 [236–385]	136 [113–183]
GTP (this study)	341 [267–417]	318 [234–427]	36.7 [19.1–84.6]

For climate policy purposes, metrics that compare pulse emissions are of prime relevance since they allow the instantaneous emissions trading between the abatement of one gas in a given year or short-term accounting period and increased emission of another gas. However, it is worth noting that metrics have also been constructed to compare emissions over extended time frames. Such sustained-emission metrics tend to result in higher values for short-lived gases than the same metric for pulse emissions.

Examples are the sustained-emissions based GTP (Shine et al. 2005), and an evaluation of historical changes in radiative forcing and temperature based on sustained substitution of historical emissions of CO_2, CH_4 and N_2O (Tanaka et al. 2009). The latter results in an effective historical exchange rate between CH_4 and CO_2 of 44, compared to 25 for the 100-year GWP. However, exchange metrics based on sustained emissions changes would be much harder to implement in an emissions-trading based climate policy context, as each trading activity would generate an extended liability for parties to fulfil emissions obligations over an extended (if not infinite) future time period (see also Manning and Reisinger 2011 for a discussion of the long-term forcing equivalence between methane and carbon dioxide). To maintain the direct relevance and applicability to climate policy with its current clear focus on emissions trading as key mechanism, the remainder of this study uses only pulse-emissions based metrics.

A variant of the GTP metric evaluates warming not at a fixed time horizon into the future (e.g. 100 years after the emission pulse), but for a specific target year in the future (e.g. for the year 2100, or the year when global temperatures are expected to peak for a given global emissions path). In this case, the value assigned to emissions of CH_4 would start from a low base at present (reflecting that present-day CH_4 emissions cause only little warming 100 years into the future) but would gradually increase over the course of the 21st century until they attain much higher values as emissions occur closer and closer to the target date. This metric is attractive because it reflects that the relevance of emissions reductions of short-lived gases might change over time compared to reductions of long-lived gases such as CO_2. Such time-dependent GTPs are also similar to metrics developed by economic models aiming to identify the most cost-effective trade-off between mitigation of different gases (Johansson 2011).

Even though each of those alternative proposals may address one or several of the above shortcomings of 100-year GWPs, all are subject to different criticisms of their own. Key shortcomings of alternative biophysical metrics generally include that:

- No single biophysical metric is obviously *the* metric to compare the climatic effects or damages resulting from the emission of greenhouse gases; any single metric remains subjective as it represents different value judgements of which climate change effects and impacts *matter* (Tanaka et al. 2010; Tol et al. 2008).
- Metrics that are closer to the issue of concern (e.g. that represent temperature change or damages from climate change) generally are more uncertain than metrics that represent underlying physical processes and hence are higher up the chain of cause and effect of climate change (such as radiative forcing, used in GWPs) (Fuglestvedt et al. 2003; Reisinger et al. 2010). Greater uncertainties could make it harder to reach consensus about the numerical values to be used, and open governments up to the risk of more radical changes in numbers as scientific knowledge progresses. On the other hand, metrics that are more removed from the issue of concern imply that the specific choice of indicator is more arbitrary, and hence its legitimacy for driving climate policy design and abatement priorities may be more limited and open to challenge.
- Almost all biophysical metrics must make some arbitrary choice about the time horizon of relevance, i.e. at what point in time, or over what period of time, the climatic effects of emissions are to be evaluated. Given the very different atmospheric residence times of different greenhouse gases, particularly CO_2 and CH_4, alternative choices inevitably lead to very different quantitative results.

Shortcomings of alternative economics-based metrics include much of the above, with the addition that uncertainties and dependence on model-specific assumptions generally increases further once not only bio-physical issues but also economic aspects of mitigation potentials and social or environmental side-effects of mitigation are included. As a result, despite the broad range of criticism of 100-year GWPs, no single alternative metric has gained comparable status.

Studies that focus purely on the policy goal of limiting the long-term increase in radiative forcing or temperature (e.g. by 2100) consistently find that the most cost-effective metrics would initially assign a much lower value to CH_4 emissions than 100-year GWPs, but that the value would increase over time and eventually exceed the 100-year GWP value (by more than a factor of two) towards the end of the 21st century (Johansson 2011; Johansson et al. 2006; Manne and Richels 2001). If additional constraints such as limiting the rate of temperature increase are also considered, then the value assigned to CH_4 emissions reductions increases and becomes much closer to the value assigned by the 100-year GWP (Manne and Richels 2001).

These existing studies indicate that the global economic cost of using fixed 100-year GWPs compared to time-dependent metrics that minimise costs overall is relatively small. At the global level, the additional cost from using GWPs is about 5% of total mitigation costs for achieving the same long-term stabilization target, which may be compared with cost differences of 100% or more for different stabilization targets (e.g. 450 or 550ppm) or different assumed baseline emissions (Johansson et al. 2006; van Vuuren et al. 2006a). However, given regional differences in non-CO_2 emissions and mitigation potentials from different sectors, the economic and social implications of different metrics at regional and national scales could nonetheless be significant, but have as yet been explored very little (an exception is Godal and Fuglestvedt 2002, who explored the implications of alternative metrics for Norway).

The UNFCCC had considered during its negotiations for a global post-2012 climate agreement to either update the values currently used for 100-year GWPs based on IPCC (2007) or replacing GWPs with GTPs as an alternative metric (UNFCCC 2008, 2009b, e). 100-year GWPs currently used by the UNFCCC and its Kyoto Protocol are based on the IPCC Second Assessment Report issued in 1996. The most recent UNFCCC decision now agrees to used updated values from the IPCC Fourth Assessment Report issued in 2007, which differ to previous values owing to revision of some key processes that result in radiative forcing from individual gases (see Table 1). A work programme under the Subsidiary Body for Scientific and Technical Advice (SBSTA) will continue to explore the implications of alternative metrics for non-CO_2 greenhouse gas reporting and accounting.

1.3 Purpose and outline of this study

In the context of these scientific discussions and associated policy considerations, the purpose of this study is threefold:

- To provide consistent quantifications of the GWPs and alternative metrics for CO_2 and the two most important non-CO_2 gases, CH_4 and N_2O, including their uncertainties. The key metrics evaluated are updated GWPs (based on the IPCC Fourth Assessment Report) and GTPs with a variety of time horizons. We also evaluated possible future changes of these metrics over time, given the interest by the global policy community in updating metrics under the UNFCCC and its Kyoto Protocol in line with more recent scientific discoveries.
- To explore the global economic costs and broad regional implications if different metrics were used to achieve a range of long-term climate change stabilization goals. Previous studies have shown that emissions pathways under different metrics can be different, but no study has explicitly compared the economic cost of achieving mitigation targets under the two most 'popular' biophysical metrics and their variants, GWPs and GTPs. This aspect of our study also evaluates the sensitivity of those results to alternative assumptions of the technological mitigation potential for agriculture in the near- and long-term, and of alternative policy choices for the treatment of agriculture in global agreements.
- To evaluate the potential costs and benefits for New Zealand if different metrics were used in setting targets under future global agreements, taking into account that not only the emissions target and mitigation burden would change for New

Zealand with different metrics, but also the global carbon price and hence cost or benefit to New Zealand of meeting part of its emissions obligations through participation in international emissions trading.

Section 2 gives an overview of the modelling tools used to answer the above questions.

Section 3 describes the climate model (MAGICC) and results for different metrics and their uncertainties.

Section 4 gives details of the set-up of the global integrated assessment model (MESSAGE) and the global land-use model GLOBIOM used to determine global costs and regional implications on agricultural production to achieve global stabilization targets and presents the results.

Section 5 describes the design and results of economic modelling of the implications of different metrics for New Zealand.

Section 6 discusses the results in an integrated way, including key caveats and assumptions, and offers some perspectives on the policy implications of the results obtained in this study.

2. Overview of modelling approach

This study employed a suite of three different model types to achieve the goals described in the introduction. Figure 2.1 at the end of this section gives a graphical overview of the way in which the different models were linked.

2.1 Reduced-complexity climate model MAGICC

The climate model MAGICC (Wigley and Raper 1992) was used to calculate the radiative forcing and temperature response of the climate system to pulse emissions of different greenhouse gases. MAGICC is a reduced-complexity climate model with an upwelling-diffusive ocean and is coupled to a simple carbon cycle model including CO_2 fertilization and temperature feedback parameterisations of the terrestrial biosphere and oceanic uptake. We used MAGICC version 6 and its calibrations to 19 Atmosphere-Ocean General Circulation Models (AOGCMs) (Meehl et al. 2007) and nine C4MIP coupled climate-carbon cycle models (Friedlingstein et al. 2006) used in the IPCC Fourth Assessment Report (Meinshausen et al. 2011a; Meinshausen et al. 2011c). The simplified carbon cycle model used in MAGICC6 incorporates climate-carbon cycle feedbacks as well as temperature-dependent CO_2 fertilization and the buffering effect of ocean CO_2 uptake (Meinshausen et al. 2011a; Meinshausen et al. 2011c).

MAGICC in its version 6 is a sophisticated tool that allows one to estimate the climatic responses to greenhouse gas emissions based on the results of much more complex models. Also, its ability to emulate a wide range of different models offers the opportunity to explore the uncertainty of results represented by different parameterisations of key climate and global carbon cycle processes.

In section 3 we describe the detailed model setup and results for different metrics using MAGICC. We re-analysed current GWPs and compared them with the results contained in the IPCC Fourth Assessment Report (Forster et al. 2007), and we calculated both fixed time-horizon and time-dependent GTPs for CH_4 and N_2O, as well as for other gases that make up the Kyoto basket of gases. In addition, we explored likely future changes of GWPs, given the UNFCCC's decision to update the numerical values currently used with those from the most recent IPCC assessment, which implies a potential continuous updating of GWP values in future.

We also present an uncertainty analysis specifically of GWPs and GTPs of CH_4, whose values are most sensitive to alternative choices of time horizons and metrics due to the much shorter atmospheric lifetime of CH_4 compared to CO_2. We also offer an illustrative comparison of uncertainties of GWPs and GTPs of N_2O, but this is not investigated in the same level of detail. Greater levels of uncertainty generally could make it more difficult to switch to new metrics in international agreements, not least because high levels of uncertainty imply a greater risk of future significant but unpredictable changes in numerical values as a result of new scientific findings.

Finally, we compare these biophysical metrics with the exchange rates derived from economics-based studies, and also compare and contrast those metrics and the numerical changes over time in exchange rates with those that could result from specific policy choices, such as not to include agricultural emissions in international agreements (either indefinitely or for a limited period of time).

2.2 Global Integrated Assessment model MESSAGE and GLOBIOM

2.2.1 MESSAGE

A subset of the different metrics presented in section 3 was used in the global integrated assessment model MESSAGE to determine the global and broad regional costs of mitigation, impacts on GDP, and necessary prices on greenhouse gas emissions to achieve various long-term stabilisation targets.

MESSAGE is a bottom-up systems engineering model based on a least cost optimization framework, developed and hosted by the Austrian International Institute for Applied Systems Analysis (IIASA). It has been used widely to estimate mitigation costs and required carbon prices to achieve low-level stabilisation targets, including through multi-gas abatement strategies (Rao and Riahi 2006; Rao et al. 2008; Riahi et al. 2011; Riahi et al. 2007). The model has a very detailed representation of the global and regional energy systems including resource extraction, imports and exports, conversion, transport and distribution to end-use services. It is a long-term global model.

In the setup used for this study, MESSAGE determines the mitigation actions that would minimise the aggregated and discounted global mitigation costs over the 21st century to meet a *prescribed cumulative global emissions constraint*. This constraint is set such that the climatic outcomes meet a prescribed policy goal (e.g. a given total radiative forcing from all gases and aerosols in the year 2100, or a temperature limit). For this study, we evaluated costs for prescribed long-term radiative forcing targets of either 450 or 550ppm CO_2-eq in 2100, which would be consistent with best estimate long-term warming of about 2 and 3°C above pre-industrial levels, respectively. Non-CO_2 gases contribute to cumulative emissions via a prescribed metric that converts those emissions into CO_2-equivalents. The model then calculates least-cost emissions trajectories and mitigation actions to remain within those constraints, assuming complete flexibility of when and where mitigation actions occur so as to minimise global mitigation costs.

The main outputs of the model are primary energy and greenhouse gas emissions as well as local pollutants like aerosols, NO_x and CO, and the costs of mitigation (which can be converted into discounted net present value over the entire 21st century). It also includes a global computable general equilibrium model that allows an estimate of the global and regional losses in GDP resulting from mitigation relative to assumed baseline developments. The results for different metrics are presented in section 4.

To represent mitigation in the agriculture sector, MESSAGE was upgraded as part of this study to incorporate regional marginal abatement cost curves for mitigation of greenhouse gas emissions from rice, agricultural soils, enteric fermentation, and CH_4 emissions from manure management (Beach et al. 2008, extending earlier work; USEPA 2006). These mitigation cost curves have been shown to be broadly consistent with the mitigation costs indicated by the last IPCC assessment and other detailed agricultural model-based mitigation cost studies (Smith et al. 2007; Vermont and De Cara 2010). These mitigation cost curves and their underlying assumptions are presented in more detail in section 4.

MESSAGE includes an earlier version of MAGICC (version 5.3) to convert greenhouse gas emissions into radiative forcing and temperature change. MAGICC has been used within MESSAGE with a single climate sensitivity and carbon cycle setting. Uncertainties in climate-carbon cycle feedbacks could have important implications for the urgency and stringency of mitigation measures to achieve climate stabilisation targets (IPCC 2007b), but this has not been explored in the present study as it would require a significant upgrade of the model architecture.

2.2.2 GLOBIOM

The main emphasis of MESSAGE lies in a detailed representation of the energy system, given the dominant role of the energy sector in emitting greenhouse gases and for mitigation actions. The representation of other sectors, including agriculture and forestry, is much less detailed. In MESSAGE, all agricultural production and associated greenhouse gas emissions are categorised either as methane from paddy rice, methane and nitrous oxide from livestock enteric fermentation and manure (using meat production as a proxy), and nitrous oxide from fertiliser use for croplands (without any assessment of production actual crops).

While this simplistic representation of agriculture still allows an assessment of the mitigation actions and costs from agriculture under different metrics, estimates of impacts on GDP calculated by MESSAGE have to be treated with much greater caution where significant mitigation occurs in the agriculture sector, given that the model is not able to represent spatially explicit land-use changes or trade-induced impacts on GDP from changes in agricultural production.

A key challenge when trying to understand the implications of alternative metrics specifically on mitigation in agriculture is the fact that applying a price on non-CO_2 emissions would result not just in the use of technological mitigation options (where they are available and cost-effective), but also in changes to agricultural production itself (switching between high- and lower emitting products so as to optimise producer returns from a given area of land) and regional land-use change (by using land for forestry or biofuels instead of food production). These changes in turn would affect commodity prices, which could have implications on food demand and security.

The potential change in commodity prices associated with global mitigation actions is a key issue for New Zealand, given that the total economic costs from emissions mitigation for New Zealand arise not only from domestic mitigation measures, but also from changes in international commodity prices driven by climate change policies and impacts of climate change overseas (Saunders et al. 2010; Stroombergen 2010). Such indirect effects of climate change via international commodity prices could be critical for New Zealand due to the important role of agricultural exports for New Zealand's real gross national disposable income (RGNDI).

To address these issues, we also used the spatially explicit land-use model GLOBIOM (Havlík et al. 2010; Valin et al. 2010), which has also been developed at IIASA. GLOBIOM is an economic partial equilibrium model of the global forest, agriculture and biomass sectors. Constraints calculated by MESSAGE in terms of biomass demand for bioenergy, and shadow prices for emissions of CO_2, CH_4 and N_2O were imposed on GLOBIOM. GLOBIOM was then used to calculate land-based activities at a regional scale such that producer and consumer surplus are maximised, subject to any existing resource, technology and policy constraints. Outputs from GLOBIOM consist of detailed production quantities on a regional basis, along with effects on aggregate global commodity prices for livestock products and crops.

GLOBIOM does not assume any specific technological mitigation options for agriculture that would be applied purely in response to external prices on greenhouse gas emissions (such as treatment options for manure to reduce CH_4 emissions). The main responses modelled by GLOBIOM are changes in the level of production intensity, changes between crops given their combined effect on producer returns and penalties for greenhouse gas emissions, and (to a lesser extent) changes in demand for specific products given the changes in commodity prices.

The main results from GLOBIOM with regard to global commodity prices are also presented in section 4, serving as input to the New Zealand economic analysis that is covered in section 5 (and 2.3 below).

2.2.3 Linking MESSAGE and GLOBIOM, and key caveats / assumptions

There is an obvious inconsistency between MESSAGE and GLOBIOM in that MESSAGE assumes only technological mitigation options for agricultural non-CO_2 emissions but no changes in demand, production intensity or alternative products, whereas GLOBIOM assumes only the latter three but no technological mitigation options that would aim solely to reduce greenhouse gas emissions. For the purpose of the present study, we rely primarily on carbon prices computed by MESSAGE, but on changes in commodity prices (for those external carbon prices) computed by GLOBIOM. Given that those two models are not dynamically coupled, their inconsistent treatment of agricultural mitigation implies that both carbon and commodity prices should only be regarded as indicative estimates of how those prices might *change* with different metrics, but not necessarily of their 'real' future values in an absolute sense.

Given that the main purpose of our study was to investigate the effect of different metrics for non-CO_2 gases specifically for agriculture, but not to determine absolute global mitigation costs, these inconsistencies are regarded as preferable over having to use only one global model. Using only the MESSAGE model would not have allowed us to explore the implications of different metrics on global commodity prices and their implications for New Zealand, while using only GLOBIOM would not have allowed us to explore the implications of alternative metrics for non-CO_2 gases on the required price on CO_2 emissions (and hence energy costs) to achieve mitigation targets.

An important assumption that underpins this study, and which is common to most global integrated assessment studies of mitigation costs, is that both MESSAGE and GLOBIOM assume that a price on greenhouse gas emissions is applied *globally wherever and whenever they occur*. The level of the price for each gas is determined by the metric in use (e.g. the price on the emission of 1 kg of CH_4 is 25 times the price on the emission of 1 kg of CO_2 if a 100-year GWP based on IPCC 4th Assessment Report is used). This situation is obviously different from the current real-world situation, where significant parts of the world do not currently apply any price to their greenhouse gas emissions (or only where they participate in activities under the Clean Development Mechanism). In particular it appears unlikely that full pricing of greenhouse gas emissions from agriculture in developing countries would apply anytime even in the medium term future due to concerns about food security and access. MESSAGE can be operated in principle assuming regional constraints, but this was not attempted in the present study.

The results from this model study should therefore be seen as demonstrating the effects of different metrics in an idealised case. If selected groups of countries or sectors are sheltered from a price on their greenhouse gas emissions because international agreements exempt certain countries or sectors, or if countries or industry actors make less effective mitigation decisions due to other social, environmental, economic or political concerns, this would increase the costs in other regions or sectors to achieve the same long-term mitigation outcomes (Edmonds et al. 2008; Krey and Riahi 2009). Exploring these effects of incomplete participation or economically sub-optimal mitigation choices and their interaction with different metrics would require a fundamentally different model design and must be left to future work.

A further important limitation of this study is that neither MESSAGE nor GLOBIOM consider the potential impacts of climate change on the energy system, agriculture or forestry. This is an important limitation (albeit common to most current integrated assessment models), particularly since there are indications that climate change impacts have the potential to increase global commodity prices over the levels they would have assumed in the absence of either climate change impacts or mitigation measures (Kaye-Blake et al. 2009; Stroombergen 2010). Climate change impacts are therefore important not only for regional food security, but also to understand the economic impacts of climate change on countries that depend significantly either on food imports or exports.

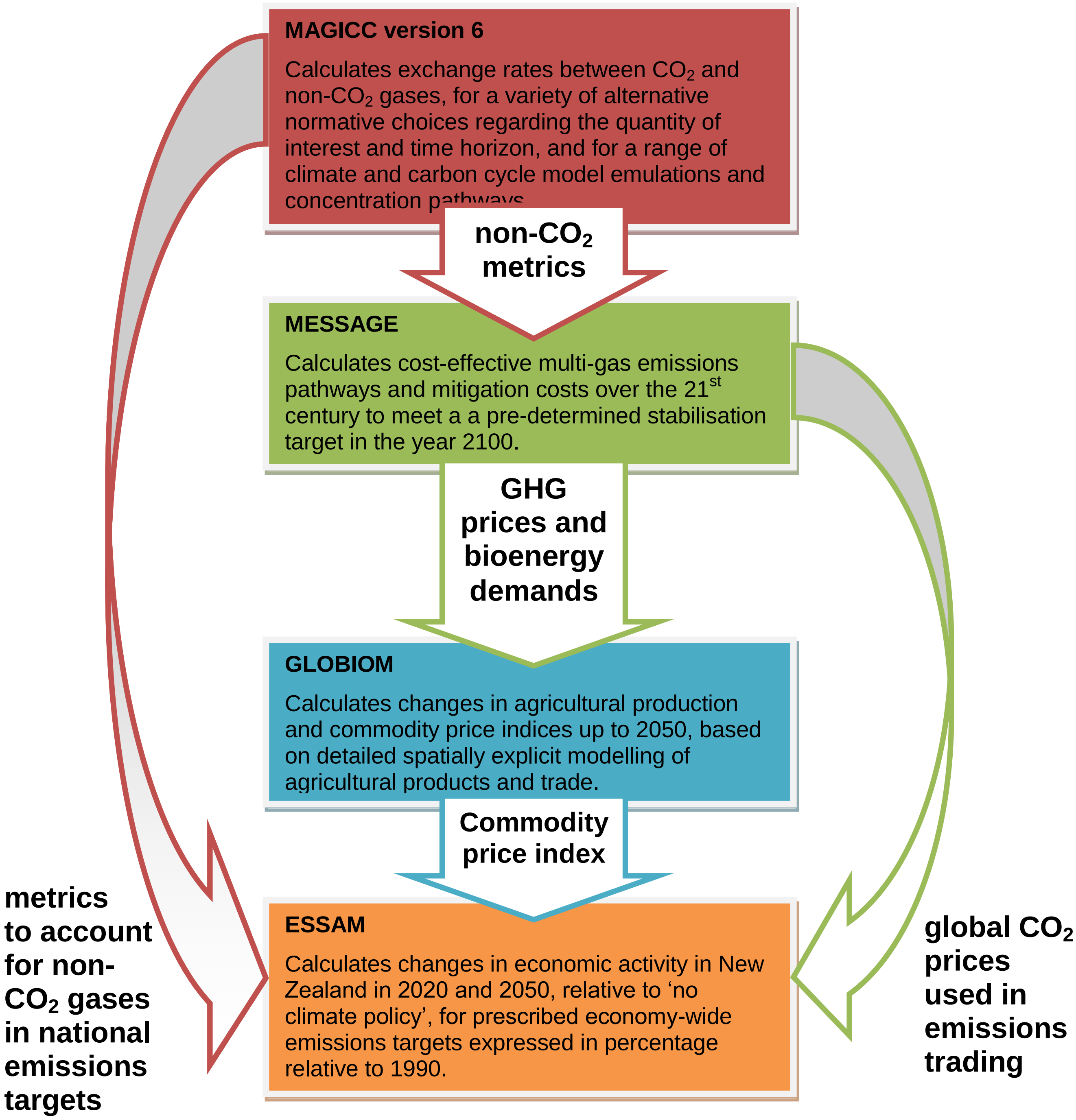
However, similar to the considerations above, given that the main focus of this study is to explore the implications of different metrics to achieve the same long-term climate outcomes (i.e. under similar levels of climate change impact), this shortcoming should not affect the key findings from this study.

2.3 New Zealand Computable General Equilibrium model

The general equilibrium (GE) model that we use is the ESSAM (Energy Substitution, Social Accounting Matrix) model of the New Zealand economy (Stroombergen 2008). It is a standard GE model that comprises 53 industry groups, each with a two-level nested translog production function that allows substitution between labour, capital, materials and energy at the first level, and between coal, oil, gas and electricity at the second level. The model has emission coefficients for CO_2, CH_4 and N_2O, covering emissions from agriculture, waste, energy combustion and industrial processes.

Substitution between domestically produced and imported goods and services is allowed in production and consumption. Household consumption is modelled by an AIDS specification and a social accounting matrix is used to track financial flows between households, government, business and the rest of the world. The model's equations are expressed in level form and solved by a non-linear algorithm.

Figure 2.1. Graphical representation of models and linkages employed in this study, and key outputs.



3. Modelling of GWP and GTP metrics

In this section we describe in detail modelling work to calculate median and, in selected cases, uncertainty ranges for a variety of metrics, including their changes over time. We focus on biophysical metrics (GWPs and GTPs) since they can be determined independently of economic models or technological assumptions about the current or future abatement potential in various sectors. For comparison purposes and to assist in analysing alternative policy choices, we include two hypothetical special cases of metrics that assign specific weights to non-CO_2 emissions from agricultural activities.

3.1 Model set-up and methodological approach

The approach to modelling GWPs and GTPs, using the climate model MAGICC, has been described elsewhere (Reisinger et al. 2011; Reisinger et al. 2010). The description in those studies is repeated here without substantial change to facilitate understanding for readers without access to the original scientific publications.

We used the climate model MAGICC (Meinshausen et al. 2011a; Meinshausen et al. 2011c; Wigley and Raper 1992) to simulate the radiative forcing and resulting climate responses to pulse emissions of CO_2, CH_4 and N_2O. MAGICC is a reduced-complexity climate model with an upwelling-diffusive ocean and is coupled to a simple carbon cycle model including CO_2 fertilization and temperature feedback parameterisations of the terrestrial biosphere and oceanic uptake. The simplified carbon cycle model used in MAGICC6 incorporates climate-carbon cycle feedbacks as well as temperature-dependent CO_2 fertilization and the buffering effect of ocean CO_2 uptake (Meinshausen et al. 2011a; Meinshausen et al. 2011c).

The GWP and GTP of CH_4 are defined as the ratios of its absolute Global Warming Potential (AGWP) and absolute Global Temperature Change Potential (AGTP) to those for CO_2 (equation 1, using CH_4 as example). The AGWP is the time integrated radiative forcing of the climate system following a pulse emission of a gas over a specified time horizon. Following *Shine et al.* (2005), the AGTP is here defined as the increase in global annual mean surface temperature after a specific time horizon following an emissions pulse. Standard time horizons for AGWPs are 20, 100 and 500 years, and for comparability we use the same time horizons to evaluate AGTPs.

(1) $$GWP_{CH_4} = \frac{AGWP_{CH_4}}{AGWP_{CO_2}}; \quad GTP_{CH_4} = \frac{AGTP_{CH_4}}{AGTP_{CO_2}}$$

To calculate present-day AGWPs and AGTPs, we first ran MAGICC with prescribed concentrations of all greenhouse gases following historical concentrations up to the year 2005, and with concentrations set constant thereafter at year 2005 levels (consistent with the IPCC definition GWPs and the reference year in the most recent IPCC assessment). These runs were used to infer, for each AOGCM and carbon cycle calibration, the emissions of CO_2, CH_4 and N_2O that would give rise to those prescribed concentration pathways.

We then ran MAGICC in forward mode with those inverse emissions, and added a further emissions pulse of 10 Gt CO_2, 100 Mt CH_4 or 1 Mt N_2O in 2005, after confirming that AGWPs were related linearly to pulse heights up to these values. The difference in integrated radiative forcing (AGWPs) or temperature (AGTPs) between the runs with and without pulse emissions over time horizons of 20, 100 and 500 years allows us to calculate the AGWPs and AGTPs for each gas (i.e. up to model years 2025, 2105, and 2505). GWPs and GTPs for those time horizons are then calculated by dividing the AGWP/AGTP of the target gas by the AGWP/AGTP of CO_2 according to equation 1.

3.1.1 Evaluation of uncertainties

We use two complementary approaches to determine median and mean values and uncertainties of GWPs and GTPs, described below. The first approach is based on the current range of Atmosphere-Ocean General Circulation Models (AOGCMs) and Coupled Climate-Carbon Cycle Models (C4MIP), while the second approach uses historical constraints from temperature and ocean heat uptake data combined with carbon cycle models. Those uncertainty calculations were only performed for GWPs and GTPs of CH_4, but not for N_2O due to the time-consuming nature of the model calculations. However, inferences regarding uncertainties can be drawn from the CH_4 evaluations for GWPs and GTPs of other trace gases.

AOGCMs and coupled climate-carbon cycle models exhibit different climate sensitivities, time dependence of response to forcing, and feedback strengths. Hence the spread of results from different models may be taken as an indication of the current scientific uncertainty about the climate system's response to future emissions of greenhouse gases and greenhouse gas metrics based on those responses.

MAGICC version 6 has been calibrated to 19 different AOGCMs (Meehl et al. 2007) and 10 carbon cycle models (Friedlingstein et al. 2006) used in the latest IPCC assessment (see Meinshausen et al. 2011a; Meinshausen et al. 2011c for details). Varying the parameters in MAGICC to emulate various AOGCM/C4MIP model combinations allows an exploration of the range of AGWPs and AGTPs spanned by the current range of complex climate models.

Although MAGICC was calibrated by a limited set of model runs, a recent study of rapidly declining emissions consistent with stabilisation at 450ppm CO_2-eq suggests that the calibration is robust for a wider range of emissions pathways (Lowe et al. 2009) and hence can reasonably emulate the response of those more complex models to pulse emissions into an atmosphere with constant background concentrations. However, our confidence in results for the 500-year time horizon is lower than for 20- and 100-year horizons, because only 100-year runs were available to calibrate the carbon-cycle parameters of MAGICC against simulations by complex coupled climate-carbon cycle models (Friedlingstein et al. 2006). Over multi-century time scales, uncertainties in model-specific representations of the carbon cycle and its coupling to the climate system become increasingly important and are difficult to constrain.

Our second, complementary, approach to evaluating uncertainties in GWPs and GTPs uses 600 different and 82-dimensional MAGICC parameter sets such that each individual parameter set is consistent with historical changes in hemispheric land-ocean temperatures for 1850-2006 as well as with ocean heat uptake for 1961-2003 (seeMeinshausen et al. 2009, for details). The complete group of parameter sets was sampled to reproduce the climate sensitivity distribution of (Frame et al. 2006). Radiative forcing parameters were drawn randomly from within published uncertainty estimates (Forster et al. 2007). Parameters related to the future carbon cycle behaviour cannot be sufficiently constrained by historical observations. Each individual historically constrained AOGCM parameter set was therefore randomly combined with a carbon cycle parameter set based on C4MIP emulations in a Monte Carlo-type approach (see Meinshausen et al. 2009, for details).

The resulting different parameterisations of MAGICC thus allow a semi-independent evaluation of uncertainties of GWPs and GTPs based on historical constraints that complements the uncertainty analysis based on AOGCM model emulations.

3.1.2 Treatment of indirect effects

The AGWP of CH_4 requires consideration of indirect effects. Those considered by the IPCC in the AR4 are the extension of the atmospheric lifetime of CH_4 through its feedback on tropospheric OH, its influence on tropospheric ozone levels and the production of stratospheric water vapour from CH_4 oxidisation. These indirect effects are parameterised in MAGICC to produce values consistent with the IPCC AR4 and added to the direct forcing (Forster et al. 2007; Reisinger et al. 2010).

Consistent with the definition of the CH_4 GWP used by the IPCC (Forster et al. 2007), radiative forcing from CO_2 produced in the oxidisation of CH_4 is excluded from the calculations. There have been various proposals to adopt two separate GWPs for CH_4. This would apply a value of 25 for biogenic CH_4, where later oxidisation to CO_2 is ignored because it is assumed that one CO_2 molecule was absorbed originally (e.g. through growing plant material) for each molecule of CH_4 that is later emitted from animals or landfills. Another value would apply to CH_4 that is of 'fossil' origin (e.g. from mining or fugitive emissions associated with oil and gas exploration), which would be about 27 due to the additional warming from CO_2 (Boucher et al. 2009).

Gas-aerosol interactions, as well as more complex interactions between different greenhouse gases and with land-use or land-cover, could also significantly influence the total radiative forcing from a pulse emission of CH_4 (Ganzeveld et al. 2010; Prather and Hsu 2010; Shindell et al. 2009). Some of these complex interactions and feedbacks have the potential to alter GWPs significantly but require further scientific investigation to substantiate and quantify their ranges across different models and scenarios. Since our main aim was to study already foreseeable changes in GWPs using a definition that is based on that currently employed in IPCC assessments (Forster et al. 2007), we did not attempt to model such additional effects in our study, nor did we include the indirect effects of non-CO_2 emissions on the airborne fraction of CO_2 via climate-carbon cycle coupling (Gillett and Matthews 2010).

A scientific or policy decision to include any of those feedback effects would have the potential to alter the numerical value of the 100-year GWP of CH_4 significantly. For example, consideration of gas-aerosol interactions and inclusion of climate-carbon cycle feedbacks would increase the 100-year GWP by 15-20% each, but those changes would not necessarily be additive. Due to the limited current knowledge about the magnitude of those effects and their dependence on specific model parameterisations and assumptions, consideration of those processes would also increase significantly the uncertainty of GWPs (and presumably GTPs).

3.1.3 Potential changes in GWPs and GTPs over time

A key question is how the values assigned by various biophysical metrics to individual gases might change over time. Such changes would shift the relative balance of greenhouse gases within national inventories and, if large enough, could alter the costs and strategic priorities that would be assigned to emissions reductions from different sectors. The UNFCCC decided its recent negotiations to update GWPs from the numerical values based on the Second Assessment Report of the IPCC in 1995 (IPCC 1996) to the values provided in the IPCC's Fourth Assessment Report in 2007 (IPCC 2007a). This change results in an increase in the 100-year GWP of CH_4 from 21 to 25, while the change in the GWP for N_2O is smaller and in the opposite direction, from 310 to 298. Collectively, these changes are non-trivial particularly for countries with a large fraction of CH_4 emissions in their national inventory. In the case of New Zealand, these changes increase the percentage of agricultural emissions in the total national inventory from 46% to 49% (based on emissions data for the year 2008).

Apart from policy choices to switch metrics or time horizons, changes in the numerical values assigned to the exchange rate for individual gases could arise from essentially three different processes:

1. new scientific discoveries about the warming effect associated with the emission of a gas, re-evaluation of already known feedbacks, or consensus by the scientific and/or policy community to include mechanisms that have hitherto been identified only tentatively (Ganzeveld et al. 2010; Gillett and Matthews 2010; Prather and Hsu 2010; e.g. Shindell et al. 2009)

2. changes in atmospheric composition and climatic conditions over time, which could alter both the warming effect from or the atmospheric lifetime of a gas
3. use of a metric that is in itself designed to change over time. One key such metric is the time-dependent GTP, which uses a fixed target year (e.g. the warming caused in the year 2100) rather than a fixed time horizon (e.g. the warming caused 100 years into the future following the emission).

3.1.3.1 Future changes due to new scientific discoveries

The main reason for the change in the 100-year GWP of CH_4 from 21 to 25 between the Second and Fourth Assessment Reports of the IPCC is point (1), namely the re-evaluation and increased value assigned to feedback effects associated with CH_4 emissions on tropospheric ozone and stratospheric water vapour (Forster et al. 2007). Re-evaluation of the atmospheric lifetime and warming efficiency of CO_2 and thus the denominator in GWP calculations played only a secondary role in this change.

It is clearly not possible to predict, let alone model, the effect or magnitude of new scientific discoveries and their impact on GWPs and GTPs. However, we note that our model simulations indicate a significant uncertainty for GWPs, and an even greater uncertainty for GTPs based on the current spread of different models and uncertainties of key climate parameters (see 3.2). This uncertainty implies that changes in the best estimate of GWPs and GTPs of ±20% are possible in future even without any major new scientific discoveries.

A key further uncertainty in future changes to the GWP and GTP of CH_4, which is not included in the quantified uncertainty assessments presented in this and most other studies on metrics, arises from potential changes in the atmospheric abundance of the hydroxyl radical (OH). This radical acts as the dominant sink for atmospheric CH_4 and thus is critical in determining the atmospheric lifetime and long-term warming effect of CH_4 emissions. The IPCC Fourth Assessment Report used the parameterisation of the previous IPCC assessment (Ehhalt et al. 2001) but included a broader discussion on future uncertainties in OH abundances that highlights the range of competing factors that could result in either increases or decreases in OH concentrations (Denman et al. 2007; Forster et al. 2007).

Given these uncertainties, we assumed in our model study that the relative magnitude of these indirect feedbacks would not change in future, as there is insufficient information to quantify such changes reliably (Isaksen and Dalsøren 2011; Manning and Reisinger 2011). We note, however, that based on the range of mechanisms currently identified, future changes in OH concentrations in the order of ±15% appear well possible and could occur rapidly as a result of non-linear atmospheric chemistry processes. Such changes in OH abundance would translate directly into changes in the perturbation lifetime for CH_4 and hence its GWP and GTP.

3.1.3.2 Future changes due to changes in atmospheric composition and climate

GWPs and GTPs will change over time simply as a result of predictable changes in atmospheric concentrations and climatic changes over the 21st century. Such foreseeable change can arise from changes in atmospheric concentrations of greenhouse gases and associated changes in the radiative efficiency of these gases, temperature-related feedbacks on their lifetime, e.g. of CH_4, and climate-carbon cycle feedbacks (Brühl 1993; Caldeira and Kasting 1993; Frank et al. 2010; Gillett and Matthews 2010; IPCC 2009; Tanaka et al. 2009; Wuebbles et al. 1995).

The radiative efficiency of CO_2 decreases approximately logarithmically with its concentration because its main absorption bands gradually saturate. On the other hand, climate-carbon cycle coupling increases the fraction of a pulse emission that remains in the atmosphere. An earlier study (Caldeira and Kasting 1993) had estimated that these two effects would roughly cancel, and hence the denominator of all GWPs would remain broadly constant over time. We test this conclusion for a range of future emission and concentration pathways (see 3.2.2), based on an emulation of the range of latest coupled climate-carbon cycle and Atmosphere-Ocean General Circulation models.

Furthermore, GWPs can also change because of a change in the numerator, i.e. the radiative efficiency of the target gas itself can depend on its concentration and other aspects of radiative balance in the atmosphere such as cloud cover. To a first approximation, the radiative efficiencies of CH_4 and N_2O decrease with the square root of their background concentrations (Myhre et al. 1998; Ramaswamy et al. 2001). Departures from this simple dependence result from an overlap of the absorption bands of CH_4 and N_2O. In addition, the CH_4 chemical loss processes depend on ambient concentrations of NO_x, CO and volatile organic compounds (VOCs) as well as atmospheric temperature. These effects are also parameterised and modelled in MAGICC (Meinshausen et al. 2009; Meinshausen et al. 2011a) and imply a dependence of the AGWP of CH_4 not only on emissions trajectories but also on the specific AOGCM being emulated, because this will affect the rate of temperature increase and hence temperature-dependent loss processes.

Given those multiple drivers for future changes in GWPs, we explored the predictable changes in the 20-, 100- and 500-year GWPs of CH_4 and N_2O for four Representative Concentration Pathways (RCPs) over the 21st century, which have been developed to inform climate change scenario studies and span a broad range of potential future greenhouse gas emissions and concentrations (Meinshausen et al. 2011b; Moss et al. 2010; van Vuuren et al. in press).

The method for calculating future changes in GWPs was similar to the default method, except that concentrations were prescribed not just to 2005 but out to 2100. Pulse emissions were then simulated for the years 2000, 2020, 2040, 2060, 2080 and 2100, to calculate the GWPs that would apply for those target years. Note that the definition of GWPs used by the IPCC assumes that pulse emissions occur in an atmosphere with constant background concentrations. One may assume, even though this is not stated explicitly by the IPCC, that this definition also assumes a constant background state of the climate system. Our methodology for calculating GWPs also applies constant background concentrations from the time an emissions pulse occurs, but we allow the climate system to change following an emissions pulse to realise the ‘committed warming’ from increasing background concentrations up to the time the emissions pulse occurs (Meehl et al. 2007). Our method for calculating future GWPs is thus based on but not fully identical to that of the IPCC, since these further changes in ambient temperature alter the carbon cycle feedbacks and loss processes for CH_4 and N_2O following emissions pulses of those gases, and thus affect the modelled AGWPs.

3.1.3.3 Future changes due to metric design

A third key reason for why the numerical weight assigned to a gas may change over time is that some metrics are in themselves designed to change. The most prominent example of such a metric, which we also used in our study, is the time-dependent GTP (Shine et al. 2007).[2] This metric is based on the argument that a key objective of climate policy is not to exceed a given long-term threshold, e.g. to limit global warming to no more than 2°C above pre-industrial conditions. This level of warming will not be approached within the next two decades, but only towards the end of the 21st century. Therefore the critical question, this metric argues, is how much the emission of any gas at any time contributes to warming at a specific, fixed future time when temperatures are expected to peak, not how much it contributes after some arbitrary time following its emission (as GTPs with fixed time horizons assume).

The exact timing of the warming peak is obviously dependent on the emissions pathway being followed. The relevant peak year can either be determined by assuming a specific emissions pathway and using a climate model to determine the year of peak warming, or

[2] We note that other metrics with changing weights have also been presented (Berntsen et al. 2010).

(given uncertainties and political choices about actual future emissions) the peak year can be arbitrarily set to a target year that roughly approximates the actual peak warming based on broad expectations. The former is more scientifically consistent but introduces another layer of uncertainty and complexity. Most stabilisation scenarios that limit global warming to no more than 2°C above pre-industrial conditions exhibit a warming peak close to the year 2100, while scenarios that result in higher warming have their temperature peak after 2100 (Meinshausen et al. 2011b).

For this study, we decided to use the year 2100 as target year for time-dependent GTPs and assumed emissions occurring along a scenario that would limit global average warming to less than 2°C as best estimate (the RCP-3PD scenario, see Moss et al. 2010), given that this is the policy goal that has been agreed to under the recent UNFCCC negotiations (UNFCCC 2009a, 2010). We use the year 2100 because this is the year up to which detailed emissions scenarios are available and up to which long-term climate outcomes are routinely evaluated using both physical climate models and complex economic models to estimate the costs of mitigation.

The time-dependent GTP is equivalent to using a standard GTP metric whose time horizon automatically shrinks over time. In other words, for emissions that occur in the year 2010, the relative weight of those emissions is determined by the warming caused 90 years into the future, for emissions that occur in the year 2050, their relative weight is determined by the warming caused 50 years into the future, and for emissions that occur in the year 2099, their weight is determined by their instantaneous warming effect. This approach generally results in increasing weight assigned to short-lived gases such as CH_4 because most of their warming occurs in the decades immediately after their emission, whereas the warming caused by CO_2 extends more smoothly for many decades and centuries.

This increasing value placed on CH_4 emissions over time is similar (though not identical) to results obtained from economic cost-effectiveness models. This similarity is one reason for the relative attractiveness of time-dependent GTPs, as their use would offer more cost-effective mitigation without relying on complex and often non-transparent or assumption-laden economic models for the calculation of numerical cost-effective metric values (Johansson 2011).

3.2 Results

3.2.1 Current (year 2005) GWPs and GTPs and their uncertainties

Our modelling approach obtained 20- and 100-year GWPs that are closely comparable with those presented in the IPCC Fourth Assessment Report (identical for CH_4, and within ±3% for N_2O). However, our 500-year GWPs are about 13% lower than those given by IPCC (Forster et al. 2007), which we attribute to stronger climate-carbon cycle feedbacks in the models we used to evaluate GWPs. Stronger climate-carbon cycle feedbacks result in a greater fraction of CO_2 remaining in the atmosphere for longer times, resulting in a higher AGWP for CO_2 for long time horizons and correspondingly lower GWPs (see equation 1). Results are shown in Table 2.

Our results for GTPs are also broadly consistent with other studies, though we find systematically higher values for GTPs than other studies with a time horizon of 100 years. The differences are not significant because they fall well within the uncertainties quantified by our study (see below), but we note that the higher values in our study could be due to slightly different methodological approaches. Our method first determines emissions pathways that result in constant background concentrations of all gases, and then adds a pulse emission of a gas. This allows the emission of a non-CO_2 gas to trigger climate-carbon cycle feedbacks that increase the atmospheric fraction of CO_2 emissions that remain in the atmosphere, which add to the total warming caused by the emission of a non-CO_2 gas. This indirect climate-carbon cycle feedback effect is not included in the standard definition of GWPs, and has not been discussed explicitly in the definition of GTPs. However, a recent study found that including such climate-carbon cycle feedbacks in the definition of GWPs would increase the 100-year GWP of CH_4 by almost 20% (Gillett and Matthews 2010). Our method of calculating GTPs includes those climate-carbon cycle feedbacks, which could explain the higher values. Results for GTPs and comparisons with other studies are shown in Table 2.

Table 2. Values for GWPs and GTPs for CH_4 and N_2O for different time horizons (based on Forster et al. 2007 in IPCC (2007); Fuglestvedt et al. 2010; IPCC 1996; Reisinger et al. 2010, and unpublished data based on this study; Shine et al. 2005). Values shown are medians across a range of climate models (AOGCMs and carbon cycle models); values in square brackets indicate the 5-95% uncertainty range based on the emulated model range (Reisinger et al. 2010).

	20-year horizon	**100-year horizon**	**500-year horizon**
CH_4			
GWP (IPCC 1996)	56	21	6.5
GWP (IPCC 2007)	72	25	7.6
GWP (Reisinger 2010)	72.3 [60.6–86.6]	25 [19.3–31.5]	6.5 [5.4–8.8]
GTP (Shine et al 2005)	46	5	0.8
GTP (Fuglestvedt et al 2010)	57	4	(not evaluated)
GTP (Reisinger 2010)	49.7 [37.5–65.6]	6.9 [3.9–13.5]	0.7 [0.0–2.3]
N_2O			
GWP (IPCC 1995)	280	310	170
GWP (IPCC 2007)	289	298	153
GWP (this study)	294 [248–355]	303 [236–385]	136 [113–183]
GTP (Shine et al 2005)	290	270	35
GTP (Fuglestvedt et al 2010)	303	265	(not evaluated)
GTP (this study)	341 [267–417]	318 [234–427]	36.7 [19.1–84.6]

A key advance in our study is that our methodology allows us to evaluate uncertainties of GWPs based on the spread from different emulations of state-of-the-art complex climate models as well as the use of historical constraints on key climate parameters. A comprehensive evaluation of uncertainties was carried out for GWPs and GTPs of CH_4, with results shown in Table 3. Key conclusions from this assessment are that while uncertainties (expressed as 90 percentile confidence intervals) are significant for GWPs (more than ±20% for the 100-year GWP) and larger than estimated by IPCC (Forster et al. 2007), uncertainties for GTPs are greater still, about -50/+100% for the 100-year GTP and exceeding ±100% for the 500-year time horizon.

Table 3 shows two sets of results, one from the spread of different climate and carbon cycle models, and one from the spread of carbon cycle models and historical constraints on a broad range of other key climate parameters. The uncertainties in the latter case are significantly greater because some key parameters, such as the radiative forcing from a given addition of CH_4 to the atmosphere, are identical across climate models but are in fact uncertain (to about ±5%). The medians of GWPs and GTPs are also slightly different using those two different approaches, but well within the uncertainty range of either approach. Since the methodology using historical constraints is computationally far more expensive, we used the simpler methodology based on different model emulations to calculate medians for all other metrics used in this study. The probability distribution for GWPs and GTPs for CH_4 is shown in Figure 3.1.

Table 3. Uncertainties for GWPs and GTPs of CH_4 for three different time horizons. Values shown are mean, median, and 90% confidence intervals for climate/carbon cycle model emulations and for historical constraints (see section 3.1.1). Other published values for GWPs [*Forster et al.*, 2007] and GTPs [*Shine et al.*, 2005] are given in the bottom row. Table adapted from (Reisinger et al. 2010).

	GWP			**GTP**		
	20	100	500	20	100	500
(model range)						
mean	72.8	25.0	6.7	50.5	7.6	0.9
median	72.3	25.0	6.5	49.7	6.9	0.7
90% conf. interval	[60.6 - 86.6]	[19.3 - 31.5]	[5.4 - 8.8]	[37.5 - 65.6]	[3.9 - 13.5]	[0.0 - 2.3]
(historical constraints)						
mean	72.3	25.1	6.7	52.7	8.7	1.3
median	71.4	24.7	6.5	52.1	8.4	1.1
90% conf. interval	[54.8 - 92.6]	[17.4 - 34.5]	[4.6 - 9.4]	[36.6 - 72.0]	[4.2 - 14.7]	[0.0 - 3.6]

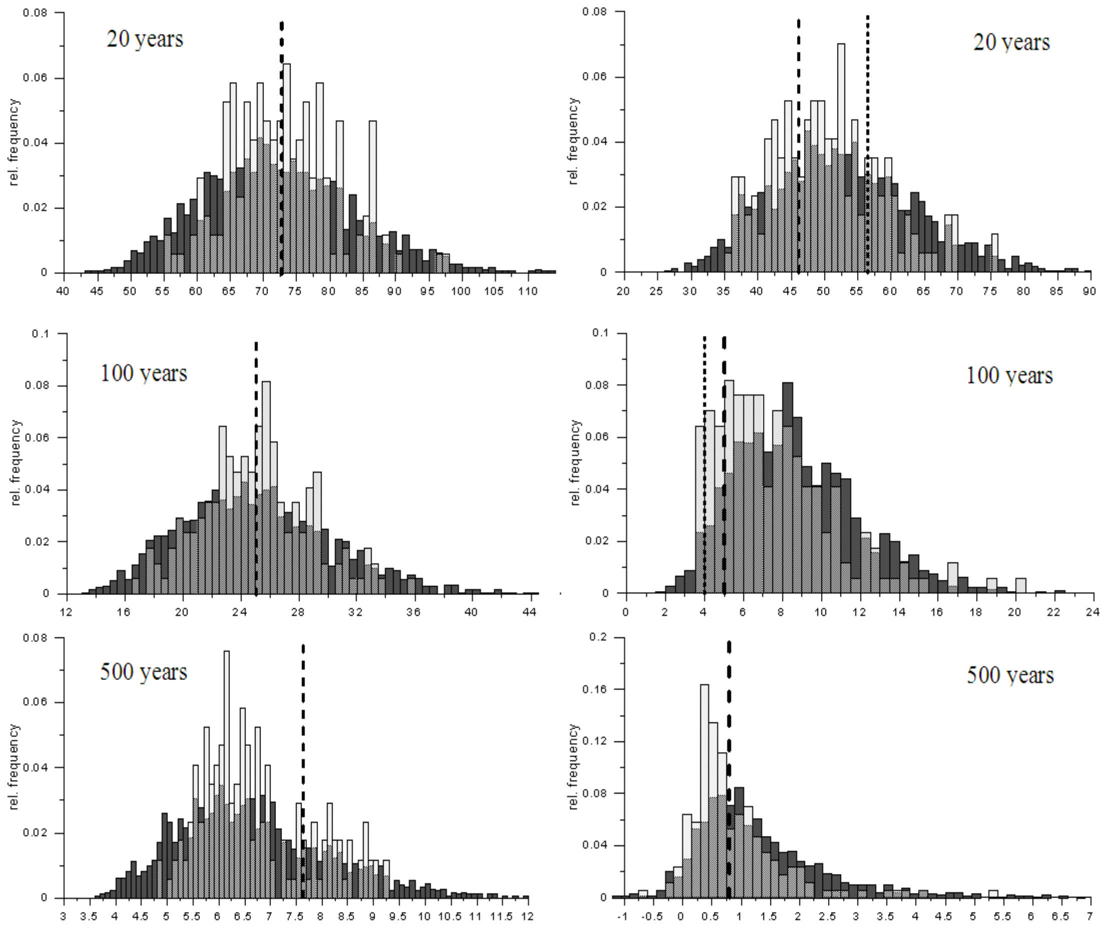


Figure 3.1. Frequency distributions for GWPs (left panels) and GTPs (right panels) of CH_4, for time horizons of 20, 100 and 500 years. Light bars are based on MAGICC tunings for 19 AOGCMs and 9 carbon cycle models, dark bars are based on historical constraints; see text for details. In the left panels, dashed lines illustrate values for GWPs from IPCC (*Forster et al.* 2007). In the right panels, dashed and dotted lines illustrate values from *Shine et al.* (2005) and *Fuglestvedt et al. (*2010), respectively, based on the particular climate sensitivities chosen in those studies. Figure adapted from (Reisinger et al. 2010).

This comprehensive uncertainty analysis has only been undertaken for GWPs and GTPs of CH_4. For N_2O, uncertainties were evaluated only for the model-based range. However, we note that a large fraction of the uncertainties in GWPs for CH_4 up to 100 years is due to uncertainties in the denominator (the AGWP of CO_2). As a result, even though this has not be modelled explicitly, we would expect uncertainties for GWPs of N_2O to be of similar order of magnitude as GWPs of CH_4 once the full uncertainty range of parameters is taken into account.

Results for GWPs and GTPs of CH_4 and their uncertainties have been published in the peer-reviewed scientific literature (Reisinger et al. 2010).

3.2.2 Future changes in GWPs

We explored potential future changes in GWPs, based on already foreseeable changes in atmospheric concentrations of greenhouse gases and attendant climatic changes and already known processes that will influence the radiative efficiency of the different gases. The processes considered include:

- Change in radiative efficiency as a result of increasing concentrations and gradual saturation of absorption bands for CO_2, CH_4 and N_2O, including overlap between absorption bands of CH_4 and N_2O
- Temperature-dependent loss processes for CH_4
- Loss processes for CH_4 also depend on ambient concentrations of carbon monoxide, nitrogen oxides, and non-methane volatile hydrocarbons

These processes are parameterised in MAGICC consistent with IPCC assessments (Ehhalt et al. 2001; Forster et al. 2007; Ramaswamy et al. 2001). We note that other processes could also affect the radiative efficiency and atmospheric lifetime of gases (such as changes in abundance of the hydroxyl radical OH, or changes in cloudiness), but information is too limited at this stage to justify the assumption of any particular change in either direction. Results of this work have been published (Reisinger et al. 2011) and are presented here for ease of access.

We evaluated foreseeable changes for a set of four alternative future emissions pathways, which are designed to explore a wide range of potential future emissions futures. The resulting 'representative concentration pathways' (RCPs; see Figure 3.2) have been described in several recent studies (Meinshausen et al. 2011b; Moss et al. 2010; van Vuuren et al. 2011).

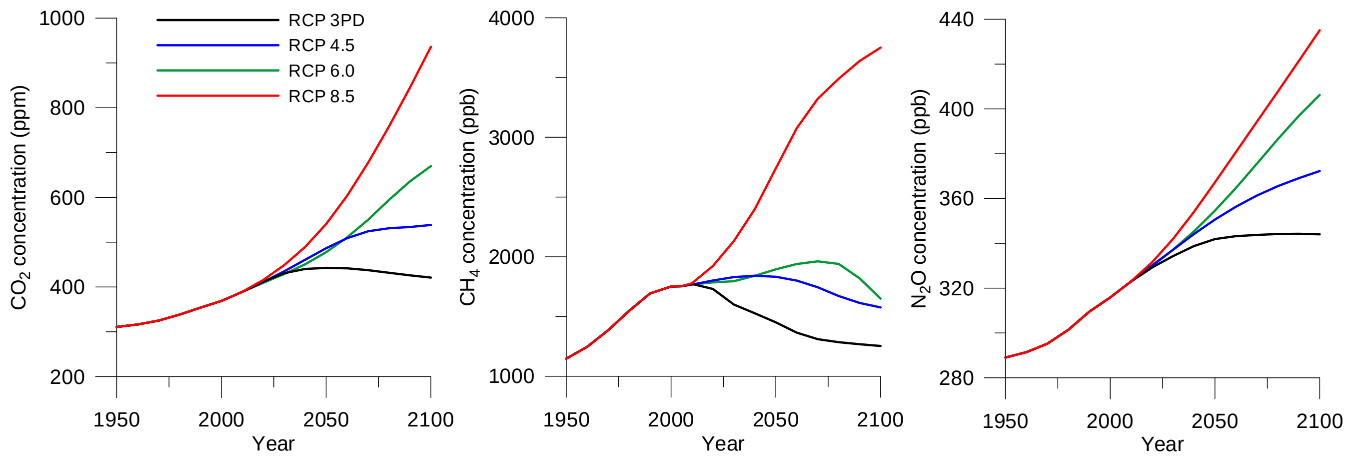


Figure 3.2. Representative Concentration Pathways (RCPs) depicting a four alternative potential future changes in greenhouse gas concentrations, based on four alternative assumptions about plausible and internally consistent socio-economic and technological changes and climate policy choices. Data downloaded from RCP database, http://www.iiasa.ac.at/web-apps/tnt/RcpDb.

The concentration pathways demonstrate the wide range of alternative futures that could unfold, depending on socio-economic and technological outcomes and climate policy choices. The lowest concentration pathway is consistent with climate warming being limited (as best estimate) to less than 2°C above pre-industrial conditions; all other pathways result in greater (and in some cases, substantially greater) warming, possibly exceeding 6°C by 2100. CO_2 and in particular CH_4 concentrations exhibit a very wide range of potential future concentrations, which affects their radiative efficiency and hence AGWPs and GWPs considerably.

Based on the range of models emulated in our study, AGWPs of CO_2 decrease for higher CO_2 concentrations because climate-carbon cycle feedbacks partially but not entirely offset the declining radiative efficiency at higher concentrations. This finding implies that, other things being equal, GWPs of non-CO_2 gases will increase over time proportional to the decline in CO_2 AGWPs. This means that mitigation of CO_2 would be valued less and mitigation of non-CO_2 gases more as the 21st century progresses. The amount of change would depend on the future concentration pathway. Under the lowest RCP, the 100-year AGWP of CO_2 would decrease by only about 2% by 2100 relative to the year 2000 value, and hence the GWPs of other non-CO_2 greenhouse gases would increase by only 2%. By contrast, under the highest RCP, the 100-year AGWP of CO_2 would decrease by 36% by 2100 and hence GWPs of non-CO_2 gases would increase by more than 50% (Reisinger et al. 2011).

The above conclusions only hold for non-CO_2 gases whose radiative efficiency is independent of their concentration or the concentration of other gases or other atmospheric variables. Changes in the GWPs of CH_4 and N_2O (see Figure 3.3) are more complex because their radiative efficiency also depends on their own concentration changes (see Figure 3.2) and associated climate changes, in addition to changes in the denominator (the AGWP of CO_2).

We find that the 100-year GWP of CH_4 would be expected to increase by up to about 10% by 2040 under all but the highest RCP, which would result in a smaller 100-year GWP throughout the 21st century. This different behaviour is due to the rapidly increasing CH_4 emissions in the highest RCP, which would result in a strong reduction in the AGWP of CH_4. By comparison, the 100-year GWP of N_2O would show relatively little change over the next 30-40 years under all but the highest RCP, because in the case of N_2O, the numerator changes only little but the increasing CO_2 concentrations in the highest RCP lead to a reduction in the denominator (see also Figure 3.2 for concentration changes).

A more detailed discussion of the causes of those changes and some caveats about the assumptions and uncertainties can be found in (Reisinger et al. 2011). The changes under the highest RCP scenario are noteworthy outliers, but in our view warrant only limit attention. A world that allows global atmospheric CO_2 concentrations to climb to almost 1000ppm by the year 2100, and CH_4 concentrations to exceed 3000ppb, would appear unlikely to regularly update scientific metrics for the comparison of greenhouse gas emissions for mitigation policy purposes.

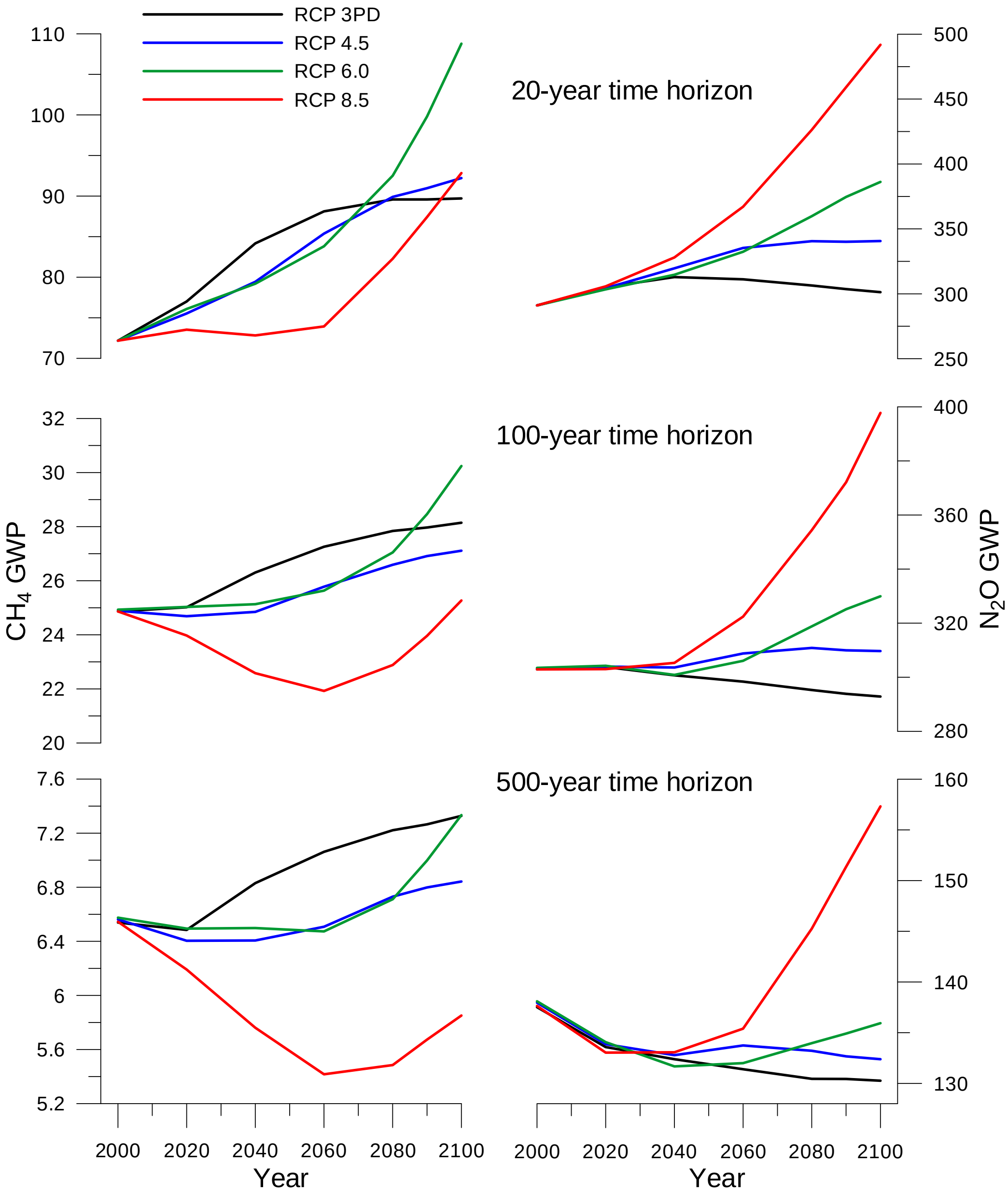


Figure 3.3. Projected changes in GWPs for CH_4 and N_2O for four different representative concentration pathways (RCPs) for three different time horizons (20, 100 and 500 years). Values shown are the medians for the range of complex climate models emulated by MAGICC (see section 3.1.1). Data are from (Reisinger et al. 2011).

3.2.3 Time-dependent Global Temperature Change Potentials

We used the same model set-up as for determining future changes in GWPs to calculate time-dependent GTPs (Shine et al. 2007), using a fixed target year of 2100. The results of these model runs are shown in Figure 3.4. The time-dependent GTP of CH_4 starts at a low value of about 7 (consistent with the 100-year GTP), and increases steadily to values in excess of 100. The time-dependent GTP of CH_4 shows relatively less dependence on the concentration pathway than that of N_2O, because the changes in CO_2 and CH_4 concentrations and associated changes in radiative efficiencies under the different pathways largely cancel each other out. By contrast, the concentrations of N_2O change relatively less than those of CH_4 under the representative concentration pathways considered in this study (see Figure 3.2). Accordingly, as we approach the year 2100, the time-dependent GTP of N_2O is increasingly determined by the different CO_2 concentrations and radiative efficiency of CO_2 for the different pathways, which declines with higher CO_2 concentrations.

Since the main objective of our study is to identify economic and policy implications of different metrics in the context of global efforts to limit global warming to no more than 2°C above pre-industrial levels (UNFCCC 2009a, 2010), we use time-dependent GTPs modelled ex-ante for the lowest RCP pathway (RCP 3-PD) in the remainder of this study to explore global and regional cost implications (see section 4).

We note that we obtain GTPs for CH_4 that are higher towards 2100 than those in the original study that first proposed the use of time-dependent GTPs (Shine et al. 2007, in whose study the time-dependent GTP only just reaches a value of 100 as the target year is approached). We assume that this is because we use different concentration pathways. In the lowest RCP, CH_4 concentrations are presumed to fall below 1990 levels in the lowest RCP scenario, which increases the radiative efficiency of CH_4 and hence its radiative efficiency and near-term GTP. For other scenarios, the presumed greater increase in CO_2 concentrations results in reduced radiative efficiency of CO_2, which again leads to a higher GTP for CH_4 (which compares the near-term warming effect from CH_4 with that of CO_2). We also note that the same radiative forcing could be obtained by a different mix of CO_2 and CH_4 mitigation depending on assumptions e.g. about the economic mitigation potential for CH_4, which would result in different GTPs towards the end of the 21st century. However, we did not consider such dynamic feedbacks between mitigation pathway and metric in this study.

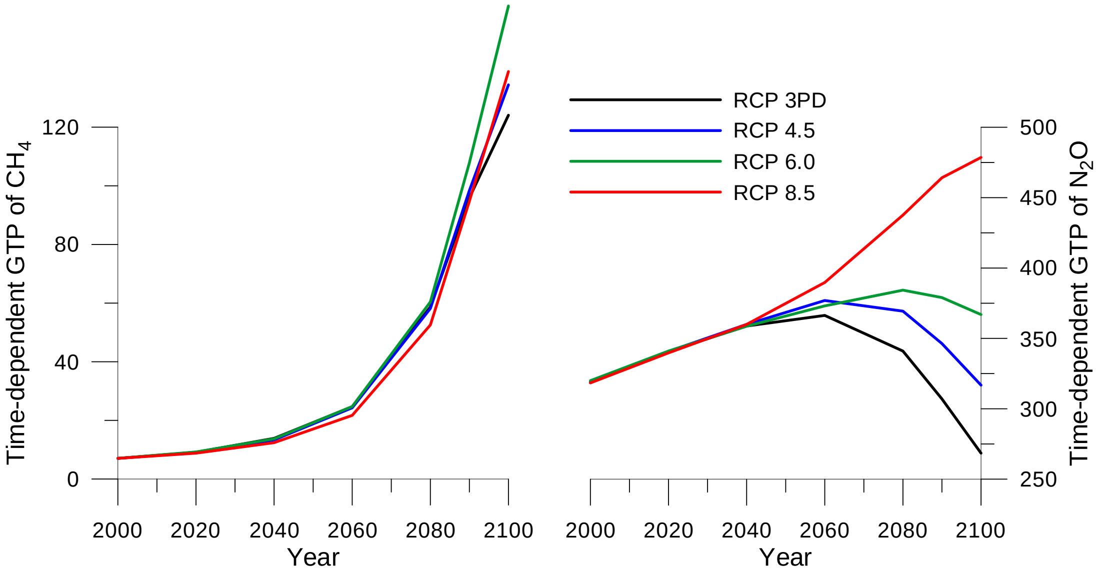


Figure 3.4. Time-dependent GTPs for CH_4 and N_2O under the four different Representative Concentration Pathways. For details, see text.

3.2.4 Illustrative policy-driven 'metrics' for the treatment of agriculture

Given that a motivation of this study is to better understand how alternative treatments of non-CO_2 gases could affect New Zealand with its high fraction of non-CO_2 emissions from agriculture, we introduce and explore in later sections of this report two additional policy-driven metrics specifically for agricultural non-CO_2 emissions.

These 'metrics' have no biophysical or economic basis, but will be used to explore the following questions: what would be the economic (and potential policy) implications if the world decided to exclude agricultural non-CO_2 greenhouse gas emissions from any emissions targets and abatement obligations? What if it excluded those gases only for a limited time and after that treated them like other non-CO_2 greenhouse gases?

The motivations for exploring such policy options are several:

- abatement of non-CO_2 gases from agriculture is more difficult as it deals with a complex biological system
- the range of mitigation options tends to be more limited than for CO_2 emissions

- monitoring and verification of emissions reductions is more challenging
- food security and the potential impact of strong mitigation targets on food prices is a strong concern particularly in developing countries
- virtually all countries to date have in practice excluded their agricultural emissions from a price measure or other stringent emissions constraints, even if they are responsible for those emissions under the basket approach of the Kyoto Protocol (Johansson and Persson 2005).

None of these issues necessarily preclude the inclusion of agricultural non-CO_2 emissions in future price-based and stringent mitigation policies. However, these issues and the salience such arguments hold with some stakeholders suggest it is worthwhile to explore the economic consequences if such emissions were not included in international agreements or if countries continue to choose to exempt agriculture from stringent mitigation obligations in practice. For this reason, we included two additional policy choices, which could also be described as policy-driven 'metrics':

1. one metric sets a value of zero to all agricultural non-CO_2 emissions but uses 100-year GWPs or 100-year GTPs for all other non-CO_2 emissions from other sectors (i.e. agricultural emissions are excluded from future mitigation efforts)
2. the second metric makes the same choice but only until 2050, and after that applies 100-year GWPs to agricultural non-CO_2 emissions.

Those 'metrics' would imply that no mitigation is undertaken in agriculture (at least until 2050). However, agricultural non-CO_2 emissions of course contribute to radiative forcing and global climate change. This implies that a greater mitigation effort and higher carbon prices will be required in other sectors to meet the same long-term stabilisation targets. The purpose of our study then is to quantify how large those changes in prices and mitigation costs are to provide a quantitative basis for considering whether such 'metrics' and policy options to exclude agricultural non-CO_2 emissions, or limit their contribution to overall mitigation strategies, are feasible or desirable.

We emphasise that these particular 'metrics' and policy choices are purely hypothetical and should be considered thought or sensitivity experiments. There are numerous potential co-benefits of mitigating agricultural non-CO_2 emissions, such as enhanced productivity and increased soil carbon storage as well as lower environmental pollution and reduced mitigation cost burdens for other sectors. Completely excluding agriculture from mitigation obligations should therefore be regarded as the most extreme end of a spectrum of potential policy choices for the treatment of agricultural emissions.

3.3 Summary – potential metrics and their implications

In the preceding sections we presented consistent model calculations of a variety of metrics that could be used to compare greenhouse gas emissions for the purpose of information mitigation policies and abatement priorities. These are GWPs and their predictable changes over time, and GTPs with fixed time horizons as well as time-dependent GTPs, and two hypothetical policy-driven 'metrics' that would provide special treatment for agricultural emissions.

Our calculations and analysis allow a number of key conclusions:

1. As is widely known and accepted, GTPs with fixed time horizons would result in significantly lower weight for CH_4 emissions than GWPs for the same time horizons, due to the relatively short lifetime of CH_4. Differences for N_2O are much smaller and, perhaps more importantly, GTPs derived in our study would assign a *greater* weight to N_2O than GWPs for time horizons up to 100 years.
2. Uncertainties of present-day GWPs with a 100-year time horizon are in the order of ±20%, but uncertainties of GTPs are significantly greater in the order of -50/+100%. This could make a potential change in metrics difficult since the greater uncertainty

makes it harder to settle on and politically agree a single best estimate for the exchange rates between gases. Greater uncertainty also implies that the potential for future changes of best estimates within this broad uncertainty range, as a result of growing scientific knowledge, is even greater for GTPs than for GWPs.

3. Additional processes that could affect the radiative forcing exerted by CH_4 emissions indirectly (through interactions with aerosols, the carbon cycle, or atmospheric chemistry affecting the abundance of the hydroxyl radical), could alter the GWP of CH_4 substantially. Some of these processes have been quantified tentatively. If they were included in GWP calculations, some of these processes would result in an increase in the 100-year GWP of CH_4 to more than 30, but they would also increase the uncertainty of GWPs. For some other changes (particularly changes in OH abundance), scientific uncertainty is currently too great to allow best estimates of future changes and these require further research.

4. The significant uncertainties of GWPs and GTPs underline that even in the absence of major new scientific discoveries, best estimates for GWPs and GTPs of CH_4 and N_2O could alter by up to about 20% simply by a gradual convergence of the currently wide spread of model parameterisations. This poses significant challenges to national multi-gas mitigation policies that need to make strategic decisions about the priority to give to abatement of CO_2 and non-CO_2 gases.

5. Even in the absence of new scientific discoveries, GWPs can be expected to change over time because of predictable future changes in atmospheric composition and climate. The 100-year GWP of CH_4 will increase by about 10% over the next 30 years under a variety of plausible future emissions pathways that would be consistent with global mitigation efforts of various levels of stringency. The 100-year GWP of N_2O would be less prone to change under the same emissions pathways. GWPs of both gases could change more substantially beyond 2050.

6. The benefit and appropriateness of updating GWPs based on such foreseeable changes depends on the goals that climate policy wishes to achieve. Updating 100-year GWPs over time would be appropriate if the primary goal of climate policy is to limit the integrated radiative forcing resulting from greenhouse gas emissions over a 100-year time horizon. If other climate policy goals are seen as more relevant, such as stabilising long-term radiative forcing, minimising the rate of temperature change, or limiting near- or long-term temperature increases, then the use of alternative metrics and/or alternative time horizons may be more effective than updating the 100-year GWP metric currently in use.

7. A time-dependent GTP offers an alternative way of dealing with the fundamentally different nature of long- and short-lived greenhouse gases such as CO_2 and CH_4. Assuming a fixed target year of 2100, we find that a time-dependent GTP would initially assign a low value of about 7 to CH_4, but this value would increase to reach 25 by about 2050 and climb to well over 100 before 2100. The evolution of the time-dependent GTP of N_2O is more dependent on the emissions pathway that unfolds over the 21st century. It would increase from currently about 318 to about 350 by 2050, and then either increase further or fall to below 300 depending on the specific emissions pathway that the world follows.

8. Apart from those physically-defined metrics, it is possible to construct alternative policy-driven metrics that provide for special treatment for agriculture. For the purpose of this study, we define two policy ‘metrics’, one that excludes agricultural non-CO_2 emissions from all emissions obligations, and one that does so only until 2050 and then weighs them using current 100-year GWPs.

A selection of the variety of metrics modelled in this study is shown in Figure 3.5 specifically for agricultural emissions of CH_4 and N_2O, for a global emissions pathway that would limit global temperature increase to 2°C above pre-industrial levels. With the exception of the policy-driven metrics, all other metrics and the resulting ‘exchange rates’ for CH_4 and N_2O and their changes over time can be robustly argued for based on various sound and transparent scientific principles, but they lead to very different results. This highlights the importance of testing economic and policy implications, as well as applying guidance through articulation of underlying policy goals, when selecting or advocating any particular metric for use in climate policy.

Given the relatively small predictable changes in 100-year GWPs compared to the influence of alternative choices for metrics, we explore the economic and policy implications of the following metrics in the remainder of this study:

- Present-day fixed 100-year GWPs (the default case for current climate policy)
- Present-day fixed 100-year GTPs
- Time-dependent GTPs (based on a target year of 2100, and an assumed emissions pathway consistent with limiting global warming to no more than 2°C above pre-industrial levels as best estimate)
- Policy-driven metrics that simulate the exclusion of agriculture from mitigation obligations (either in perpetuity, or until 2050 followed by 100-year GWPs).

We do not explore scenarios where metrics are switched at some stage later in the 21st century, because a change in metrics at some later stage would effectively be a new time-dependent metric, which is unlikely to offer substantial additional insights over and above those gained from the simulations for the metrics already considered.

A more policy-relevant issue relates to costs if metrics are changed at some stage without 'perfect foresight' that this change will occur. However, this would constitute a significantly different and more complex model setup which was beyond the scope of our study. In Section 4 we explore the global and broad sectoral/regional costs of the above set of metrics, for a variety of assumptions such as different actual long-term stabilisation outcomes and different effectiveness and change over time in agricultural mitigation potential. Section 5 explores the implications of a subset of these global and broad regional results for New Zealand. We assume that all metrics are in place consistently from 2010 to the end of the 21st century.

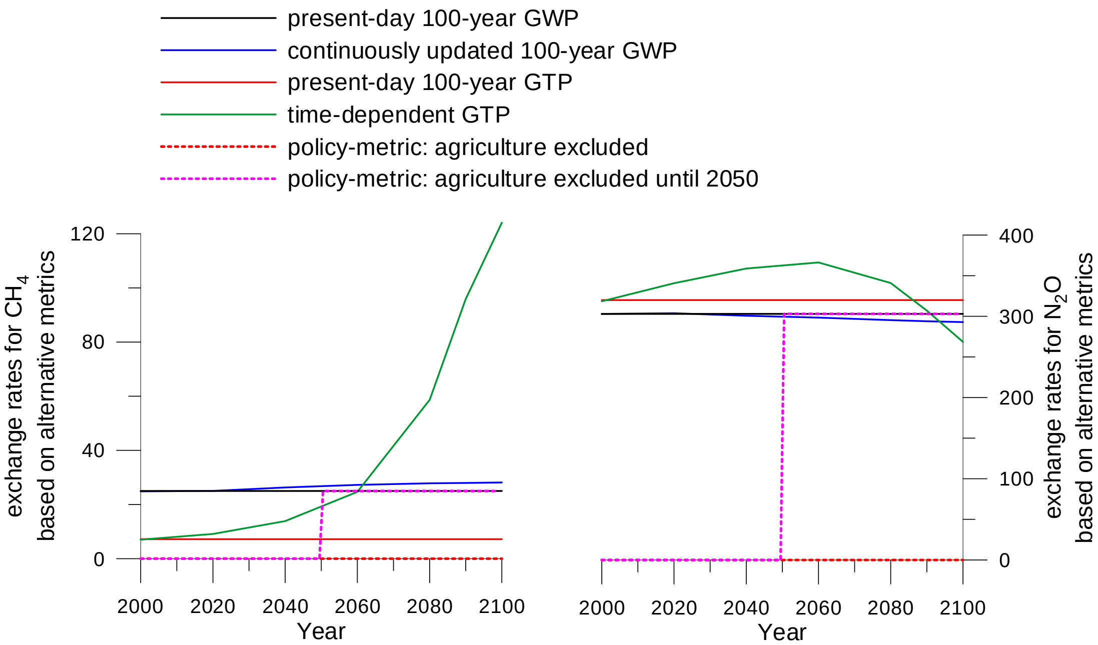


Figure 3.5. Selected summary of exchange rates for agricultural emissions of CH_4 and N_2O for a variety of metrics discussed in this report. Not shown are exchange rates based on metrics with a 20- or 500-year time horizon, although these could also be argued for if a particular type of policy goal were adopted that either focuses *only* on near-term rates of change (20-year horizons) or is *only* concerned with very long-term outcomes (500-year horizons).

4. Global abatement costs under different metrics

4.1 Overview and general assumptions

We used the multi-gas version of the MESSAGE integrated assessment model (Rao and Riahi 2006; Rao et al. 2008; Riahi et al. 2007) to analyse the global and broad regional mitigation costs, shadow carbon prices and impacts on GDP for meeting stabilisation targets. In the standard configuration of the model, the model selects the most cost-effective mix of mitigation options to achieve a prescribed cumulative emissions constraint. This cumulative emissions constraint is chosen so that a prescribed long-term climate policy goal (such as limiting radiative forcing to a given level) will be met. The contributions of different greenhouse gases are calculated based on their cumulative emissions over the 21st century, using prescribed metrics (see section 3). The detailed set-up and additional assumptions and environmental, economic and social constraints are described elsewhere (Riahi et al. 2011).

Mitigation options are defined through various technologies that have prescribed investment or variable operating and maintenance costs. In some cases (e.g. bioenergy supply) additional limits to technology deployment and resource availability apply. International trading of energy carriers is modelled at a high level of detail. The drivers and mitigation options for agricultural emissions used in MESSAGE are described in more detail below (section 4.2).

The model applies the available mitigation technologies wherever and whenever they are cost-effective after 2010.[3] This is identical to assuming that a single global price is applied to all greenhouse gas emissions (at cost ratios defined by the prescribed metrics). We note that this is an idealising assumption, as currently a price on emissions from developing countries applies only in a very muted form through the CDM, and even developed countries have tended to exempt some emissions from a price signal (although they may have applied regulations and standards that force emissions reductions, sometimes at a cost that is higher than an under an explicit carbon price).

The most noteworthy exemption from a New Zealand perspective is the fact that no country to date has applied a direct price on all agricultural non-CO_2 greenhouse gas emissions, although other environmental regulations (e.g. on nitrogen pollution) can have an implicit effect on emissions. We therefore explore in this and the subsequent section the potential implications on mitigation costs and carbon prices if agricultural non-CO_2 emissions were to be exempted entirely from emissions prices and mitigation obligations (either by international agreement or as collective domestic practice).

In the MESSAGE model, the world is split into 11 different regions. New Zealand is part of the ‘Pacific OECD’ region, which comprises Japan, Australia and New Zealand. As noted earlier (section 2), the main strength of the MESSAGE model is a detailed representation of the energy sector, while its representation of land-based emissions sources, in particular agriculture, are much more simplistic. For these reasons, estimates of mitigation costs are reasonably robust but obviously depend on the specific mitigation cost curves chosen for the model (see section 4.2), but estimates of impacts on GDP (which would need to consider changes in supply and demand for agricultural products and changes in trade patterns) need to be treated with caution.

The model does not assume any specific national or regional emissions targets, but assumes that all costs are met where they fall. In general, this would imply a disproportionate cost of mitigation falling on developing regions (relative to per capita incomes), and it can only be assumed that such disparities would be addressed by international agreements setting up separate targets, initial allocations and trading mechanisms. Such policy details have not been considered in this model.

[3] The model runs in 10 year time steps, so that the first model output year with a carbon price is 2020.

In the idealised approach used in the MESSAGE model (as well as many other global integrated assessment models), a country that does not have any technical mitigation options would not bear any mitigation costs (other than through changes in commodity prices). This is obviously different to a situation where countries have set emissions targets and have to meet those targets either by domestic measures or by emissions trading. The prices revealed by MESSAGE thus are not 'carbon taxes' that are imposed externally on countries or sectors, but they are '*shadow prices*' that reveal the threshold at which various mitigation options would become cost-effective. Whether such mitigation options would in fact be motivated via emissions pricing (taxes or capped permits) or other policy mechanisms is not considered or prescribed in the model.

Countries or regions that do not have any technological mitigation options below the current shadow price of greenhouse gas emissions would not face any mitigation costs. For these reasons, impacts of mitigation measures on *global* GDP modelled by MESSAGE are relevant, but *regional* GDP effects may not be because they do not consider possible emissions targets, allocations and effects of changes in trade patterns on national GDPs.

We note that in our model setup, the only constraint on MESSAGE are the allowed global cumulative emissions (based on a desired long-term stabilisation target in 2100), and the model is only used to determine the most cost-effective emissions path, based on weighted cumulative emissions, to reach that target. If other constraints were imposed on the model (such as limiting the rate of temperature change, setting limits on radiative forcing also before or after 2100, or assuming different rates of participation or burden sharing by different world regions), both global costs and their regional distribution would change. However, these issues and their interactions with alternative metrics were not explored in this study and must be left to further research if this is deemed to be important for policy purposes.

We determined mitigation costs for a number of metrics, and tested the sensitivity of results for a number of key assumptions of relevance to an agricultural systems perspective. In short, the metrics and key sensitivity tests include:

- costs for the following metrics: 100-year GWPs, 100-year GTPs, time-dependent GTPs, and two hypothetical policy-driven metrics that would exclude agricultural gases globally from price measures (either until 2050, or in perpetuity)
- two alternative stabilisation targets of 450ppm and 550ppm CO_2-equivalent in 2100 (corresponding to radiative forcing of about 2.6 and 3.7 Wm^{-2}, with best-estimate equilibrium warming of about 2 and 3°C relative to pre-industrial levels)
- alternative assumptions about the future evolution of agricultural mitigation potential and costs, including the availability of (unspecified) additional mitigation technologies for CH_4 emissions from enteric fermentation.

4.2 Agricultural abatement cost curves and baseline assumptions

4.2.1 Marginal abatement cost curves for 2020

For the purpose of this study, the MESSAGE model was upgraded to use a revised set of detailed agricultural mitigation cost curves (Beach et al. 2008, extending earlier work; USEPA 2006). These mitigation cost curves are broadly consistent with the mitigation costs indicated by the last IPCC assessment and other detailed agricultural model-based mitigation cost studies (Smith et al. 2007; Vermont and De Cara 2010). The mitigation cost curves are based on detailed model studies for 37 different sub-regions of the world that take agricultural, climate and soil conditions into account as well as labour and energy costs. Those cost curves were aggregated to the 11 regions represented in MESSAGE, and aggregated into six discrete cost levels, ranging from a minimum cost of US\$1/tCO_2-eq to more than US\$300/tCO_2-eq..

Figure 4.1 shows the mitigation cost curves for mitigation of CH_4 from paddy rice, N_2O (and soil carbon) from agricultural soils, and CH_4 from livestock (enteric fermentation and manure management), aggregated to the global level for the year 2020. Mitigation options include the effects of some measures on more than one greenhouse gas, e.g. low-till reduces N_2O emissions but also increases soil carbon storage, or improved feed conversion reduces CH_4 from enteric fermentation but may also affect N_2O emissions from manure/urine. In most cases, mitigation measures affect mainly one (the primary target) gas, but for soil management, enhanced soil carbon storage can make a significant contribution to the overall mitigation potential. No mitigation options were implemented for N_2O from manure due to a lack of literature.

Two features of the cost curves are particularly noteworthy, which are consistent with several other model-based estimates of mitigation costs for these agricultural emissions:

- the total mitigation potential in most regions in the year 2020 is limited to between 14 and 28% percent of baseline emissions even for very high carbon prices, due to limited mitigation technologies
- a substantial fraction (between a quarter and about one half) of the total mitigation options are indicated to come at net-negative costs, with costs rising relatively steeply thereafter.

The limited overall mitigation potential is consistent with many other global studies. It implies that while rising greenhouse gas prices can promote some mitigation of agricultural emissions, even very high prices will not result in complete abatement of all emissions. This is a crucial difference to emissions of CO_2 from fossil fuel burning, where technologies exist to reduce net emissions to or even below zero, given sufficiently high carbon prices. In the real world of course, rising carbon prices and associated increases in some agricultural commodities could result in regional or even global changes in demand and switch between different commodities. The MESSAGE model has a fixed global demand for agricultural products, so that agricultural commodities are produced at whatever cost, which contributes to emissions remaining at some minimum level eve when carbon prices reach very high levels of more than US$1000/t$CO_2$-equivalent.

The substantial fraction of low-cost mitigation options is common across many bottom-up model based studies (Vermont and De Cara 2010). We do not judge the validity of those assumptions here, other than to note that most New Zealand mitigation cost studies assume that mitigation options for agriculture are very limited or in fact zero (Ballingall et al. 2009). The discrepancy between findings from global modelling studies and assumptions about New Zealand-specific mitigation costs may be due to peculiar features of the New Zealand agricultural production system or due to systematic biases in model-based global mitigation assessments. It is clear that the assumption of *zero* mitigation options in New Zealand is a simplification that is unlikely to be entirely accurate. Nonetheless, for the purposes of this global model study, it was decided that a consistent global characterisation of mitigation potentials was more important than consistency with New Zealand-specific assumptions, and thus the mitigation cost curves from Beach et al. (2008) were used without adjustment for New Zealand.

An added complication is that the MESSAGE modelling framework assumes that under business-as-usual (i.e. without any carbon prices or emissions constraints), each sector performs at optimum efficiency, which would be contradictory to the presence of substantial net negative cost abatement options. Consistent with other studies (Lucas et al. 2007; van Vuuren et al. 2007), we assumed that there are some unspecified barriers to realising those net negative cost abatement options, but that these barriers do not in themselves represent major costs. We therefore assumed (Lucas et al. 2007) that all mitigation options with net negative costs could be realised at small positive costs of US$1/t$CO_2$-equivalent, i.e. that barriers to their implementation are removed via non-price regulatory, information or incentive-based mitigation policies as soon as the carbon price is greater than zero (which is the case by 2020 under all scenarios).

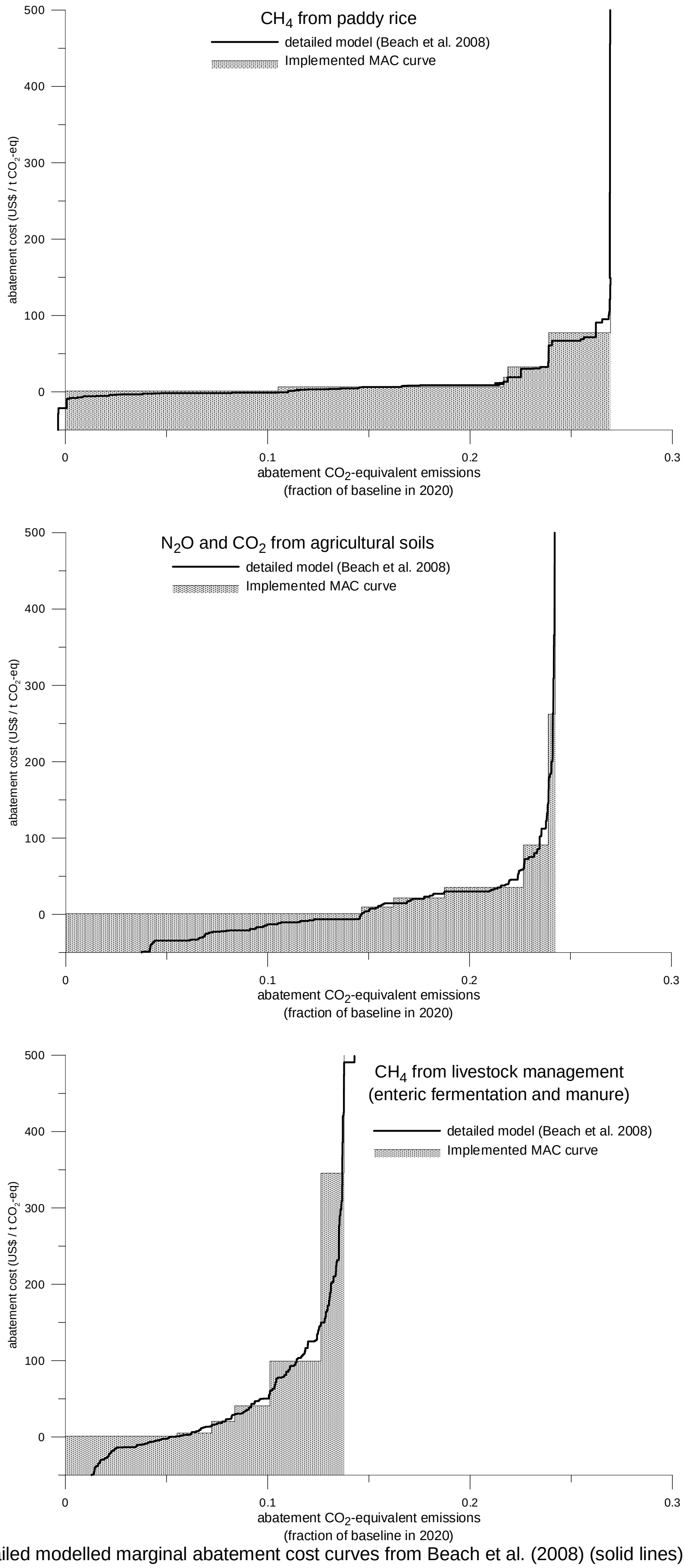


Figure 4.1. Detailed modelled marginal abatement cost curves from Beach et al. (2008) (solid lines) and their implementation in MESSAGE via six discreet cost steps (shaded areas).

4.2.2 Future evolution of abatement potential

A key question for long-term mitigation modelling is the future evolution of abatement potential. This issue has received very little attention internationally. At one extreme, one could assume that current knowledge has already fully exhausted all mitigation potential in agricultural systems, and hence the abatement cost curves shown in Figure 4.1 remain static throughout the 21st century. Another, more technology-optimistic view, would hold that the abatement potential continues to increase due to improvements in farming practices and technological advances. Historical evidence from New Zealand and other countries suggests that emissions intensity per unit of agricultural product would improve significantly over time even under business-as-usual scenarios. The formation of the Global Research Alliance for Agricultural Greenhouse Gases (NZ 2009b; Shafer et al. 2011) is an international collaboration specifically to advance mitigation options beyond business-as-usual. However, given the exploratory nature of the research involved, predicting the pace and quantity of future advances is difficult.

We explored the sensitivity of our results to two alternative assumptions:

- ***No improvement:*** static abatement cost curves throughout the 21st century, based on year 2020 costs from Beach et al. (2008)
- ***Rapid improvement:*** a continuous improvement of mitigation potential from 2020 to 2050 at the same rates assumed by (van Vuuren et al. 2006b):
    - 3.9% per year 2020 to 2050 for N_2O emissions from soils and CH_4 from enteric fermentation
    - 1.5% per year 2020 to 2050 for CH_4 emissions from paddy rice
    - 2.4% per year 2020 to 2050 for CH_4 emissions from manure
    - 0.4% per year 2050 to 2100 for all emissions.

It must be noted that this extension of future mitigation potential is quite simplistic, since the baseline mitigation potential for the year 2020 includes measures such as removing existing inefficiencies in herd sizes or treatment of diseases that cannot necessarily be extended in future, and some cost estimates rely on labour and energy costs that could change dramatically over time (in either direction, depending on future changes in energy and labour inputs to achieve a specified mitigation outcome). The specific assumptions made here should thus be regarded as tools to test the sensitivity of our results to a fairly wide range of potential future improvements in mitigation potential, not as predictions of how mitigation potential would in fact evolve.

4.2.3 Addition of hypothetical future mitigation technologies

To further test the sensitivity of our results to the assumed mitigation potential, we ran two scenarios where an unspecified additional future mitigation technology is introduced. Again, the purpose of this is to test how the costs and benefits of alternative metrics might depend on the size and timing of future mitigation options, they are not intended to predict the potential or cost of future mitigation technologies, let alone predict what specific technology might deliver such results.

We tested the implications of either of the following two assumptions:

- a mitigation technology that ***abates a further 30% of enteric CH_4 emissions*** in all world regions, by 2030, at a cost of US$1750/t$CH_4$ (US$70/t$CO_2$-eq)
- a mitigation technology that ***abates a further 70% of enteric CH_4 emissions*** in all world regions, by 2070, at a cost of US$2500/t$CH_4$ (US$100/t$CO_2$-eq)

These hypothetical additional mitigation options are assumed to apply in addition to the steady mitigation potential improvement rates assumed under the ‘high rate of improvement’ scenario and are illustrative of a global ‘success scenario’ for current research efforts such as those conducted by New Zealand and through the Global

Research Alliance. Care was taken not to allow the total mitigation potential to exceed 100% for any region.

The costs assumed for those mitigation ‘solutions’ are high by today’s standards and carbon prices. Those high costs were chosen to explore the benefit of mitigation technologies in a carbon constrained world that faces increasing costs on emissions. If mitigation options were available at much lower costs, this would reduce mitigation costs further but would be more akin to reducing baseline emissions, since in that case the mitigation options would be taken independently of the actual carbon price and metric.

4.2.4 Interactions between mitigation technology and policy choices

Policy choices that exclude agriculture from mitigation obligations for the next few decades could influence the future evolution of the technological mitigation potential (4.2.2, 4.2.3). This is because such an exclusion would not only reduce incentives to invest in research but also reduce opportunities for learning-by-doing and implementation options that match regional farm systems.

Such interactions are explored for the agriculture policy scenario that excludes agriculture from any obligations until 2050 through the following assumptions:

- Mitigation potential does not improve over time
- Mitigation potential improves at the same rates as in the ‘high rate of improvement’ scenario, but this improvement only starts from 2050 onwards.

In addition, we also explored the impacts on global costs and carbon prices if only the lowest cost mitigation options were implemented globally (which would not require any price signal but could still rely on additional regulatory policies such as environmental standards, or information or incentive-based mitigation policies). Given the lack of information regarding why the presume net negative cost mitigation options are not taken up in the current environment, this scenario again should be viewed as exploratory rather than a firm statement about the amount of emissions reductions that could be achieved at net negative costs.

4.3 Results

4.3.1 Concentrations, emissions and carbon prices under different metrics

Figure 4.2 shows the global concentration pathways under business-as-usual and the two stabilisation targets (450 and 550ppm CO_2-equivalent in 2100), for various combinations of the above assumptions (section 4.2). All stabilisation trajectories result in the same two alternative end points in 2100, but the degree of ‘overshoot’ varies between different scenarios, depending on what timing of mitigation measures is most cost-effective for the different sets of assumptions.

The scenario with the largest overshoot for 450ppm is the scenario that assumes that a new mitigation technology for CH_4 from enteric fermentation becomes available in 2070. In this scenario, greenhouse gas concentrations reach 538ppm CO_2-equivalent in 2060 before declining rapidly to 450ppm in 2100 once the mitigation option is implemented and CH_4 concentrations fall rapidly, given the short lifetime of CH_4 in the atmosphere. By contrast, the scenario with the lowest overshoot is the scenario that assumes agricultural non-CO_2 emissions are excluded from any abatement obligations. In this scenario, concentrations reach a maximum of 498ppm in 2050 before declining gradually to 450ppm in 2100. The lower overshoot level in this scenario is due to the much longer lifetime of CO_2 in the atmosphere, which implies that (in contrast to CH_4 abatement) emissions reductions of CO_2 later in the century do not result in rapid reductions in CO_2 concentrations. For a stabilisation target of 550ppm, the maximum and minimum overshoot levels are 615 and 582ppm CO_2-eq, respectively.

The different levels of overshoot indicate that even though all 450 and 550ppm scenarios result in the same long-term radiative forcing in 2100, they result in different intermediate forcings in mid-century and hence lead to different absolute amounts and rates of warming. This means that their environmental effects are not strictly identical since climate change impacts depend not only on the long-term amount of warming but also on rates and intermediate levels of warming (O'Neill and Oppenheimer 2004). However, given the much larger differences in rates and absolute amounts of warming under different stabilisation levels (e.g. 550ppm compared to 450ppm) compared to alternative metrics, we have not explored those environmental differences further and use the radiative forcing in the year 2100 as the sole constraint on emissions pathways explored in this study.

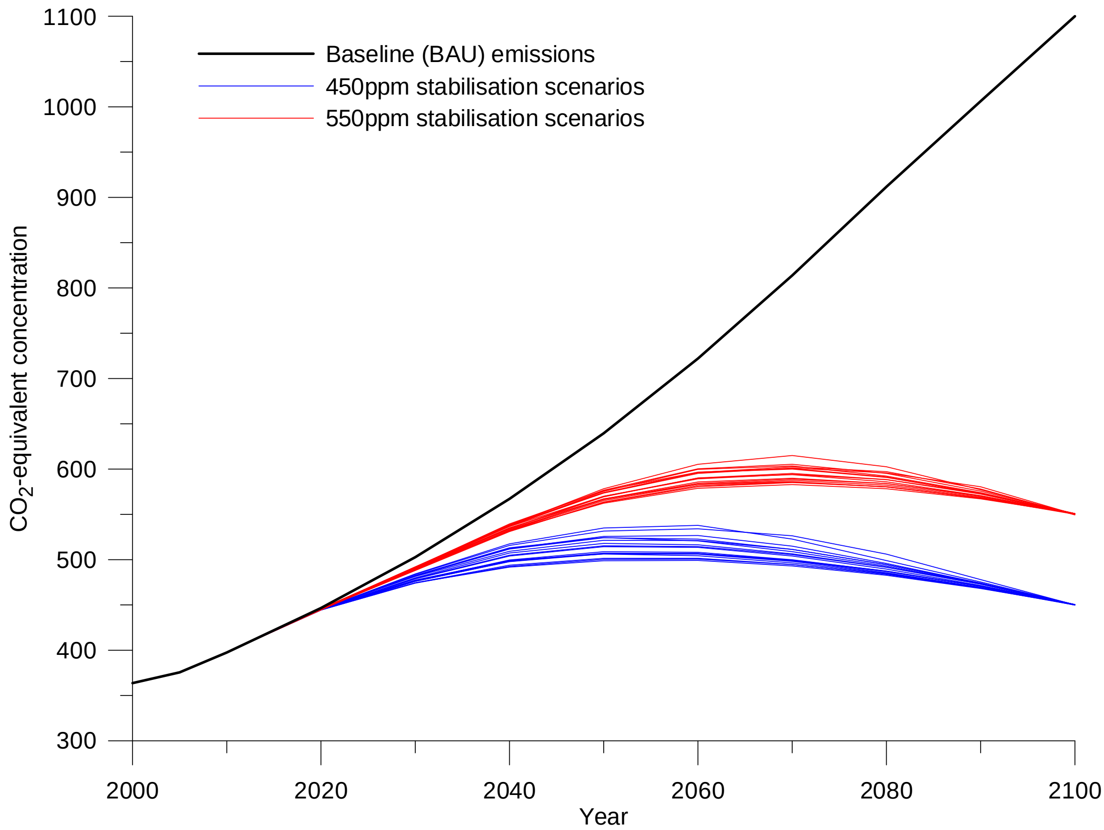


Figure 4.2. CO_2-equivalent concentrations for the full range of alternative scenarios explored in this study. The lines show baseline (business-as-usual) emissions in the absence of any emissions constraints, and cost-minimised emissions trajectories for two alternative stabilisation levels (450 and 550ppm CO_2-eq in 2100), based on alternative metrics and varying assumptions about future mitigation potentials for and policy treatment of agricultural non-CO_2 emissions. See text for details.

Figure 4.3 shows cost-minimised global emissions trajectories for CO_2 (fossil fuel and land-use change) and CH_4 under the same wide range of alternative metrics and assumptions. Several features are noteworthy:

- CO_2 emissions are reduced to below zero in all mitigation scenarios, whereas CH_4 emissions remain between about 50% and 100% of year 2000 levels. These different evolutions are the result of different marginal abatement costs for these two gases, and the existence of ‘negative emissions’ technologies for CO_2, based on the combination of bioenergy and carbon storage.
- CO_2 emissions are reduced rapidly after a global carbon price is assumed to apply (from 2010 onwards). For 450ppm stabilisation scenarios, global emissions peak before or by 2020, whereas for most 550ppm stabilisation scenarios, global emissions peak by 2030 or shortly after. The sets of emissions trajectories are distinct between the different stabilisation levels, i.e. even the least stringent

mitigation pathway for CO_2 that is consistent with an ultimate goal of stabilising at 450ppm by 2100 is still lower than the most stringent mitigation pathway consistent with stabilising at 550ppm. This suggests that choices regarding the ultimate stabilisation level that can be achieved cost-effectively via CO_2 emissions reductions need to be made very early in the 21st century – later course corrections would become increasingly difficult (i.e. cost-ineffective). This is consistent with findings from other literature (Bosetti et al. 2009; Calvin et al. 2009; Krey and Riahi 2009; Russ and van Ierland 2009; van Vliet et al. 2009; Vaughan et al. 2009).

- In contrast to CO_2 emissions trajectories, trajectories for global CH_4 emissions are more interspersed. To some extent this of course simply reflects the fact that we have deliberately explored a wide range of alternative future evolutions of the mitigation potential for CH_4 and alternative metrics that have particularly large implications for the treatment of CH_4. But the greater spread of scenarios across the two stabilisation levels also reflects the fact that due to the short lifetime of CH_4, high emissions early in the 21st century followed by very rapid emissions reductions late in the century can still be cost-effective (for some particular assumptions about the long-term evolution of its mitigation potential and for some particular metrics that would give increasing weight to CH_4 abatement).

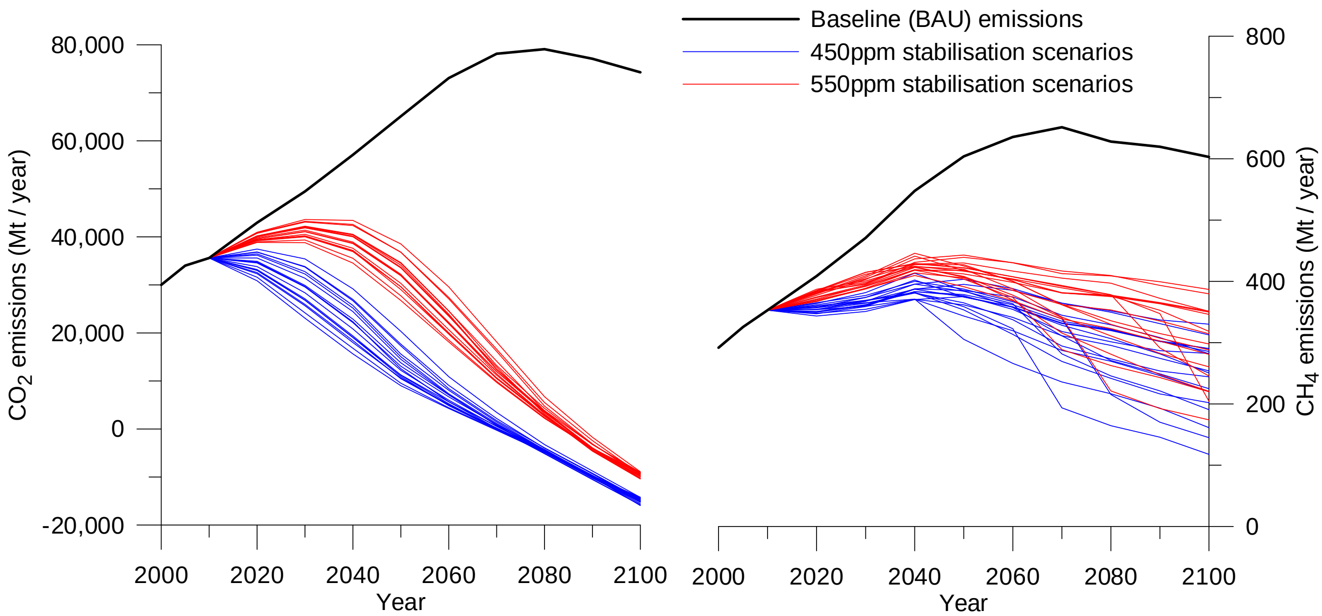


Figure 4.3. Trajectories for global emissions of CO_2 and CH_4 (from all sources), based on cost-optimal pathways for the broad range of metrics and assumptions explored in this study.

Figure 4.4 shows selected global emissions trajectories specifically for CH_4 from agriculture as modelled in the MESSAGE system, i.e. from paddy rice, enteric fermentation and manure management, for a subset of scenarios. The figure shows trajectories for a 450ppm stabilisation target for GWP and GTP (fixed and time-varying) metrics, for alternative assumptions about the future rate of improvement in mitigation potential. Figure 4.4 demonstrates that in terms of emissions, alternative assumptions about mitigation potential have a much larger effect on the most cost-effective emissions pathways than alternative metrics.

Different metrics have a larger relative effect the greater the future assumed improvement in mitigation potential. The main reason for this is the combined effect of the marginal abatement cost curve for agricultural emissions and the differences in global carbon prices under different metrics and assumptions about future evolution of the abatement potential. Rapid improvements in mitigation potential result in lower overall carbon prices. Different metrics (GWPs or GTPs) result in significant differences in shadow price on CH_4 emissions. Given the abatement cost curves used in this study, most of the agricultural abatement potential of non-CO_2 gases lies in reductions that cost less than US$50/t$CO_2$-eq (using the GWP metric). If carbon prices are high, this abatement potential is exhausted quickly regardless of the metric that is applied. However, if carbon prices are lower overall, then alternative metrics make a larger difference since under the GTP metric, some abatement options become cost-effective only much later in the century than if the GWP metric is used. For this reason, the largest difference between alternative metrics arises for the scenario where we assume that an additional mitigation technology becomes available for enteric fermentation in 2030, at a cost of US$70 per ton of CO_2-eq avoided, on top of gradual but nonetheless rapid improvements in the overall mitigation potential for agricultural gases. If the GWP metric is used, the price on CH_4 is sufficiently high to make use of this option cost-effective shortly after 2040. If the GTP metric is used, the price on CH_4 emissions remains low enough to make use of this technology cost-effective only from about 2060 onwards. By contrast, if we assume no improvement in mitigation potential over time, alternative metrics make a much smaller difference because carbon prices are higher generally, which results in most available mitigation options being cost-effective.

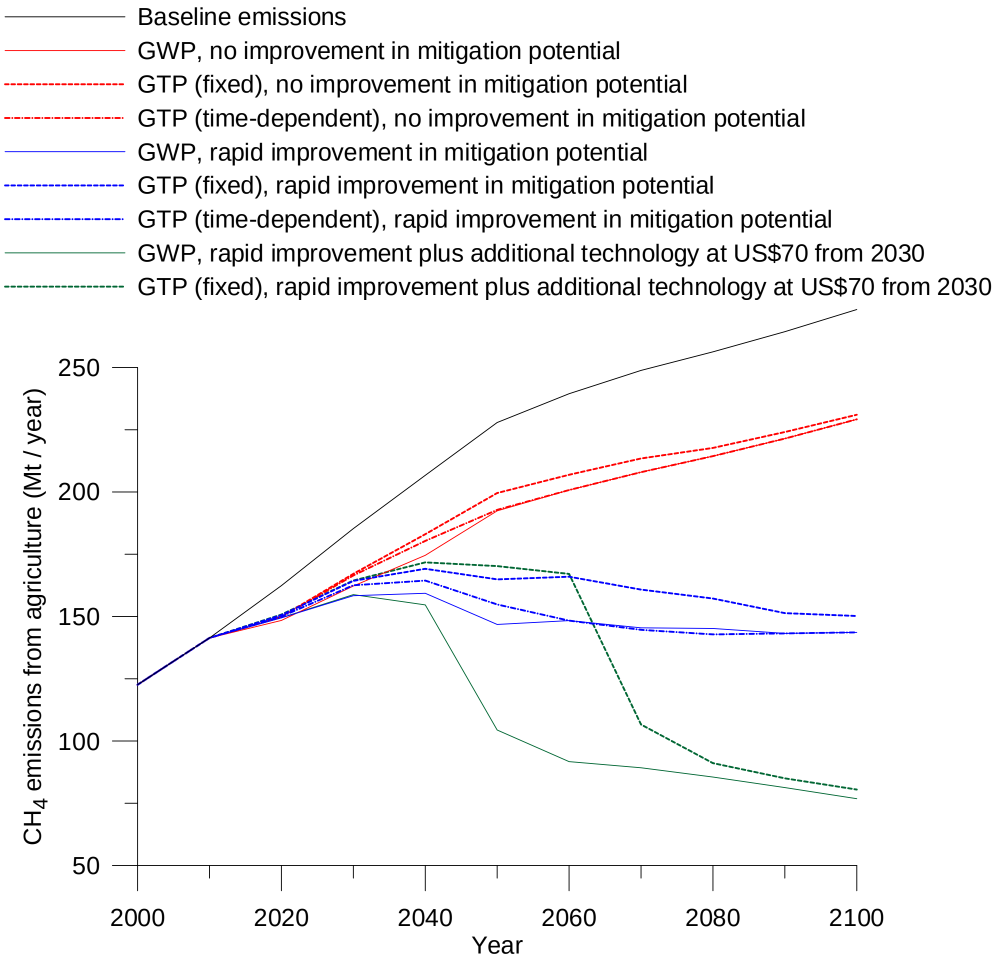


Figure 4.4. Global CH_4 emissions from agriculture, for baseline and alternative metrics and assumptions about future evolution of mitigation potential, for a stabilisation target of 450ppm CO_2-eq in 2100. The red lines assume no improvement in agricultural mitigation potential over time; the blue lines assume a rapid improvement of all options; and the green lines assume a rapid improvement of all options plus an additional mitigation technology from year 2030 onwards, at US$70/t$CO_2$-eq (US$1750/tCH_4) and a potential of abating 30% of CH_4 emissions from enteric fermentation.

The (assumed) existence of a significant low-cost abatement potential also explains why CH_4 emissions in 2020 are almost identical under of all the above assumptions and scenarios. Under any metric and scenario, carbon prices are sufficiently high (greater than US$1/t$CO_2$-eq) in 2020 to make abatement at the lowest cost level (see Figure 4.1) cost effective, resulting in a large part of the mitigation potential being realised. The remaining higher-cost options are delayed until carbon prices rise sufficiently to cover those costs. From 2030/2040 onwards, different metrics therefore result in different volume of abatement depending on the shadow prices on CH_4 emissions.

As noted earlier, there is a large question mark around the interpretation of low-cost abatement options identified by modelling studies, since those models often do not account for risk-management issues related to climate variability and other constraints and barriers that farmers might experience in implementing those low-cost options. They would suggest, however, that regulatory interventions that seek to overcome those barriers could assist in reducing emissions without requiring a high price on emissions, and that the level of emissions reductions for the next 10-20 years would be largely independent on the specific metric that is chosen to account for emissions.

Figure 4.5 shows the shadow prices for CO_2 and CH_4 associated with the specific scenarios explored in Figure 4.4, for the years 2020, 2050 and 2100. Note that the increase in carbon prices over time is purely the result of the MESSAGE model's discounting (at the social rate of 5% per annum). The more relevant observation that can be drawn from Figure 4.5 is that alternative metrics and alternative assumptions about the future mitigation potential for agricultural emissions have an effect not only on CH_4 prices but also on shadow prices of CO_2.

Figure 4.5 shows the effect of alternative metrics on CO_2 prices. The less weight is placed on abatement of CH_4, the more weight must be placed on abatement of CO_2 (equating to higher shadow prices). Consistent with theoretical expectations about the cost-effectiveness of a time-dependent GTP (Johansson 2011; Shine et al. 2007), CO_2 shadow prices under a time-dependent GTP are lower throughout the 21st century than under GWPs or fixed GTPs, even though a time-dependent GTP places much lower weight on abatement of CH_4 in the first half of the 21st century than GWPs. This is consistent with the short lifetime of CH_4, which implies that emissions in the first half of the 21st century contribute only very little to radiative forcing in the year 2100, which is used to determine total allowable cumulative emissions for the model runs.

The difference in CO_2 price between time-dependent and fixed GTPs is about 20%, with prices under GWPs being about 5% higher than under time-dependent GTPs but about 15% lower than under fixed GTPs. As noted earlier, imposing additional constraints (such as limiting the rate of change during the 21st century) could alter the relative cost-effectiveness of the different metrics. Figure 4.5 shows that alternative assumptions about the future evolution of the mitigation potential of agriculture also affect CO_2 prices for similar reasons as metrics: if more abatement is possible of CH_4, then less abatement of CO_2 is needed, resulting in lower shadow prices for CO_2. The resulting differences in carbon prices are significant and greater than the difference resulting from alternative metrics: prices under the assumption of rapid improvement of agricultural mitigation potential are about 40% lower than prices where mitigation potential is assumed to remain constant.

With regard to CH_4, alternative metrics affect the shadow prices of CH_4 emissions through the 'exchange rate' that is implied in those metrics, in addition to the above effects that apply to all prices. This additional effect can be clearly seen in Figure 4.5, including the dramatic escalation of prices for CH_4 emissions towards the end of the 21st century if time-dependent GTPs are chosen. These significant differences in prices readily explain why some abatement options for CH_4 emissions are taken later or earlier in the 21st century under different metrics (see Figure 4.4), depending on when those options become cost-effective relative to the shadow price of those emissions.

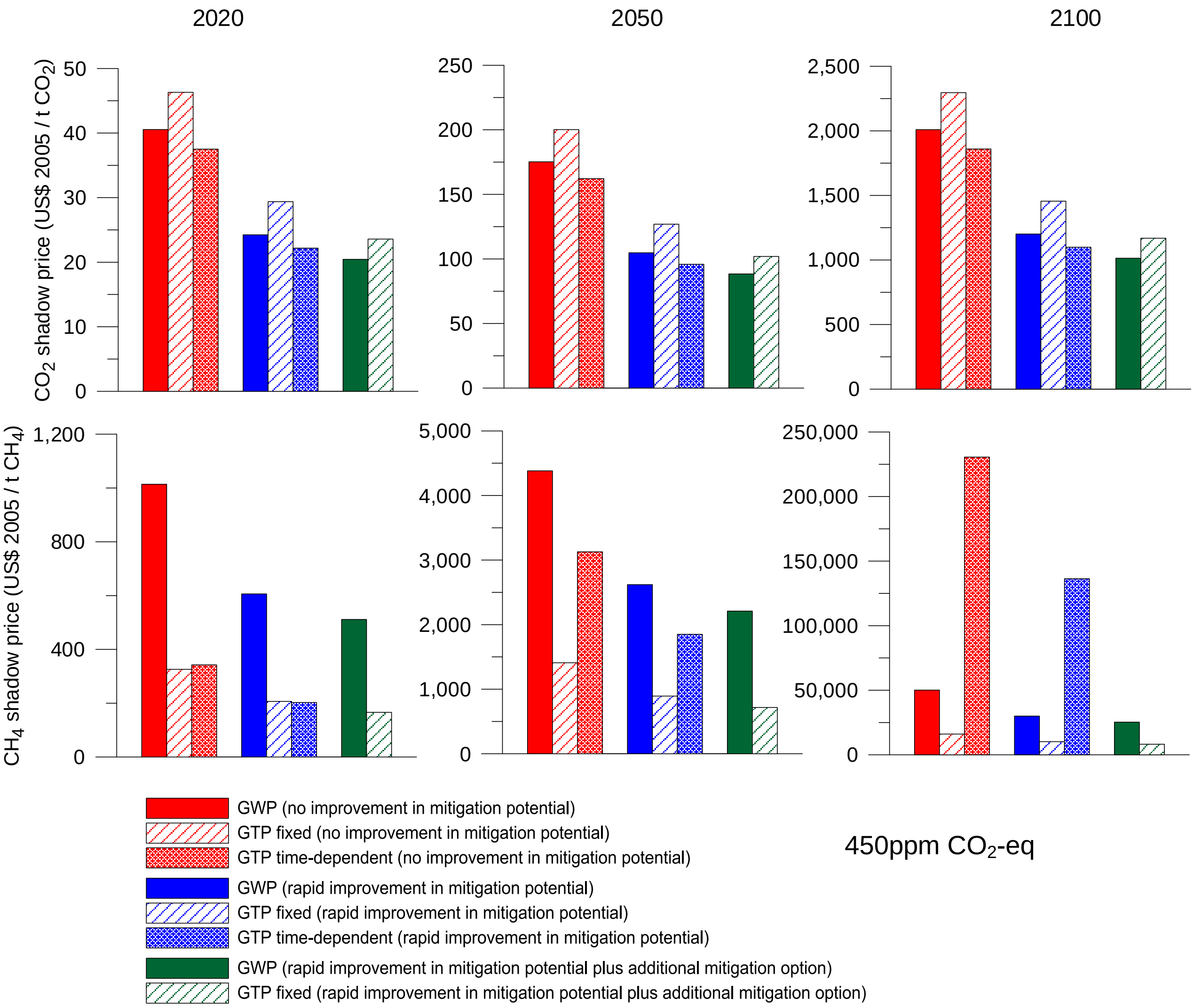


Figure 4.5. Shadow prices of CO_2 (upper panels) and CH_4 (lower panels) emissions in 2020, 2050 and 2100 under a set of alternative metrics (GWPs, GTPs fixed, and GTPs time-dependent) and alternative assumptions about the future evolution of agricultural mitigation potential. The resulting radiative forcing in 2100 under all runs is 450ppmCO_2-eq. The red bars assume no improvement in agricultural mitigation potential over time; the blue bars assume a rapid improvement of all options; and the green bars assume a rapid improvement of all options plus an additional mitigation technology from year 2030 onwards, at a cost of US\$1750/tCH_4 and a potential of abating 30% of CH_4 emissions from enteric fermentation.

Figure 4.5 shows shadow prices only for a stabilisation target of 450ppm CO_2eq, but alternative stabilisation targets would have a larger influence on shadow prices of CO_2 than alternative metrics or assumptions about agricultural mitigation potential. For the full spectrum of alternative assumptions used in this study (see section 4.2), CO_2 shadow prices in 2050 range from US\$76 to US\$233/tCO_2 for stabilisation at 450 CO_2-eq and from US\$27 to US\$55/tCO_2 for stabilisation at 550ppm CO_2-eq. This means that the lowest possible shadow price of CO_2 consistent with stabilisation at 450ppm CO_2-eq is still higher than the highest potential shadow price of CO_2 consistent with stabilisation at 550ppm CO_2-eq.

For CH_4, shadow prices in 2050 range from US\$645 to US\$5830/tCH_4, and from US\$250 to US\$1379/tCH_4 for stabilisation at 450 and 550ppm CO_2-eq, respectively. This indicates that for CH_4, alternative metric choices are of comparable importance as alternative stabilisation targets and assumptions about the future mitigation potential of agricultural non-CO_2 emissions. These findings are illustrated in Figure 4.6, which compares the shadow prices of CO_2 and CH_4 for the subset of specific assumptions and metrics used in Figure 4.5, for stabilisation at 450 and 550ppm CO_2-equivalent.

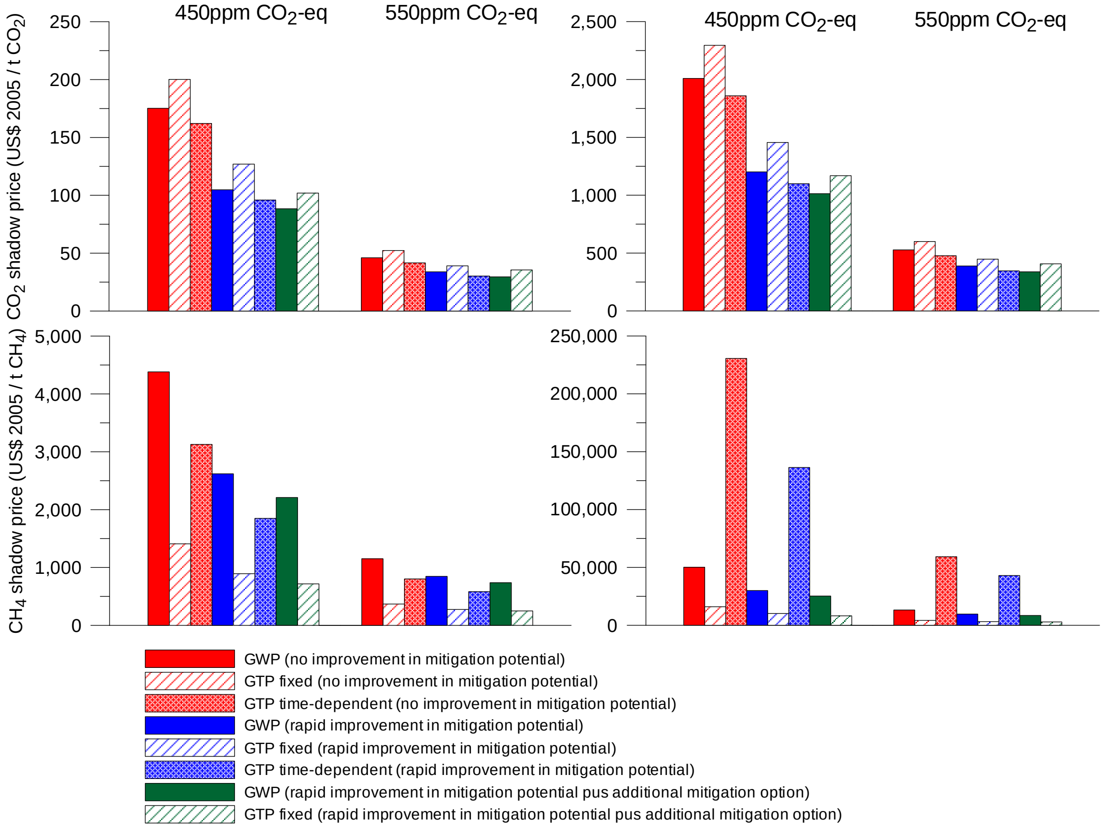


Figure 4.6. Shadow prices of CO_2 and CH_4 emissions in 2050 (left panels) and 2100 (right panels) under alternative metrics (GWPs, GTPs fixed, and GTPs time-dependent) and alternative assumptions about future evolution of agricultural mitigation potential, for radiative forcing targets of 450 and 550ppm CO_2-eq in 2100. The red bars assume no improvement in agricultural mitigation potential over time; the blue bars assume a rapid improvement of all options; and the green bars assume a rapid improvement of all options plus an additional mitigation technology from year 2030 onwards, at a cost of US$1750/t$CH_4$ (US$70/t$CO_2$-eq) and a potential of abating 30% of CH_4 emissions from enteric fermentation.

The different emissions, concentration and price trajectories shown in Figure 4.2 to Figure 4.6 represent the globally most cost-effective pathways of emissions and shadow prices for each of those individual scenarios with their specific assumptions (metrics, abatement potential and stabilisation target). The following section now explores how the total mitigation costs under those alternative scenarios differ from each other, and which scenario or group of scenarios is most cost-effective with regard to the long-term goal of limiting total greenhouse gas concentrations to 450ppm or 550ppm CO_2-eq in the year 2100.

4.3.2 Effect on global and sectoral mitigation costs and global GDP

Under the dynamic optimisation approach used in our model setup, individual mitigation options are implemented whenever and wherever the global shadow price on emissions equals or exceeds the specific cost of this abatement activity per unit of gas emission avoided. Total mitigation costs are the product of the cost of individual mitigation options per unit of gas avoided, multiplied by the total volume of gas abated. As a result, one may generally assume that scenarios that result in lower carbon prices but achieve the same stabilisation outcome would (by and large) also show lower overall mitigation costs. This expectation is mostly borne out by a detailed analysis.

In this section we report total direct mitigation costs integrated over the 21st century (from 2010-2100, discounted at the model default rate of 5% per annum, based on capital investments and fixed and variable operating and maintenance costs, for the energy, forestry, industry and agriculture sectors) as well as losses in global GDP for given target years relative to baseline. Figure 4.7 shows the net present value of modelled total global mitigation costs. The scenarios show the effect of different stabilisation targets (450 and 550ppm CO_2-eq), different metrics (GWPs, fixed and time-dependent GTPs), different assumptions about future evolution of agricultural mitigation potential (no or rapid improvement), and the effect of introducing additional abatement technology for enteric CH_4 emissions a various costs and mitigation potentials.

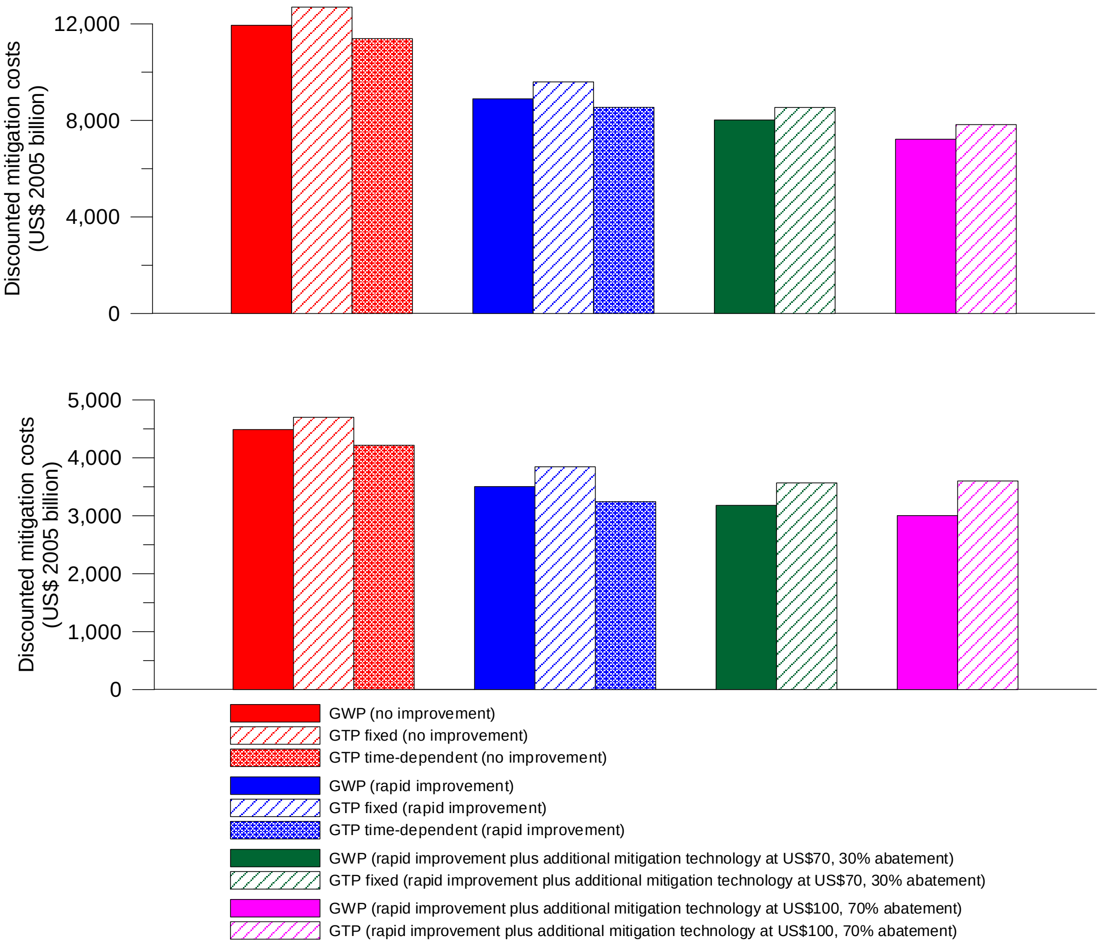


Figure 4.7. Discounted mitigation costs (2010 to 2100) for alternative metrics and assumptions about future agricultural mitigation potential. The upper panel is for stabilization at 450ppm CO_2-eq, the lower panel is for stabilization at 550ppm CO_2-eq.

Consistent with the qualitative picture offered by the preceding analysis of shadow prices for CO_2 and CH_4, the following conclusions can be made:

- ***Fixed GTPs result in higher global mitigation costs than GWPs.*** The difference varies depending on assumptions about agricultural mitigation potential and stringency of stabilisation target. For stabilisation at 450ppm CO_2-eq, costs using fixed GTPs increase by between 6.0 and 8.4% compared to GWPs. For stabilisation at 550ppm CO_2-eq, the cost increase is 4.7% if agricultural mitigation potential does not improve, but becomes much higher at up to 19% for scenarios that assume steady improvement of abatement potential as well as introduction of an additional abatement technology.
- ***Time-dependent GTPs result in lower global mitigation costs than GWPs.*** The magnitude again depends on assumptions about future evolution of agricultural mitigation potential and stabilisation level. For stabilisation at 450ppm CO_2-eq, the 'no improvement' assumption gives 4.6% lower costs than GWPs, while the 'rapid improvement' assumption gives 3.9% lower costs. By contrast, for stabilisation at 550ppm CO_2-eq, the 'no improvement' and 'rapid improvement' scenarios result in 6.1% and 7.4% lower costs than GWPs, respectively.

- **Different *assumptions about future agricultural mitigation potential, for the range of options explored in this study, have a larger effect*** on global mitigation costs than alternative metrics. For stabilisation at 450ppm CO_2-eq, global mitigation costs are 26% lower under the assumption of a rapid improvement in agricultural abatement potential compared to the assumption of no improvement. For stabilisation at 550ppm CO_2-eq, the cost difference is 22%.
- ***Different stabilisation levels have an even larger effect*** on global mitigation costs than assumptions about agricultural mitigation potential or alternative metrics. Stabilising at 550ppm CO_2-eq results in less than half the global mitigation cost of stabilising at 450ppm CO_2-eq, for otherwise similar scenarios.

To our knowledge, our study is the first to quantify the costs associated with GTP metrics relative to those under GWPs using a complex integrated assessment model that has been used to inform global climate policy about mitigation costs and feasibility of targets (Rao et al. 2008; Riahi et al. 2011).

Most other work to date has compared GWPs with cost-minimising economic models that do not rely on externally set metrics. These studies indicate that GWPs are economically sub-optimal by about 4-5% with a standard deviation of about 3-4% (Johansson et al. 2006; van Vuuren et al. 2006a). We find that time-dependent GTPs result in about 4-6% lower abatement costs than GWPs, consistent with those studies. Our findings also support a recent study that found relatively close agreement between time-dependent GTPs and cost-effective trade-off between gases, except during the last few decades of the 21st century (Johansson 2011). This suggests that time-dependent GTPs can indeed be a useful approximation to fully cost-effective metrics.

The magnitude of cost differences between fixed and time-dependent GTPs and GWPs is not constant but depends on additional assumptions about agricultural mitigation potential and stabilisation levels, because those assumptions affect the shadow price of CO_2 and the amount of abatement activity in the agriculture sector.

Total mitigation cost differences between GWPs and fixed GTPs are largest for stabilisation at 550ppm CO_2-eq and the assumption of additional abatement technologies for agriculture. Under those scenarios, the assumed enhanced mitigation potential for CH_4 is not fully used until very late in the 21st century if the GTP metric is applied. This results in a greater mitigation burden for CO_2 emitting sectors and hence greater mitigation costs overall. The difference between GWPs and fixed GTPs is less pronounced for more stringent stabilisation at 450ppm CO_2-eq because in this case, most available mitigation options in agriculture are used well before 2100 regardless of the metric being applied.

The degree to which time-dependent GTPs can save costs also depends on the evolution of agricultural abatement potential. If the agricultural abatement potential becomes large later in the 21st century, costs from agricultural mitigation will increase significantly towards the end of the 21st century under time-dependent GTPs. These increasing costs partly offset the overall cost savings for CO_2 mitigation. This effect is even more pronounced, but of smaller absolute magnitude, for mitigation from the waste sector, because this sector has some mitigation options that are only cost-effective at very high shadow prices for CH_4, which are only reached under time-dependent GTPs.

Figure 4.8 illustrates these points, by showing discounted global mitigation costs for the 2010-2050 and 2050-2100 time horizons, across the energy sector (CO_2 emissions), forest sinks, industry, waste and agriculture, for stabilisation at 550ppm CO_2-eq and two scenarios that assume either no or rapid improvement in agricultural mitigation potential. The cost differences are dominated by differences in energy mitigation costs, but the cost reductions under the time-dependent GTP are partly offset by increasing agricultural and waste mitigation costs in this scenario. For the 'rapid improvement' scenario, total aggregated direct agricultural mitigation costs are higher under time-dependent GTPs than under GWPs, because escalating shadow prices for CH_4 and increasing mitigation potential result in significantly greater costs in the second half of the 21st century (even after discounting) than under GWPs or fixed GTPs. For the 'no improvement' scenario, agricultural costs are higher under time-dependent GTPs than under GWPs in the period 2050-2100, but this cost increase is smaller than the cost savings in the period 2010-2050. As a result, time-dependent GTPs result in lower discounted costs overall for agriculture for the 'no improvement' scenario, but in higher costs under the 'rapid improvement' scenario. Not surprisingly, agricultural mitigation costs are always lower under fixed GTPs (for the 21st century as a whole, and for individual time periods), because of the much lower shadow prices on CH_4 emissions under this metric compared to GWPs throughout the 21st century.

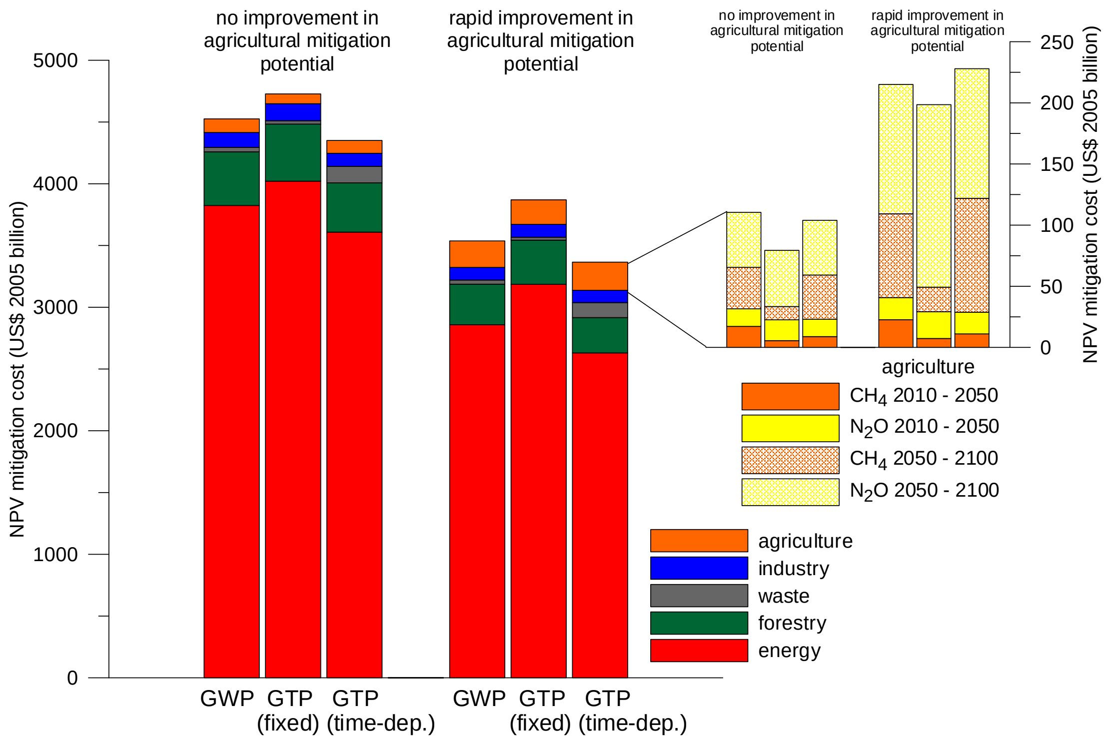


Figure 4.8. Sectoral contributions to total global discounted mitigation costs 2010-2100, for two scenarios that stabilise at 550ppm CO_2-eq and assume either no (left) or rapid (right) improvements in agricultural mitigation potential. The insert shows the agricultural mitigation cost components alone, for the periods 2010-2050 and 2050-2100 separately. Most of the agricultural mitigation cost occurs in the second half of the 21st century (even after discounting). Cost in 2050-2100 are higher under time-dependent GTPs than under GWPs, but the difference depends on the mitigation potential.

Even though the differences in costs under alternative metrics are relatively small in percentage terms, they do equate to considerable absolute amounts. For stabilisation at 450ppm CO2-eq, the reduction in total global mitigation costs under time-dependent GTPs (compared to GWPs) amounts to between US$350 to US$550 billion in net present value from 2010 to 2100. Under fixed GTPs (compared to GWPs), costs would increase by between US$620 to US$750 billion net present value.

By the same token, our modelling study shows that agricultural mitigation would have large global economic benefits under any of the metrics considered in this study: total global mitigation costs for a stabilisation of 450ppm CO2-eq are reduced by about 25% (regardless of metric) between the assumption of 'no improvement' and 'rapid improvement' of agricultural mitigation potential. This equates to a cost saving globally of between US$2.8 and US$3.1 trillion in net present value from 2010 to 2100. These cost reductions occur mostly in the energy sector, not the agriculture sector itself. This because more stringent abatement of CH_4 increases the cumulative amount of CO_2 that can be emitted for a given stabilisation target, which in turn allows a delay of the more costly abatement options in the energy sector that otherwise would need to be taken more rapidly (Cox and Jeffery 2010). This highlights the interplay between mitigation in different sectors, suggesting that there would be significant global economic benefits from increased research and policy measures to reduce agricultural emissions globally along with those from the energy sector. Development of an additional mitigation technology could further lower costs by 10-20%, or US$800 bilion to US$1.7 trillion in total direct mitigation costs (see Figure 4.7).

The variation of relative mitigation costs over time under different metrics results in some interesting effects on global GDP. Figure 4.9 shows GDP losses relative to BAU using the GWP metric for a range of scenarios covering 450ppm and 550ppm CO_2-eq stabilisation targets, and assumptions about agricultural mitigation potential ranging from 'no improvement' to 'rapid improvement' as well as introduction of additional mitigation technologies. Modelled losses range from 1.5 to 2.8% in 2050 and 3.1 to 5.3% in 2100 for stabilisation at 450ppm CO_2-eq. For stabilisation at 550ppm CO_2-eq, the range is from 0.6 to 1% in 2050 and 1.6 to 2.1% in 2100.

This wide range demonstrates the sensitivity of the global level results on assumptions: for stabilisation at 450ppm CO_2-eq, the most pessimistic assumption about abatement potential results in GDP losses that are some 70% greater than for the most optimistic assumption; for stabilisation at 550ppm CO_2-eq, losses under the most pessimistic assumption are about 30% greater. Average GDP losses for stabilisation at 450ppm CO_2-eq are more than twice as high as for stabilisation at 550ppm CO_2-eq. These results are consistent with costs reported in other modelling studies (Clarke et al. 2009; Rao et al. 2008; Schaeffer et al. 2008; van Vuuren et al. 2007; van Vuuren et al. 2008). The sensitivity of global abatement costs on assumptions about agricultural mitigation potential has also been noted (Lucas et al. 2007; van Vuuren et al. 2006b).

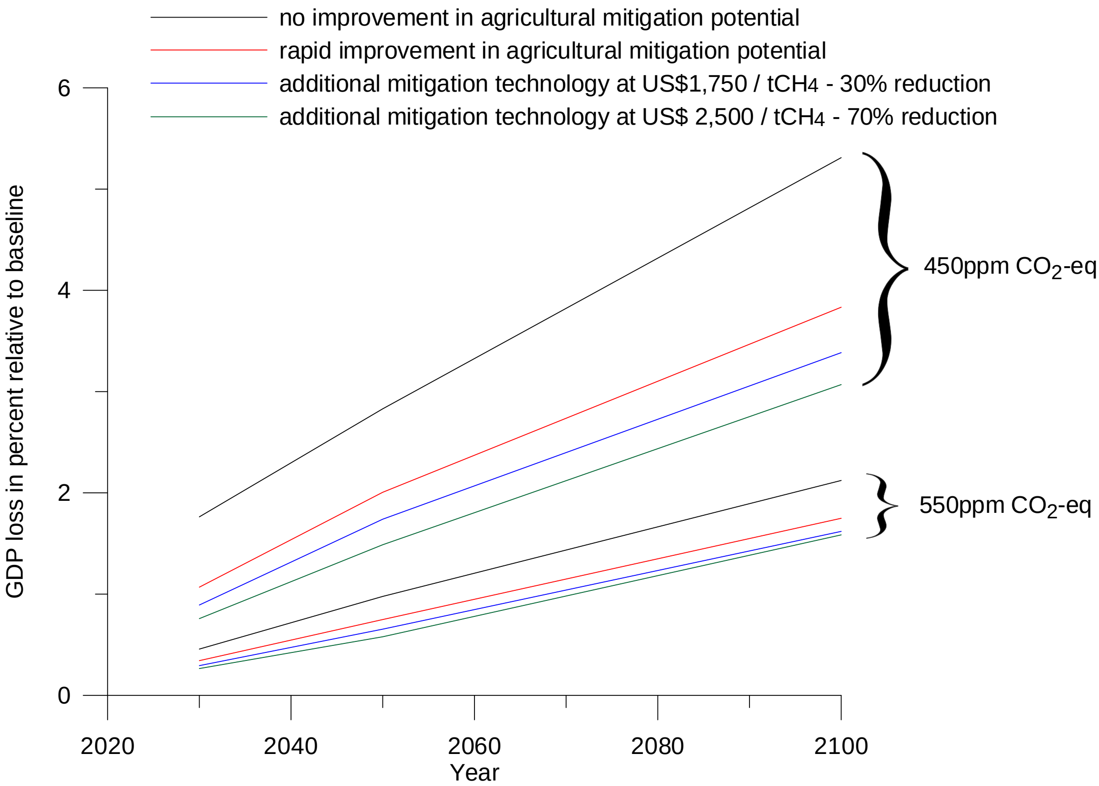


Figure 4.9. Losses in GDP relative to BAU in 2050 and 2100, under GWPs but for a wide range of other assumptions regarding stabilisation targets and future agricultural mitigation potential.

A new result from our study is the *relative* effect of different metrics on GDP losses. We find that relative differences in GDP loss are greater (in percentage terms) than differences in discounted global mitigation costs, and GDP losses are distributed differently over time. GDP losses are always higher if fixed GTPs are used as metric, compared to GWPs. GDP losses are lower under time-dependent GDPs in the first few decades, but then become higher than under GWPs in the second half of the 21st century. This is because time-dependent GTPs result in much higher shadow prices on CH_4 towards the end of the 21st century, imposing significantly higher costs on economies at that time. This leads to significantly higher economic costs towards 2100 than under GWPs, even though net present value mitigation costs aggregated and discounted over the entire 21st century are smaller than under GWPs.

This finding highlights the importance of discounting when determining what policy approaches and mitigation options are regarded as cost-effective over long time horizons. It also raises questions about the political feasibility and long-term stability of a metric such as time-dependent GTPs, which would give steadily increasing weight to abatement of CH_4 emissions from agriculture and would result in markedly greater costs to future generations. In effect, time-dependent GTPs shift part of the burden of mitigation onto future generations, whose welfare loss is discounted by the present generation. While this is consistent with standard economic concepts, it highlights the potential tensions that arise when applying discount rates for decision-horizons that go beyond a single generation (Dietz et al. 2007; Quiggin 2008; Stern 2006).

Similar to the conclusions regarding net present value mitigation cost, it should be noted that despite the noticeable differences in GDP losses for different metrics, those differences are significantly smaller than the effects of different stabilisation targets (see Figure 4.10). For a stabilisation target of 450ppm CO_2-eq, differences between metrics are also smaller than differences arising from alternative assumptions about the evolution of future agricultural mitigation potential. For stabilisation at 550ppm CO_2-eq, GDP losses in 2100 under time-dependent GTPs and rapid improvement in agricultural mitigation potential would be comparable to GDP losses under GWPs and no improvement in mitigation potential.

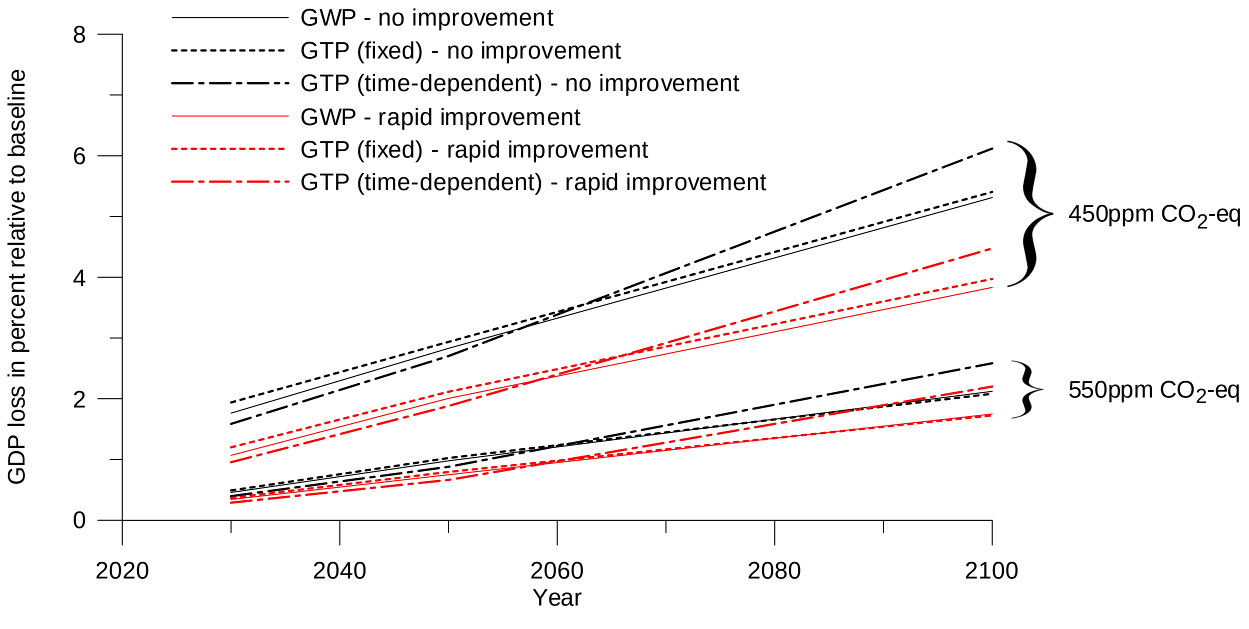


Figure 4.10. GDP losses under alternative metrics, for two stabilisation levels (450 and 550ppm CO_2-eq) and two alternative assumptions about future evolution of agricultural mitigation potential ('no improvement' and 'rapid improvement').

4.3.3 Cost-effectiveness of policy-driven metrics compared to GWPs/GTPs

We now compare and contrast the results obtained for different metrics with the implications of alternative policy choices for the treatment specifically of agricultural non-CO_2 emissions. The choices we tested are:

- complete exclusion of emissions (using GWPs or GTPs for the treatment of non-CO_2 emissions from sectors other than agriculture), and

- exclusion of agricultural emissions up to 2050, following which they are compared using current GWPs.

The effect of excluding agriculture entirely from emissions obligations at a global scale is significant. For a stabilisation target of 450ppm CO_2-eq, if the remaining non-CO_2 emissions from other sectors are measured using the GWP metric, CO_2 prices reach US$233 in 2050 and US$2673 in 2100. These prices are 30% higher than if agriculture emissions are included and no improvement in agricultural mitigation potential takes place, and more than 100% higher than when rapid improvement takes place. If other non-CO_2 emissions were measured using fixed GTPs, CO_2 prices would be even higher at US$267 in 2050 and US$3057 in 2100.

The reason for those very high CO_2 prices is that if no mitigation of agricultural non-CO_2 emissions takes place, the total cumulative CO_2 emissions consistent with any given stabilisation target are considerably smaller (Cox and Jeffery 2010). Essentially, the atmospheric 'space' into which CO_2 emissions can occur is reduced by the greater concentration of CH_4 and N_2O in the atmosphere if agricultural emissions are not mitigated. Given the cumulative effect of CO_2 emissions, this means that mitigation of CO_2 has to occur much more rapidly to avoid exhausting the available cumulative emissions budget, requiring the use of much more costly emissions reductions options.

Note that in the global cost-minimisation approach used in our study, it does not matter whether agriculture emissions are excluded by international agreement, or because all countries nominally accept abatement obligations for all sectors but choose to shelter agriculture from any price signal or other stringent abatement requirements. The net effect remains the same: if agriculture emissions are not reduced relative to business-as-usual, then emissions from other sectors have to be reduced more.

The higher shadow prices result in significantly higher total mitigation costs. Excluding agricultural non-CO_2 emissions increases mitigation costs (net present value 2010-2100) by 16% compared to agricultural emissions being included and no improvement of agricultural mitigation potential, and by 56% compared to rapid improvement taking place. This equates to about US$1.9 and US$5.0 trillion additional global mitigation costs, relative to full inclusion of agriculture and assumptions of no or rapid improvement in agricultural mitigation potential. GDP losses would rise from between 2.0 and 2.8% to about 3.4% in 2050, and from between 3.8 and 5.3% to about 6.5% in 2100. In other words, excluding agricultural non-CO_2 emissions entirely from an international climate change agreement would result in significant additional global mitigation costs and additional reduction in welfare to achieve the same long-term stabilisation outcomes.

The significant cost increases under complete exclusion of agriculture from emissions abatement motivate the second policy-driven metric used in this study, which excludes agricultural non-CO_2 emissions only up to 2050 and then includes them using the GWP metric. Here the relative increase in costs depends strongly on the assumed future evolution of agricultural abatement potential. We explored two assumptions: one is 'no improvement', and the other is 'rapid improvement'. In the latter case, we assume that rapid improvement starts only after agricultural emissions are exposed to an emissions obligation, reflecting the dynamic learn-act-learn process that underpins technological improvement cycles (IPCC 2007c). Without a requirement to reduce emissions, it appears much less likely that the rapid improvement rates used for the period from 2020 to 2050 would take place. Excluding agriculture until 2050 thus is assumed to effectively postpone the improvement in agricultural mitigation potential by 30 years.

If agricultural emissions are excluded up to 2050 and no improvement in agricultural mitigation potential takes place, then shadow prices, global mitigation costs and GDP losses are almost identical to those when agricultural emissions are included from 2010. This result is plausible, because the short lifetime of CH_4 (which constitutes the bulk of agricultural non-CO_2 emissions) implies that there is little benefit of reducing emissions before 2050 if the only constraint is radiative forcing in the year 2100. Including additional constraints such as the rate of temperature change or the maximum warming during mid-century would tip the balance again towards earlier inclusion of agricultural emissions, but such constraints were not analysed quantitatively in this study.

By contrast, a rapid improvement in agricultural mitigation potential is possible but takes place only from 2050 onwards, then delaying the inclusion of agricultural emissions to 2050 results in noticeably higher costs than if agriculture is included throughout and rapid improvement in mitigation potential takes place from 2020 onwards. In this case, shadow prices are about 21% higher and total mitigation costs are about 9% higher (for stabilisation at 450ppm CO_2-eq), or about US$800 billion in global net present value mitigation costs. These cost differences essentially reflect a global penalty for delaying the improvement of agricultural mitigation potential.

We emphasise that this delay is only a model assumption. If it were possible to achieve the same rapid improvement in agricultural mitigation potential from 2010 onwards without requiring any actual mitigation to take place until 2050 and beyond, then mitigation costs and shadow prices would again become much more similar to those when agriculture is included throughout. These findings are illustrated in Figure 4.11.

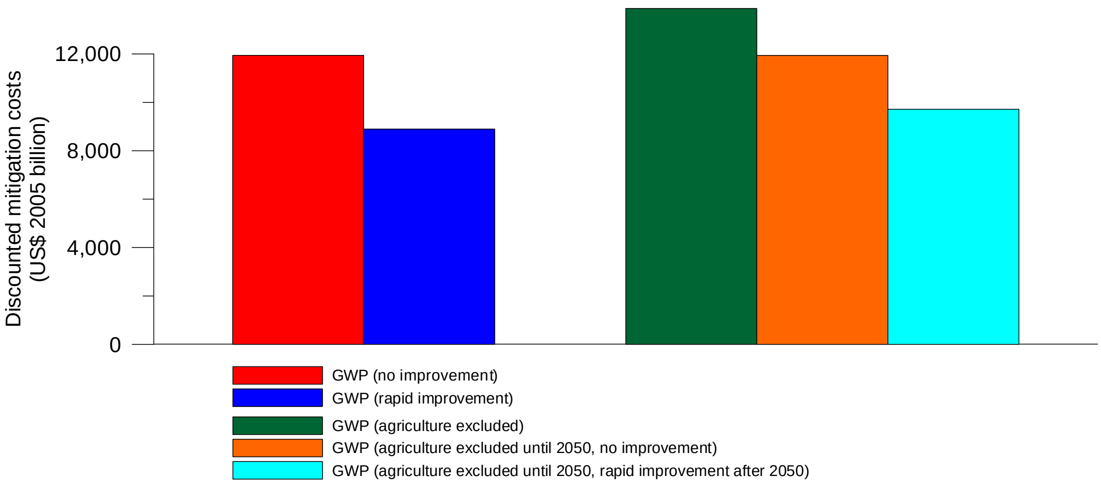


Figure 4.11. Global total mitigation costs for stabilisation at 450ppm CO_2-eq for different policy assumptions and different future evolution of agricultural mitigation potential.

4.3.4 Regional implications and effects on commodity prices

The modelling setup used for this study can offer only limited policy-relevant insights into regional effects of alternative metrics. This is because in our setup, a shadow price is applied on all emissions regardless of when and where they occur. As a result, regions or sectors that offer greater abatement potential generally experience greater mitigation costs, while regions (or sectors) that offer limited or no abatement potential experience limited or no costs. Alternative configurations of the MESSAGE model that impose different regional emissions targets and allow alternative burden-sharing mechanisms are possible but have not been implemented for this study.

This approach is useful to determine the globally most effective distribution of abatement activities to meet global mitigation targets, but it is very different to the situation of developed countries in current and expected future climate change agreements. Here, individual developed countries (and regions) face binding total emissions targets, and limited potential to reduce emissions generally implies greater costs as emissions credits need to be purchased on the international market.

In the default MESSAGE setup, cost of abatement are largest in the developing regions (particularly south Asia), which heavily rely on the large potential for relatively cheap mitigation options. The results are driven by the global cost effectiveness criteria assumed by the scenarios, and should not be interpreted as a suggestion that those regions would necessarily also be responsible for paying for the reductions. In practice, regional and national emissions targets and flexibility mechanisms would be used to balance regional mitigation costs relative to development levels, national incomes and the state of national economies. In addition, most of the mitigation costs in all regions arise from abatement of CO_2 emissions in the energy sector, and it was outside the scope of this study and the expertise of its authors to analyse the dynamics of the global and regional energy systems as reflected in the MESSAGE model.

For this reason, it was decided that a detailed regional analysis of results from MESSAGE would not be useful or indeed feasible within the constraints of this study. However, a much more relevant issue in the context of metrics, particularly with regard to agriculture and the perspective of New Zealand, is the effect that different metrics could have on agricultural commodity prices. As different agricultural products are associated with different emissions per unit of product, imposing a price on emissions is expected to change the cost of production for various products, and alternative metrics are expected to result in different changes in these costs. As a result, commodity prices should be sensitive to the choice of metric.

This in turn could be highly relevant for New Zealand because several other studies have indicated that changes in global commodity prices resulting from global climate change and climate policies could have a larger effect on New Zealand's economy than impacts occurring within New Zealand (Saunders et al. 2009a; Saunders et al. 2009b; Stroombergen 2010). However, the effect of international climate policy choices on New Zealand's economy and welfare has remained underexplored, mainly due to the lack of suitable modelling tools. Our study is the first to tentatively explore the effects of different global climate policy choices, namely different metrics and different treatment of agriculture, on commodity prices. In the remainder of this section, we provide a brief overview of how changes in commodity prices were inferred. In section 5, we then explore how the joint effect of national emissions targets, global emissions prices and changes in commodity prices under different metrics could affect New Zealand's economy.

The main focus of MESSAGE is the energy sector with only a coarse representation of the agricultural sector, focusing on GHG emissions and potential emissions mitigation options. The model does thus not represent changes in agricultural commodity prices or trade in agricultural products. For this reason, we employed the global spatially explicit land-use model GLOBIOM (Havlík et al. 2010; Valin et al. 2010) to determine detailed changes in production of agricultural products (from croplands and livestock) under various emissions prices, and to calculate resulting changes in commodity prices.

As noted in Section 2, MESSAGE and GLOBIOM are not linked dynamically and use different approaches to model the effects of emissions prices on agricultural production: MESSAGE assumes primarily technological and some management responses but externally prescribes agricultural production in all regions in a highly aggregate form. By contrast, GLOBIOM incorporates detailed management options for a broad range of individual agricultural products and includes international trade as well as the interaction between the demand for biofuels, deforestation penalties and emissions prices, but at present does not include any technological mitigation options.

We used shadow prices for CO_2, CH_4 and N_2O and bioenergy demands as calculated by MESSAGE under different metrics as external inputs to GLOBIOM, after calibrating their baselines to result in the same agricultural emissions up to the year 2050 (which is the last year for which GLOBIOM is set up to run). We only investigated changes for GWPs and fixed GTPs in GLOBIOM due to limited resources to run this model.

These external constraints are then used to derive changes in agricultural production and commodity prices as simulated by GLOBIOM. We emphasise that the changes in commodity prices inferred by this method are indicative only and should not be regarded as firm 'predictions'. The price changes are not fully self-consistent due to the non-identical approaches to simulate abatement of agricultural greenhouse gases in MESSAGE and GLOBIOM. However, within the constraints of this study, which had to use existing models operated by international research groups due to the current lack of models in New Zealand capable of simulating such changes, this is the best approximation that was possible within the time and budget constraints of this study.

The production of meat as simulated by GLOBIOM varies significantly under the different shadow prices associated with alternative metrics and stabilisation levels, whereas total milk production remains unchanged. The changes in meat production as simulated by GLOBIOM are shown in Figure 4.12.

Figure 4.12 shows that, as expected, GWPs under the 450ppm CO_2-eq stabilisation scenario result in the greatest reduction in global meat production since they are associated with the highest prices on CH_4. GTPs result in a lesser reduction, and excluding agriculture entirely results in an even lesser reduction relative to baseline. Production is still significantly lower than in the baseline though, because even if agricultural non-CO_2 emissions are excluded, the shadow price on CO_2 (which is higher in this scenario than under GWPs or GTPs – see Figure 4.5) still imposes a substantial penalty on deforestation and incentivises afforestation as well as biofuel production, which limits the potential for land clearance to deliver the increasing livestock production in the baseline.

Stabilising at 550ppm CO_2-eq results in a qualitatively similar picture, but here the difference in production between GTPs and the scenario with agriculture excluded is much smaller. This suggests that for stabilisation at 550ppm CO_2-eq, if the GTP metric is used, land-use decisions are determined equally by the price on non-CO_2 emissions as by the price on CO_2 emissions (which implies a penalty on deforestation). In contrast for stabilisation at 450ppm CO_2-eq, shadow prices on CH_4 are sufficiently high even under the GTP metric that their removal still has a significant influence on land-use decisions at the global scale that is not counterbalanced by higher CO_2 prices.

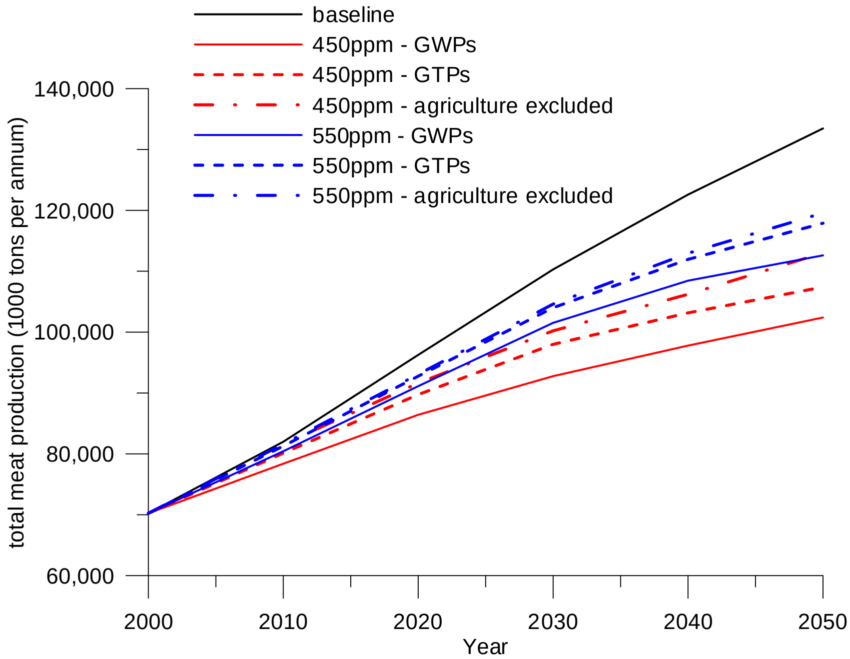


Figure 4.12. Global total meat production from cattle, buffalo, goat and sheep, for two different stabilisation scenarios and three different metrics for the treatment of non-CO_2 emissions.

The reduction in meat production is not uniform, however, and regional milk production varies between animal classes and regions even though global total milk production is constant under all scenarios. Figure 4.13 shows the changes in meat and cattle milk production relative to baseline in 2050 for the 11 regions simulated by MESSAGE and also adopted by GLOBIOM for the purpose of this study. It demonstrates that emissions pricing (assuming global participation) has a very non-uniform effect in different regions.

The largest reductions relative to baseline occur in Latin America and Africa, while net production increases in the Pacific OECD region (Japan, Australia and New Zealand) and Western Europe. These regional differences are due to a combination of factors, including differences in production efficiency in different regions and land-use changes associated with production increases in the baseline. In the Pacific OECD region and Western Europe, production could be increased without significant additional deforestation, whereas in Latin America and, to a lesser extent, also in Africa, large increases in meat production would be associated with significant deforestation. It is noteworthy that in Latin America, meat production would reduce by more if agricultural non-CO_2 emissions were excluded from any price signal. This suggests that in this region, deforestation penalties or afforestation and bioenergy production incentives would represent a much bigger constraint on increasing livestock production than pricing of non-CO_2 emissions. The same is not the case in Africa, where production would be higher if agriculture is excluded than if it is included. A very similar picture arises for modelled changes in milk production in different regions.

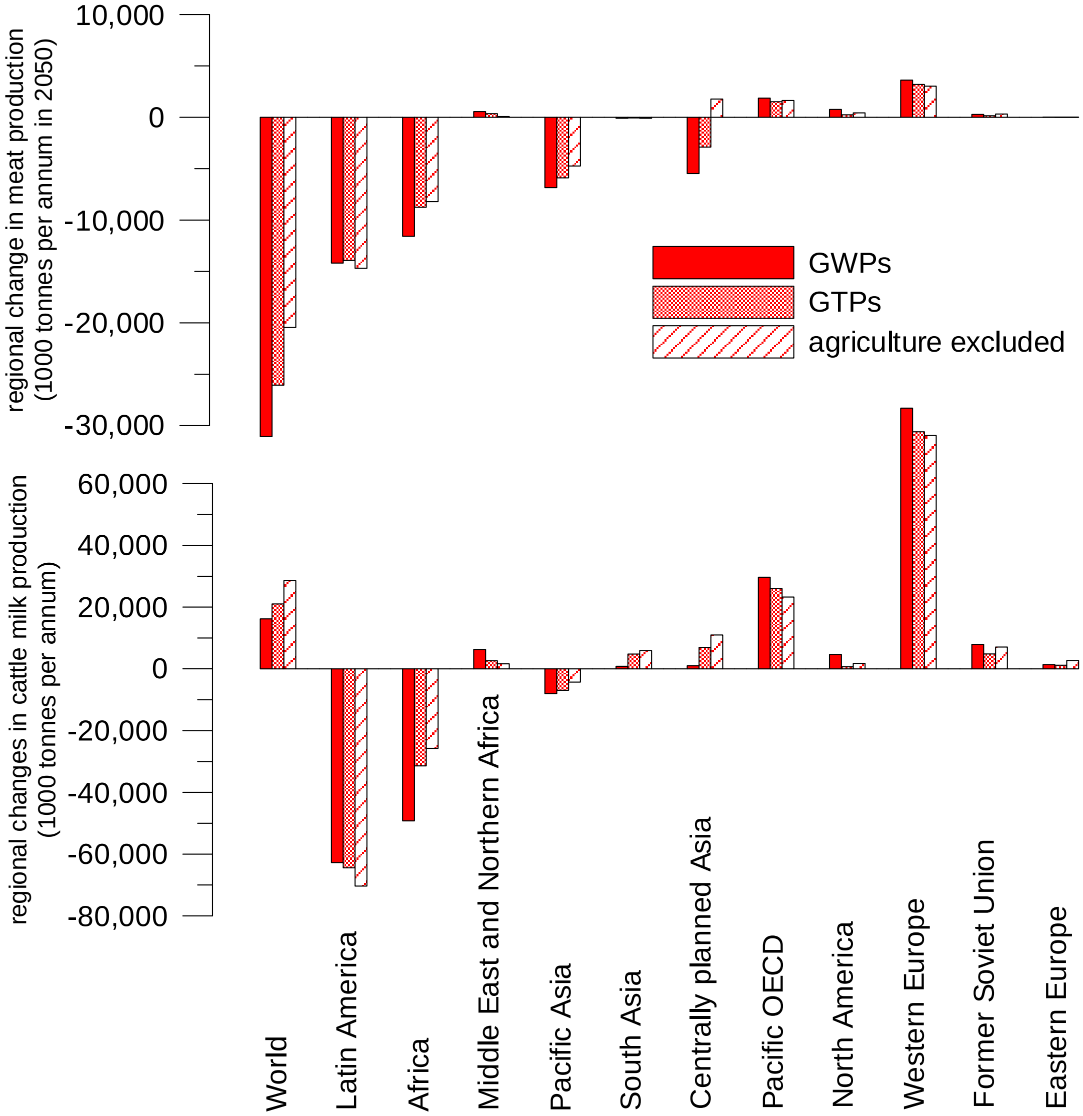


Figure 4.13. Regional changes in 2050 in total meat production (top panel) from cattle, buffalo, goat and sheep, and for cattle milk (bottom panel), for a 450ppm CO_2-eq stabilisation scenario and three different metrics for the treatment of non-CO_2 emissions (GWPs, fixed GTPs, and exlusion of agricultural non-CO_2 gases).

Changes in commodity prices result from both the global imposition of additional production costs under a comprehensive abatement approach as well as regional re-distribution of supply and demand under this changed pricing regime. For the purpose of the national economic analysis carried out in section 5, we derived changes in global aggregated commodity prices for livestock and crops. GLOBIOM is unable in its standard setting to derive commodity prices for individual milk products.

The changes in the livestock commodity price index, which is of much greater importance for New Zealand's economy than the commodity price index for crops, are shown in Figure 4.14. As expected, the commodity price index increases even in the baseline due to increasing global demand, but additional pricing of greenhouse gas emissions results in significantly greater increases. The greatest increases occur as expected for stabilisation at 450ppm CO_2-eq and the GWP metric, because this results in the greatest additional production costs for livestock systems. Switching to the GTP metric reduces the commodity price index, and excluding agriculture entirely reduces it further, but only by a much smaller margin. The same qualitative sequence holds for stabilisation at 550ppm CO_2-eq, but here the change from GTPs to excluding agricultural emissions results in much less change in the commodity price index, suggesting that (as for meat production) the reduction in costs from removal of a price on non-CO_2 emissions is counterbalanced by the greater shadow price on CO_2 and hence greater penalty on deforestation.

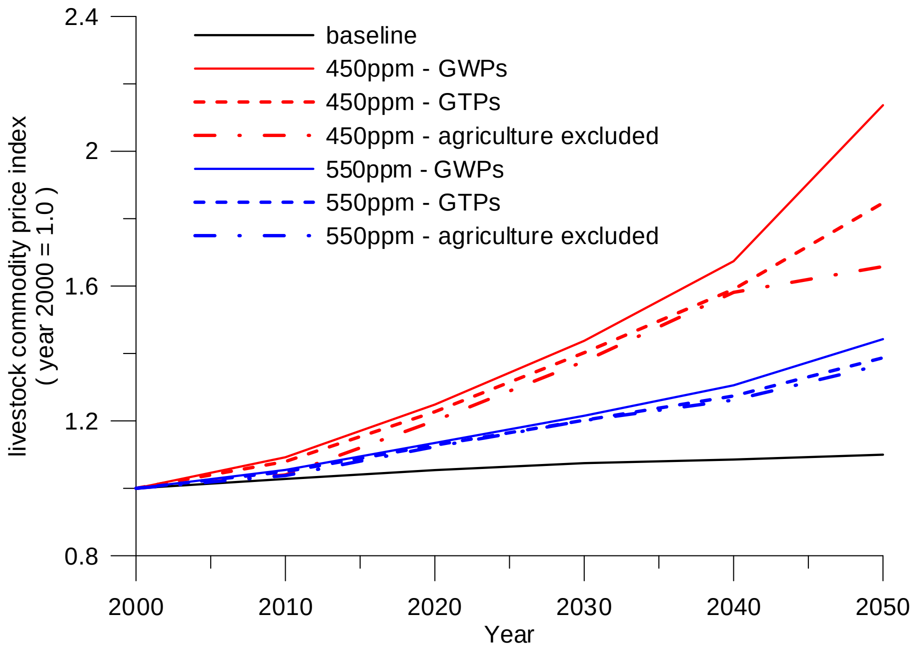


Figure 4.14. Changes in the global livestock commodity price index modelled for two stabilisation scenarios and three different metrics for the treatment of non-CO_2 emissions.

The modelled changes in the global livestock commodity price index were used in section 5 to determine the implications of alternative metrics on New Zealand's economy, together with the greenhouse gas shadow prices derived from the MESSAGE simulations.

4.4 Summary and conclusions

This section explored the global costs of mitigation to achieve two alternative stabilisation targets of 450 and 550ppm CO_2-eq in the year 2100, using different metrics and a variety of assumptions about the future evolution of agricultural mitigation potential. It also considered the implications of policy-driven choices to either exclude agricultural non-CO_2 emissions entirely, or up to the year 2050, from abatement obligations.

We focus in our conclusions on scenarios that stabilise concentrations at 450ppm CO_2-eq in 2100, given that this gives about a 50% chance to meet the internationally agreed goal of limiting the increase in global atmospheric temperatures to 2°C above pre-industrial levels. We comment on the implications of weaker stabilisation targets where they would be particularly relevant. We also focus on contrasting effects of mitigation of CO_2 and CH_4 (particularly from agriculture) since these emissions show the largest differences for different metrics and their trade-off is of key interest to New Zealand; however, we comment on the implications for other gases where relevant.

Note that the model assumes a globally consistent application of mitigation policy in all regions. Differential treatment of emissions in different regions could have a significant effect on mitigation costs and options but was beyond the scope of this study to explore.

The key conclusions from our analysis may be presented as follows:

- Under all assumptions and metrics, cost-minimising pathways result in a peak of global CO_2 emissions by or before 2020. CO_2 emissions then fall rapidly and continuously until they reach negative values in 2100, achieved through a combination of bioenergy and carbon capture and storage. By contrast, global CH_4 emissions either remain roughly constant or reduce gradually by up to 50% below year 2000 levels, depending on assumptions about agricultural mitigation potential and its changes over time.[4]
- Different metrics bring forward or delay the peak of CO_2 emissions but change the long-term emissions pathway only little. By contrast, alternative metrics can have a large impact on the timing and rate of CH_4 emissions reductions from agriculture. The differences are particularly large for scenarios that assume large increases in abatement potential over time and have lower shadow prices on emissions. Scenarios with high shadow prices mean that almost all available mitigation options are used regardless of metric.
- Shadow prices on CO_2 emissions depend, in this order, on the stabilisation level, assumptions about the future evolution of agricultural mitigation potential, and the metric. The highest shadow prices on CO_2 result from scenarios that exclude agricultural non-CO_2 emissions from emissions obligations. Fixed GTP metrics result in higher shadow prices for CO_2 than GWP metrics, which in turn are higher than prices under time-dependent GTP metrics. These results reflect the fact that the less pressure is placed on reduction of non-CO_2 gases, the greater the pressure and hence cost to reduce CO_2 emissions.
- Shadow prices on CH_4 emissions show significantly greater variations between metrics than those on CO_2, of similar magnitude as differences resulting from different stabilisation levels (450 or 550ppm CO_2-eq). This greater dependence on metrics is of course as expected by design.
- Time-dependent GTPs result in very high shadow prices on CH_4 emissions of more than US$100,000 per tonne of CH_4 by the end of the 21st century (equivalent to more than US$4,000 per tonne of CO_2-eq under GWPs). Such very large price increases raise questions about the practical feasibility of implementing time-dependent GTPs, since countries could reject this metric once very high and escalaing CH_4 prices become a reality in the second half of the 21st century.
- Global costs of mitigation depend on the metric chosen. However, as for shadow prices, cost differences are smaller than differences resulting from different assumptions about future agricultural mitigation potential, and much smaller than differences arising from alternative stabilisation targets.

[4] Note that the differences between CO_2 and CH_4 emissions reductions are driven by the differing assumptions about their abatement potential and costs, not by any concerns about food security.

- Fixed GTPs result in typically about 5 to 20% greater global costs than GWPs, while time-dependent GTPs would result in typically about 4-5% lower costs. The largest cost increase from using fixed GTPs arises for scenarios that assume a future additional abatement technology but only a weak stabilisation target, because in these scenarios, the abatement technology remains unused under the GTP metric. Aggregated costs are lower under time-dependent metrics despite very high CH_4 prices towards the end of the 21^{st} century, in part because those higher non-CO_2 mitigation costs are heavily discounted in an aggregate net present value cost analysis.
- The differences in costs for different metrics are small compared to differences from agricultural mitigation potential and alternative targets (see below), but they still amount to large absolute amounts in the order of several hundred billion US dollars (aggregated 2010 to 2100 and discounted at 5% per annum).
- Alternative assumptions about future agricultural abatement potential have a larger effect on global mitigation costs than metrics, of between 22 to 26%. These cost differences do not arise from the agriculture sector (which would incur greater abatement costs if the mitigation potential is greater), but in cost-savings in the energy sector which could postpone capital-intensive investments. In absolute terms, steady progress in agricultural mitigation potential, compared to the assumption of no progress, would result in cost savings of almost US$3 trillion net present value. This suggests that there is a strong economic case for advancing research and implementation of agricultural mitigation options and their integration into climate policy portfolios globally.
- A weaker stabilisation target of 550ppm compared to 450ppm CO_2-eq would reduce costs by more than 50% and thus dominates cost differences resulting from alternative metrics or abatement potentials. However, we emphasise that this does not mean that a weaker stabilisation target is in fact economically desirable since our study did not consider the impacts of climate change and their economic implications, but only the costs of mitigation.

- Development of an additional mitigation technology for enteric fermentation could reduce direct total global mitigation costs by between 10 and 20% (for the assumptions made in this study), equating to about US$800 billion to US$1.7 trillion in absolute terms. This shows the large economic benefits globally that could be gained from concerted action to accelerate agricultural mitigation options and implementation, even if the abatement itself is not cost-free but comes at significant costs (assumed at between US$70 and 100 per tonne of CO_2-eq in our study).
- A policy-driven choice to exclude agriculture entirely would increase the global cost of mitigation significantly by between 16 and more than 50%. The increase in cost depends on the assumption about how much agricultural mitigation potential would have improved if agriculture had been included.
- If agriculture is excluded only up to 2050 and then included using GWP metrics, the cost difference compared to the default assumption of full inclusion and GWP metrics depends on the assumed future improvement of the agricultural mitigation potential. If it is assumed that the mitigation potential would not improve over time, then the costs are almost identical, indicating that agriculture could be excluded from mitigation obligations for several decades without a cost to the global economy. However, it if is assumed that agricultural mitigation potential would improve once it is exposed to a price signal, then the cost of delaying the inclusion of agriculture until 2050 results in about 9% greater costs than when it is included from the outset. Including additional constraints on the model (e.g., limiting the rate of temperature change as well as long-term

radiative forcing) would likely increase the cost of excluding agriculture from mitigation obligations, but this was not tested in our study.

- A spatially-explicit land-use model allowed us to simulate likely changes in commodity prices for limited subset of scenarios using alternative metrics and stabilisation levels out to the year 2050, and assuming even global application of emissions prices. We find that the livestock commodity price index would increase under business-as-usual but significantly more so if an emissions constraint applies. The greatest commodity price increases would occur under GWP metrics, with lower increases under fixed GTPs, and lower increases still if agricultural non-CO_2 emissions are excluded. For stabilisation at 550ppm CO_2-eq, the same qualitative picture applies but difference are much smaller, and are negligible between fixed GTPs and fully excluding agriculture.

5. New Zealand domestic abatement costs

5.1 Introduction

In this section we explore the implications of alternative metrics and associated greenhouse gas shadow prices, as well as changes in the commodity price index, for the New Zealand economy, assuming future economy-wide emissions targets as under the current Kyoto Protocol arrangements, together with international emissions trading.

Since the introduction of the New Zealand Emissions Trading Scheme (NZETS) the domestic debate on whether agricultural methane (CH_4) and nitrogen dioxide (N_2O) emissions should be included in the scheme has intensified. For the exchange rates used currently under the United Nations Framework Convention on Climate Change and its Kyoto Protocol to convert these gases into carbon dioxide equivalents (CO_2-eq), their weight in New Zealand's total emissions is about 50%, a share which is likely to increase over time under most mitigation scenarios.

Thus different weights assigned to these gases, and/or the complete exclusion or inclusion of these gases, could have potentially significant implications for the cost to New Zealand of meeting any international emissions responsibility obligations – whether by domestic mitigation or by the purchase of emission permits from offshore.

In this section we explore three issues that are relevant to the way that agricultural non-CO_2 emissions should be treated:

1. The exchange metrics used to convert CH_4 and N_2O emissions into CO_2e emissions. The two metrics considered are Global Warming Potential (GWP) and Global Temperature Change Potential (GTP), both for a fixed time horizon of 100 years.
2. The actions of other countries with regard to the pricing of their agricultural non-CO_2 emissions. At present, even though all developed countries that have ratified the Kyoto Protocol have economy-wide emissions targets, no country has implemented stringent mitigation requirements on agriculture to date (Johansson and Persson 2005), and New Zealand is currently the only country intending to fully expose agriculture to the marginal cost of all non-CO_2 emissions through including agriculture in its NZETS from 2015, subject to a review of actions by other countries.
3. The potential development of additional mitigation options for methane from enteric fermentation. We do not aim to predict whether such options will in fact be successful, but we explore the potential economic implications if they were, in the context of alternative metrics.

By combining the multi-industry general equilibrium model of the New Zealand economy ESSAM with the global integrated assessment model MESSAGE and the spatially explicit land-use model GLOBIOM, we are able to include two effects that would be missing from a stand-alone New Zealand analysis. These are the changes in the CO_2 price, which varies with GHG exchange rates and how agricultural non-CO_2 emissions are treated (for any given stabilisation target), and the effect of different GHG prices on world agricultural commodity prices – an effect that is very important to New Zealand.

We use the greenhouse gas shadow prices and changes in the agricultural commodity price index calculated by these models as key external inputs into the ESSAM model.

5.2 Scenario specification

5.2.1 Business as Usual Scenario

All scenarios are compared to a 'Business as Usual' (BAU) scenario that has no international emissions obligations and no carbon prices.

The BAU is not intended to be a forecast of the economy. Rather it is intended as a plausible projection of the economy in 2020 and 2050 in the absence of major external events and major policy changes. As mentioned earlier, none of the models considers the impacts of climate change on agricultural production. This could have a significant impact on absolute changes, but should have a negligible effect on relative changes between alternative metrics.

5.2.2 Mitigation scenarios

Various scenarios are examined with CH_4 and N_2O converted into CO_2 equivalents in accordance with the gas exchange rates implied by either GWP (as per the most recent IPCC assessment report, the AR4) or GTP metrics. Table 5.1 summarises the exchange rates. For any given greenhouse gas concentration in the atmosphere, the different metrics imply different carbon prices and different agricultural commodity prices.

Table 5.1: GHG Exchange Rates

	CH_4	N_2O
GWP	25	298
GTP	7	318

Due to time and resource constraints, we do not explore all scenarios evaluated in the preceding section, but explore only a subset for global stabilisation at 450ppm CO_2-eq, consistent with the accepted long-term target of the New Zealand government. We explore the implications of 100-year GWP or fixed GTP metrics. We did not explore the implications of time-dependent GTPs.

The MESSAGE runs for the policy-driven 'metrics' that exclude agricultural non-CO_2 emissions from any abatement obligations can be interpreted in two ways from the perspective of New Zealand. Either, countries are nominally responsible for all emissions but choose not to require any mitigation from agriculture through domestic policy choices (as is currently done by all developed countries that have ratified the Kyoto Protocol). Or, agricultural non-CO_2 emissions are excluded from any abatement obligations by international agreement, in which case we assume that they would not be included in countries' base year or emissions targets. From a global atmospheric perspective, these two interpretations are the same, but from the perspective of an individual country that faces binding economy-wide emissions targets, they are significantly different, and we explore both interpretations for New Zealand.

The ESSAM model is not a dynamic model but calculates economic activity for given target years. We choose 2020 and 2050 as target years since these are the years for which New Zealand has offered specific emissions reductions targets that it is willing to contemplate as part of an international agreement.

The total set of scenarios evaluated is therefore:

Scenario 1: 2020, GWP exchange rates, 450 ppm

Scenario 2: 2020, GTP exchanges rates, 450 ppm

Scenario 2a: 2020, GTP exchange rates, 450 ppm, commodity prices as in Scenario 1

Scenario 3: 2020, GWP exchange rates, 450 ppm, other countries shelter agriculture from emissions charge and global CO_2 prices adjust accordingly to meet the same 450ppm target, but New Zealand remains liable for its agricultural emissions.

Scenario 4: As in Scenario 3 with agricultural non-CO2 emissions excluded from all international agreements and obligations.

Scenario 3a: Same as scenario 3, but using GTP metrics

Scenario 4a: Same as scenario 4, but using GTP metrics (for non-CO_2 gases for emissions from sectors other than agriculture)

The above scenarios are run for 2020, and analogous scenarios are run for 2050 (Scenarios 5-8). A further set of two scenarios explores the implications of a significant additional mitigation technology for methane emissions from enteric fermentation, were such a technology to become available some time before 2050 (Scenarios 9 and 10).

For each scenario and time horizon, the shadow prices for the greenhouse gases CO2, CH_4 and N_2O as well as changes in two aggregated commodity prices (livestock products and crops) were provided externally through the MESSAGE and GLOBIOM models. The greenhouse gas prices were derived from simulations using the global integrated assessment model MESSAGE and the commodity price changes were calculated for those greenhouse gas prices, and associated bioenergy demands, using the spatially explicit land-use model GLOBIOM.

All prices in this section are expressed in NZ$ unless specified otherwise, converted from US$(2005) by an exchange rate of US$0.7 = NZ$1.

5.2.2.1 Emissions Obligation

It is assumed that New Zealand takes on a 2020 obligation of responsibility for any net emissions that exceed 85% of 1990 gross emissions, irrespective of whether emissions are calculated under GWP or GTP gas exchange rates. That is, if domestic policies do not reduce emissions to 15% below what they were in 1990, New Zealand will have to purchase international emission permits to cover the excess.

Analogously, for 2050 the responsibility obligation is 50% of 1990 emissions.

5.2.2.2 New Zealand Emissions Policy

For both the 2020 and 2050 scenarios the parameters of the ETS as currently legislated are assumed to apply. In particular, agricultural emissions of methane and nitrous oxide enter the Scheme in 2015 with 90% free allocation of emissions units that is gradually reduced over time, but still provides for more than 50% of the base allocation amount in 2050. The carbon price in New Zealand is equal to the world carbon price so there is no New Zealand price maximum and there is no 2-for-1 concession as exists currently.

5.2.2.3 Forestry

For 2020 it is assumed that the ETS and the current age profile of eligible New Zealand forests is such as to generate net absorption of 16.1 Mt CO_2. This amount is invariant across scenarios.[5]

For 2050 no net effect from forestry is assumed as the net change in emissions from forestry stocks is as likely to be positive as negative.

5.2.2.4 Rest of the World Emissions Policies

The world price of CO_2 differs across the various scenarios as presented in the preceding section.

Consistent with the global modelling we make the simplifying assumption that all other countries fully impose carbon prices on all sources of greenhouse gas emissions, including manufacturing industries that compete or could potentially compete with New Zealand; essentially paper, steel, aluminium, cement, and oil refining). This will affect the absolute cost to New Zealand of meeting any given emissions obligation, but is unlikely to have a material impact on the relative costs under different GHG exchange rates.

We explore alternative policies with regard to treatment of agricultural emissions; either that the world imposes a price on all agricultural emissions, or that the world excludes agricultural emissions from price measures.

5.2.2.5 Macroeconomic Closure

The following macroeconomic closure rules apply:

1. Labour market closure: Total employment is held constant at the BAU level, with wage rates being the endogenous equilibrating mechanism. Instead of fixed employment, wage rates could be fixed at BAU levels. This implies, however, that the long run level of total employment is driven more by climate policy than by the forces of labour supply and demand, which we consider unlikely.
2. Capital market closure: We assume that post-tax rates of return on capital held constant at BAU levels, with capital formation being endogenous.
3. External closure: The balance of payments is a fixed proportion of nominal GDP, with the real exchange rate being endogenous. This means that the cost of any adverse external shock such as having to buy emissions permits on the international market is not met simply by borrowing more from offshore, which is not sustainable in the long term.
4. Fiscal closure: The fiscal position is held constant at the BAU level, with personal income tax rates being endogenous. This prevents the results from being confounded by issues around the optimal size of government.

[5] See NZIER and Infometrics (2011).

5.3 Modelling results

The scenarios are split into two groups, those pertaining to 2020 and those pertaining to 2050, as our interest is primarily in the differences caused by GWP versus GTP at a point in time, rather than in the differences over time for some given set of GHG exchange rates.

5.3.1 2020 Scenarios

The scenario specification is summarised in Table 5.2.

Table 5.2: Scenario Specification

Scenario	GHG exchange rates	GHG prices ($/tonne of gas)			Commodity prices (relative to BAU)	
		CO_2	CH_4	N_2O	Livestock (dairy & meat)	Crops (horticulture)
1	GWP	$35	$866	$10,321	18%	17%
2	GTP	$42	$295	$13,346	16%	18%
2a	GTP	$42	$295	$13,346	18%	17%
3	GWP	$77	$1,927	$22,966	14%	12%
3a	GTP	$88	$618	$27,963	14%	12%
4	GWP	$77	$0 (ag. only)		14%	12%
4a	GTP	$88	$0 (ag. only)		14%	12%

In Scenarios 3 and 4 countries shelter agricultural non-CO_2 emissions from the emissions price. In scenario 3, this sheltering is done as a domestic policy choice; that is, countries are responsible for agricultural non-CO_2 emissions, but they choose not to impose a price on those emissions.

In scenario 4, we assume that agricultural non-CO_2 emissions are excluded by international policy agreement. That is, countries are not responsible for agricultural non-CO_2 emissions.

In both cases, international prices on CO_2 and non-CO_2 gases from sectors other than agriculture have to adjust so as to meet the same stabilisation target, as agricultural gases still contribute to overall radiative forcing, even if countries are not required or choose not to abate them.

Table 5.3 shows the results.

5.3.1.1 Scenarios 1 and 2

In scenario 2, the CO_2 price is higher than in scenario 1 due to the lower prices on non-CO_2 gases, which results in less abatement of those gases and hence requires more abatement of CO_2 to reach the same stabilisation target. The lower prices on methane emissions result in a slightly lower increase in livestock commodity prices.

The results show a net gain to New Zealand in both scenarios as the benefit of higher commodity prices easily outweighs the costs of a domestic carbon price coupled with an emissions responsibility target.

Interestingly, the gain in RGNDI is almost the same in both scenarios, but the gain is slightly greater under GWPs than under GTPs. This implies that the benefit of the smaller reduction (in terms of net BAU emissions compared to a -15% target) that would be required under the GTP option is outweighed by the higher carbon price and the slightly smaller rise in average commodity prices. New Zealand is affected more by dairy and meat prices than by horticultural prices.

Thus the contention that a lower weight on methane emissions would lower the cost to New Zealand of meeting any given proportionate emissions obligation, is not supported by these results – at least not for 2020 and under the assumption that the world as a whole applies a price on agricultural emissions.

It is also worth noting that under the parameters of the ETS, free allocation is intensity based. Thus the expansion in agricultural output in response to higher commodity prices occurs largely without that industry facing any additional emissions costs. That cost falls on the rest of the economy in the form of the need to buy emissions units from offshore.

5.3.1.2 Scenario 2a

This scenario has the GHG prices from Scenario 2 (i.e. applies the GTP metric), but the commodity prices from scenario 1. It is therefore an artificial scenario in the sense that the GHG prices and the commodity prices are not consistent with the results from the global models. Its purpose is purely to isolate the relative influence of the change in GHG prices and the change in commodity prices on the difference between Scenarios 1 and 2.

A shown in Table 3, the change in private consumption is less than in Scenario 2. To one decimal place the change in RGNDI is the same as in Scenario 2, although at two decimal places (which is spuriously accurate) the change is 0.73% compared to 0.65% in Scenario 2. The direction of these differences is consistent with the difference in commodity prices.

That the change in RGNDI is less than in Scenario 1 is interesting, as one might have assumed intuitively that a scenario that applies GTPs but uses the same commodity prices as Scenario 1 should result in a greater, not lesser welfare gain than Scenario 1, as the net emissions deficit to be financed by purchasing offshore emission units is smaller. While the emissions deficit cost is indeed smaller, this effect is not sufficient to offset the decline in the terms of trade between Scenarios 1 and 2a. Even though world agricultural prices are the same, the lower agriculture production costs under a GTP regime lead to an increase in output (as reflected by the increments in CH_4 and N_2O emissions), forcing exporters to move down the demand curve. Exporters are not pure price takers as no commodity group in the model is entirely homogeneous, nor perfectly substitutable with competing sources of supply.

It is worth noting, however, that all of these effects are very small and finely balanced, given the 2020 scenario specifications. Modelling those same effects for 2050 gives different results (see below).

5.3.1.3 Scenario 3

Scenario 3 has a similar specification to Scenario 1 (i.e. using the GWP metric) except that countries other than New Zealand choose not to apply a price on agricultural non-CO_2 emissions, although such emissions are still included in the calculation of global emissions and in countries' emissions responsibility obligations.

New Zealand continues to include Agriculture in the ETS, with free allocation.

This scenario applies a significantly higher CO_2 price as the abatement of CO_2 emissions has to increase and occur more rapidly as a result of the global non-abatement of agricultural non-CO_2 emissions. There is also a lower increase in commodity prices given the exclusion of agricultural non-CO_2 gases from price measures in all countries other than New Zealand.

The results in Table 3 now show a small macroeconomic loss as the carbon price is much higher than in Scenario 1 while commodity prices are lower. It is noteworthy though that the loss to New Zealand is relatively small, largely thanks to the pressure on commodity prices resulting from disincentives globally to land clearing, incentives for afforestation, and increased bio-energy demands.

5.3.1.4 Scenario 4

Scenario 4 is a variation on Scenario 3: here we assume that agricultural non-CO_2 emissions no longer form part of any international emissions obligations and hence are also excluded from the NZETS and New Zealand's base year and emissions target calculations. The carbon price and world commodity prices are the same as in Scenario 3 as in both scenarios the world aims to meet the same stabilisation target without applying a price on agricultural non-CO_2 emissions.

Comparing Scenarios 3 and 4 provides an estimate of the net cost to New Zealand of including or excluding agricultural emissions in its obligations (while assuming that the rest of the world is not pricing their agricultural emissions regardless of whether they are responsible for them). The comparison shows that New Zealand would benefit from agriculture being excluded from emissions obligations via international agreement, if the alternative is that the rest of the world *de facto* excludes agriculture but countries nominally retain responsibility for those emissions.

The difference in RGNDI is 0.5% and the difference in GDP is 0.2%. So the GDP gain from the removal of agricultural CH_4 and N_2O emissions from countries' and in particular, New Zealand's targets contributes about 40% of the total welfare gain (RGNDI), with the rest being attributable to the much smaller number of emission units that need to be purchased on the international market – 3.7 MT versus 14.5 MT.

Even though New Zealand would benefit from having agriculture excluded if other countries *de facto* shelter agriculture from price measures, it would be economically more beneficial for New Zealand if all countries included agriculture in a price measure. Comparing Scenarios 1 and 4 tells us that aggregate economic welfare is higher if New Zealand is liable for its agricultural emissions in the context of a relatively lower carbon price, high commodity prices and global participation, than if New Zealand has to face a higher carbon price coupled with lower commodity prices if agriculture is excluded globally. The difference in RGNDI is about 0.4%. This conclusion holds even though we assume in our model that New Zealand has no abatement technologies for agricultural emissions.

5.3.1.5 Scenarios 3a and 4a

We do not have corresponding GLOBIOM scenarios and hence commodity price changes for Scenarios 3a and 4a. We assume the same world commodity prices as in Scenarios 3 and 4, reasoning that:

- In both sets of Scenarios, 3 and 3a, and 4 and 4a, agriculture is effectively excluded from any direct price signal and thus additional production costs. Hence, to a first approximation, commodity prices should be identical across those four scenarios.
- The only difference between Scenarios 3 and 3a (and 4 and 4a) is that the global CO_2 price is slightly higher by about 14%. The higher CO_2 price would imply a marginally greater demand for bio-energy, and greater penalty on deforestation and incentive for afforestation. These drivers would tend to act against expansion of pastoral livestock and hence could increase commodity prices in scenarios 3a and 4a relative to scenarios 3 and 4.
- Given that the total increase in the cost of production for livestock is predominantly from prices on non-CO_2 gases, and the difference in CO_2 prices is only about 14%, the resulting change in commodity prices from Scenarios 3 and 4 to Scenarios 3a and 4a is likely to be within the margin of error.

Just as Scenario 3 produced a worse welfare outcome than in Scenario 1, so Scenario 3a produces a worse welfare outcome than in Scenario 2.

It is also noteworthy that New Zealand incurs a (small) net welfare loss if it is the only country to *de facto* put a price on its agricultural emissions, irrespective of whether GWP or GTP prevails. In contrast if agricultural emissions are excluded by international agreement, then New Zealand receives a small welfare increase, again irrespective of the GHG exchange metric. Comparing Scenarios 3 and 3a, New Zealand is economically slightly worse off if the rest of the world shelters agriculture from a price signal and the GTP metric is used to account for non-CO_2 emissions than if the GWP metric is used. The difference is only small though and minor changes in commodity prices associated with higher CO_2 prices (see above) could re-balance this outcome.

By construction the only significant difference between Scenarios 4 and 4a is the level of the price on CO_2 emissions, the effect of GWP v GTP having been made virtually irrelevant (for New Zealand) by the exclusion of non-CO_2 emissions from agriculture – although there are still some non-CO_2 emissions from waste, which are not irrelevant on a global scale. We find that in this case, New Zealand is in the same economic position regardless of the choice of metric for non-CO_2 gases from sectors other than agriculture. Intuitively the lower carbon price in Scenario 4 should deliver a better outcome. At two decimal places there is indeed a small (0.03%) difference in favour of Scenario 4, but the essence of the result is that the macroeconomic effects of a carbon price of $77/tonne are not significantly different from those when the price is $88/tonne.

Between Scenarios 3 and 4 the effects of totally removing agricultural non-CO_2 emissions from global and New Zealand's domestic GHG obligations raised RGNDI by 0.5%. Between Scenarios 3a and 4a the increase is only 0.2%, with none of it attributable to an increase in GDP. All of it is attributable to the drop in the number of emission units that need to be purchased on the international market – and this effect is smaller under GTP than under GWP.

Analogously to the above comparison, comparing Scenarios 2 and 4a tells us that aggregate economic welfare is higher if New Zealand is liable for its agricultural emissions in the context of a relatively lower carbon price, high commodity prices and global participation, than if New Zealand has to face a higher carbon price coupled with lower commodity prices if agriculture is excluded globally. The difference in RGNDI is about 0.3% under GTP compared to 0.4% under GWP.

Table 3: Summary of Results (2020)

	BAU	Scenario 1	Scenario 2	Scenario 2a	Scenario 3	Scenario 3a	Scenario 4	Scenario 4a
		GWP	GTP	GTP	GWP	GTP	GWP	GTP
		\$35/t	\$42/t	\$42/t	\$77/t	\$88/t	\$77/t	\$88/t
				Commodity prices from Scenario 1	Other countries shelter agr emissions		Agr non-CO_2 excluded for all countries	
	(% pa on 2005/06)				% Δ on BAU			
Private Consumption	2.6	1.1	0.9	1.0	-0.2	-0.2	0.6	0.5
Exports	3.7	1.0	1.3	1.4	0.2	1.1	-0.3	-0.5
Imports	3.7	2.6	2.6	2.8	1.1	1.4	1.7	1.7
GDP	2.8	0.3	0.3	0.3	-0.4	-0.3	-0.2	-0.3
RGNDI	3.2	0.8	0.7	0.7	-0.1	-0.2	0.4	0.4
	MT	MT	MT	MT	MT	MT	MT	MT
CO_2e 1990 (GWP)		65.3			65.3		23.7	
CO_2e 1990 (GTP)			46.7	46.7		46.7		23.7
AAU (GWP)		55.5			55.5		20.1	
AAU (GTP)			39.7	39.7		39.7		20.1
CO_2e 2020 (GWP)	90.9	91.0 (0.1%)			86.1 (-5.3%)		39.9 (-16.2)	39.2 (-17.6)
CO_2e 2020 (GTP)	69.5		67.1 (-3.4%)	67.4 (-3.0%)		63.7 (-8.4%)		
Forestry net		-16.1	-16.1	-16.1	-16.1	-16.1	-16.1	-16.1
Net deficit		19.4	11.3	11.6	14.5	7.8	3.7	3.0
- as % of BAU		21.3%	16.3%	16.7%	16.0%	11.2%	7.9%	6.5%
CH_4 & N_2O (GWP)	44.9	49.2 (9.6%)			47.8 (6.6%)		NA	
CH_4 & N_2O (GTP)	23.4		26.0 (10.9%)	26.2 (11.8%)	-0.2	26.0 (10.9%)		NA

5.3.2 2050 scenarios

The scenario specification is summarised in Table 5.4 and the results presented in Table 5.5. Scenarios 5-8 are specified identically to Scenarios 1-4 respectively, but the GHG prices and commodity prices are different.

Table 5.4: Scenario Specification

Scenario	GHG exchange rates	GHG prices ($/tonne of gas)			Commodity prices (relative to BAU)	
		CO_2	CH_4	N_2O	Livestock (dairy & meat)	Crops (horticulture)
5	GWP	$150	$3,744	$44,606	94%	57%
6	GTP	$181	$1,277	$57,676	68%	61%
6a	GTP	$181	$1,277	$57,676	94%	57%
7	GWP	$333	$8,330	$99,256	51%	39%
7a	GTP	$381	$2,667	$121,158	51%	39%
8	GWP	$333	$0 (ag. only)		51%	39%
8a	GTP	$381	$0 (ag. only)		51%	39%
9	GWP	$126	$8,330	$99,256	94%	57%
10	GTP	$146	$2,667	$121,158	68%	61%

5.3.2.1 Scenarios 5 and 6

Both scenarios show a macroeconomic gain that is considerably higher than the corresponding 2020 scenarios. Thus the positive effect of the higher commodity prices outweighs the negative effect of the higher GHG prices by even more in 2050 than in 2020.

Again it is clear and noteworthy that switching from a GWP metric to a GTP metric does not benefit New Zealand as the carbon price is higher and the increase in commodity prices is smaller than under GWP, provided full international pricing of agricultural non-CO_2 emissions prevails.

5.3.2.2 Scenario 6a

Like Scenario 2a, Scenario 6a is an artifice, having the GTP carbon price from Scenario 6, but the world commodity prices from Scenario 5. Unlike the 2020 case, however, the results of Scenario 6a do not fall in between the two scenarios from which it is constructed. It is better than both of them.

This time the results are as expected with the change in RGNDI exceeding that in Scenario 5. Although the CO_2 price is higher in Scenario 6a than in Scenario 5, $21,200m has to be spent on purchasing emission units from offshore under Scenario 5, compared to only $17,700m of credits that would need to be purchased under Scenario 6a. This easily outweighs a reduction in the terms of trade caused by agricultural exports moving down the demand curve.

This is not the case for the analogous 2020 scenarios where at $490m and $680m for the purchase of credits offshore in Scenarios 2a and 1, respectively, the difference in costs for credit purchases is not large enough to offset the decline in the terms of trade.

An inference which may be drawn then is that absent any changes in world agricultural commodity prices, a switch from GWP to GTP does not benefit New Zealand if carbon prices are low (in the order of NZ$30-60 per tonne of CO_2), but at higher carbon prices in excess of NZ$100 per tonne of CO_2 New Zealand does benefit from a GTP regime.

Unfortunately this benefit is likely to be offset by less favourable changes in commodity prices under GTP (Scenario 6 versus Scenario 6a) if the rest of the world also applies a price on agricultural emissions and hence production costs fall globally under GTP relative to GWP. It needs to be noted though that full international pricing of agricultural non-CO_2 emissions may be a tentative prospect for 2050 but appears very unlikely for 2020, which is why alternative scenarios where the world excludes agricultural emissions from any price measure are also considered in this study.

5.3.2.3 Scenario 7

Scenario 7 is analogous to Scenario 3; countries are responsible for agricultural non-CO_2 emissions, but no countries except New Zealand impose a price on those emissions. In New Zealand agriculture remains in the ETS with free allocation. By 2050 free allocation still amounts to over 60% of the initial free allocation – on an intensity basis.

While Scenario 3 shows only a modest reduction in welfare when compared to Scenario 1 (and only a very small reduction in welfare relative to BAU), the difference between Scenarios 7 and 5 is much starker. The relative change in RGNDI between Scenarios 5 and 7 is -9.2% (and -5.6% for Scenario 7 relative to BAU), compared to only -0.9% between scenarios 1 and 3. In other words, the negative impact on New Zealand if the rest of the world chooses not to impose a price on agricultural emissions, but New Zealand does so, is much greater in 2050 than in 2020.

The contrast is driven by both the lesser increase in commodity prices that occurs in 2050 than in 2020, if agricultural emissions are sheltered by the rest of the world compared to a scenario where they are not, and by the marked lift in the carbon price from $150/tonne to $333/tonne (albeit that the relative change in carbon prices is the same between Scenarios 1 and 3, and between Scenarios 5 and 7).

It has to be conceded that the changes in the relative prices of goods and services throughout the whole economy under such a high carbon price would be so great that the parameter values in the model's demand functions and production functions may no longer be reasonable approximations of behaviour. In particular we could expect to see the development of some step-change mitigation technologies and potential behavioural changes that affect the demand for various products and services. Nevertheless we should not totally disregard the model's estimated effects of a $333/tonne carbon price. What we can infer is that the true effects are probably less severe than estimated by the model.

In the context of this caveat we look below at the effects of a new mitigation technology for enteric fermentation in Scenarios 9 and 10.

5.3.2.4 Scenario 8

Scenario 8 is a variation on Scenario 7, analogous to the relationship between Scenarios 4 and 3 respectively: agricultural non-CO_2 emissions are excluded from the NZETS and New Zealand's target as they no longer form part of any international emissions obligations.

We find that as in 2020, New Zealand would benefit from agriculture being excluded from emissions obligations via international agreement, if the alternative is that the rest of the world *de facto* excludes agriculture but countries nominally retain responsibility for those emissions. Running the same comparisons as before, RGNDI and GDP are 6.4% and 2.0% (respectively) higher than in Scenario 7. Thus 31% of the welfare benefit from removing the charge on agricultural CH_4 and N_2O emissions is attributable to the change in GDP, which is lower than that the 40% observed for 2020. Given the bigger reduction in emissions liability in 2050 when agricultural non-CO2 is removed from international obligations, this is not surprising.

Also similar to 2020, comparing Scenarios 5 and 8 tells us that aggregate economic welfare is higher by 3.6% if New Zealand is liable for its agricultural emissions in the context of a relatively lower carbon price and higher commodity prices resulting from full pricing of all agricultural non-CO_2 emissions globally, compared to facing a higher CO_2 price coupled with lower commodity prices if agriculture is excluded everywhere. This difference is an order of magnitude larger than for 2020, indicating that in the long-term, achieving a globally comprehensive agreement on climate change becomes more and more important for New Zealand.

This finding is consistent with a finding in NZIER and Infometrics (2011) that as the international carbon price rises the welfare cost of excluding agricultural non-CO_2 emissions becomes progressively higher, irrespective of what the rest of the world is doing with regard to agricultural non-CO_2 emissions. However, that work does not consider the effects of any reduction in commodity prices when the whole world excludes agricultural non-CO_2 emissions, which clearly has an additional negative effect on New Zealand.

5.3.2.5 Scenarios 7a and 8a

As before we do not have corresponding GLOBIOM scenarios for Scenarios 7a and 8a. Thus we assume the same world commodity prices as in Scenarios 7 and 8, for the same reasons as for the 2020 runs.

The relative change in RGNDI between Scenarios 6 and 7a is -7.8%, somewhat smaller than the -9.2% change between Scenarios 5 and 7. This is consistent with the results for 2020 whereby the effect of countries being responsible for agricultural non-CO_2 emissions, although no countries except New Zealand imposing a price on those emissions, is larger under GWP than under GTP. The main reason for this is smaller net deficit under the GTP metric and hence lower cost of purchasing emissions permits from overseas. Nevertheless the change in RGNDI in 2050 is still much larger than the change in 2020, as also occurred under GWP, which is attributable to the very high price of NZ$381/tonne of CO_2.

Scenario 8a with agricultural non-CO_2 emissions completely excluded from country obligations shows a gain in RGNDI of 4.7% compared to Scenario 7a. This not as large as the corresponding change under GWP, as is also the case in the analogous 2020 scenarios.

Comparing Scenarios 6 and 8a also reinforces the previous message that aggregate economic welfare is higher if New Zealand is liable for its agricultural emissions in the context of a relatively low carbon price, high commodity prices and global participation, than if New Zealand has to face a higher carbon price coupled with lower commodity prices if agriculture is excluded globally. The difference in RGNDI is about 3.1% under GTP compared to 2.8% under GWP. That the difference under GTP is the larger of these two numbers is a reversal of the result for 2020.

This seems counter intuitive as a lower weight on CH_4 would suggest a smaller gain from ignoring it completely. In level terms the intuition is correct as economic welfare is higher in Scenarios 5 and 8 than in Scenarios 6 and 8a respectively. However, the gain from a reduction in the carbon price from $381 to $181 (under GTP) exceeds the gain from a reduction from $333 to $150 (under GWP). For the 2020 scenarios the changes in the carbon price are much closer in absolute terms between GWP and GTP.

In summary, New Zealand is better off under GWP than under GTP if agriculture emissions are excluded via international agreement from all abatement obligations, but by 2050 the relative gain from removing agricultural non-CO_2 emissions from any GHG obligations is greater under GTP.

Table 5.5: Summary of Results (2050)

	BAU	Scenario 5	Scenario 6	Scenario 6a	Scenario 7	Scenario 7a	Scenario 8	Scenario 8a
		GWP	GTP	GTP	GWP	GTP	GWP	GTP
		$150/t	$181/t	$181/t	$333/t	$381/t	$333/t	$381/t
				Commodity prices from Scenario 5	Other countries shelter agr emissions		Agr non-CO_2 excluded for all countries	
	(% pa on 2005/06)				(% Δ on BAU)			
Private Consumption	2.5	4.6	4.2	5.2	-7.1	-5.6	1.0	0.3
Exports	2.8	9.7	10.0	11.1	11.4	13.1	7.4	8.0
Imports	3.1	11.1	10.8	12.6	-3.0	-0.5	5.2	4.6
GDP	2.3	2.6	2.4	2.9	-0.7	0.0	1.3	1.1
RGNDI	2.6	3.6	3.3	4.1	-5.6	-4.5	0.8	0.2
	MT	MT	MT	MT	MT	MT	MT	MT
CO_2e 1990 (GWP)		65.3			65.3		23.7	
CO_2e 1990 (GTP)			46.7	46.7		46.7		23.7
AAU (GWP)		32.7			32.7		11.9	
AAU (GTP)			23.4	23.4		23.4		11.9
CO_2e 2050 (GWP)	147.9	173.9 (17.6%)			149.6 (1.1%)		56.5 (-21.5%)	
CO_2e 2050 (GTP)	108.9		115.6 (6.1%)	121.1 (11.2%)		109.4 (0.5%)		56.2 (-22.0%)
Net deficit		141.2	92.2	97.7	116.9	86.0	44.6	44.3
- as % of BAU		95.5%	84.7%	89.7%	79.0%	79.0%	64.8%	64.3%
CH_4 & N_2O (GWP)	79.0	114.7 (45.2%)			94.1 (19.2%)		NA	
CH_4 & N_2O (GTP)	40.0		57.2 (43.1%)	61.9 (54.7)		53.7 (34.3%)		NA

5.4 Hypothetical mitigation technology for enteric CH_4

We return now to Scenarios 5 and 6, and look at how the results change under the assumption that from 2030 onwards there is a global mitigation technology which reduces enteric fermentation emissions by 30% at a cost of US(2005)$70/t CO_2e.

There is full international participation with all countries pricing all emissions, and every country benefits from the new technology with equal effectiveness. Since we assume this technology would only become available in 2030, we do not run scenarios for 2020.

Scenario 9 is set in a GWP context while Scenario 10 is set in a GTP context. Apart from GHG prices, the scenario specifications are as in Scenarios 5 and 6 respectively (i.e. we assume that commodity prices would not (yet)_have been affected by the availability of this mitigation technology). As the GHG prices are slightly lower than in Scenarios 5 and 6, we might expect some flow-on to lower commodity prices as well. However with the cost of the new technology being not much cheaper than the carbon price the effect on commodity prices would be small. Thus we have not re-run the GLOBIOM model to calculate commodity price changes for these specific assumptions.

The results are shown in Table 5.6.

In Scenario 9 the welfare gain (RGNDI) is about 40% higher than in Scenario 5, with the emissions benefit of the new technology and the lower carbon price contributing to the improvement in roughly equal proportions.

In Scenario 10 the welfare gain is about one third higher than in Scenario 6. Again the split is about equal in terms of the relative contribution of the lower emissions price and the lower quantity of emissions attributable to the new technology.

In absolute terms the relative welfare gain between Scenarios 6 and 10 is smaller than between Scenarios 5 and 9. This makes sense. With the lower weight on CH_4 emissions under GTP, the value of a technology that reduces CH_4 emissions is less than under GWP. Acting in the opposing direction, but of less significance, is the larger reduction of the carbon price in the GTP case – from $181 to $146 compared to a reduction from $150 to $126 in the GWP case.

This means that if a significant new abatement technology for CH_4 from enteric fermentation were to become available, New Zealand would gain more from this technology under a GWP metric than under a GTP metric.

Nevertheless the important effect that a new technology can have on economic welfare is clearly demonstrated under both GHG metrics. The results also underline the point made earlier that ignoring new abatement technologies under high carbon prices, even if those technologies are not cost-free, could significantly overstate the welfare cost of mitigating emissions.

Table 5.6: Summary of Results (2050): agricultural abatement technology

	BAU	Scenario 5	Scenario 6	Scenario 9	Scenario 10
		GWP $150/t	GTP $181/t	GWP $126/t	GTP $146/t
				lower CH_4	lower CH_4
	(% pa on 2005/06)	(% Δ on BAU)			
Private Consumption	2.5	4.6	4.2	6.5	5.6
Exports	2.8	9.7	10.0	9.1	9.0
Imports	3.1	11.1	10.8	13.3	12.2
GDP	2.3	2.6	2.4	3.1	2.8
RGNDI	2.6	3.6	3.3	5.1	4.4
	MT	MT	MT	MT	MT
CO_2e 1990 (GWP)		65.3		65.3	
CO_2e 1990 (GTP)			46.7		46.7
AAU (GWP)		32.7		32.7	
AAU (GTP)			23.4		23.4
CO_2e 2050 (GWP)	147.9	173.9 (17.6%)		152.3 (3.0%)	
CO_2e 2050 (GTP)	108.9		115.6 (6.1%)		109.5 (0.5%)
Net deficit		141.2	92.2	119.6	86.1
- as % of BAU		95.5%	84.7%	80.9%	79.1%
CH_4 & N_2O (GWP)	79.0	114.7 (45.2%)		92.5 (17.2%)	
CH_4 & N_2O (GTP)	40.0		57.2 (43.1%)		50.7 (26.7%)

5.5 Comparison of results for 2020 and 2050

While the main focus of the research has been on GWP versus GTP, the foregoing discussion has also noted some contrasts between the modelling results for 2020 and those for 2050. The RGNDI results are shown in Figure 5.1.

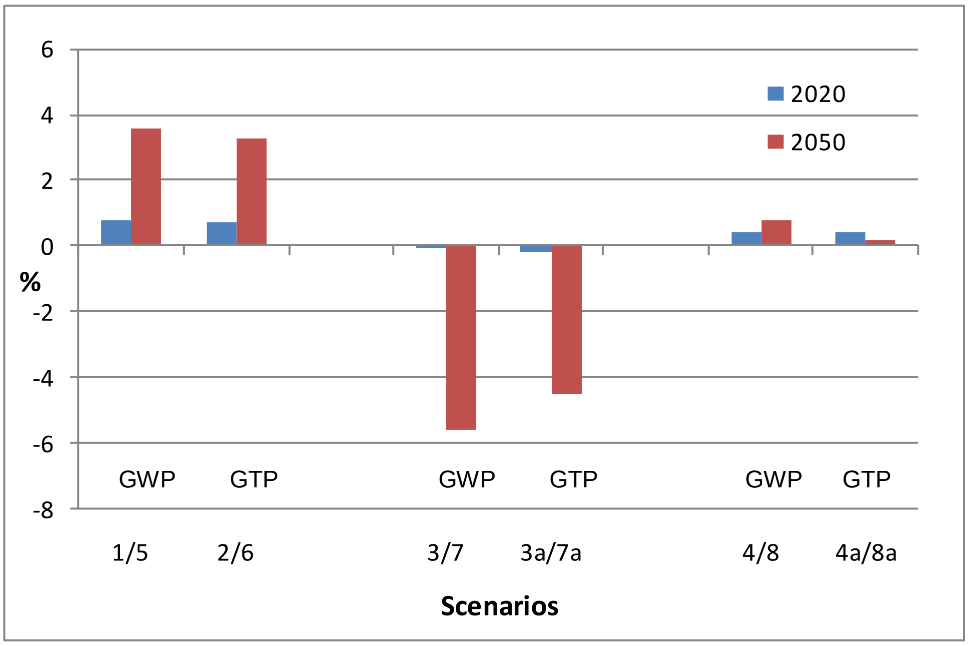
It is clear that for four of the six scenario specifications the effects of the various input assumptions on RGNDI in 2050 are considerably larger than the effects in 2020. For the core scenarios (1 & 2 for 2020 and 5 & 6 for 2050) the difference in horizon years completely dominates the difference between GHG exchange metrics. This is also true for the scenarios where other countries shelter agriculture from an emissions charge, but New Zealand still includes agriculture in the ETS, albeit with free allocation (Scenarios 3 & 3a for 2020 and 7 & 7a for 2050). Of course the main reason is the much higher GHG prices in 2050.

Figure 1 graphically illustrates that the GTP metric generally mutes the economic effect on New Zealand in both directions: where New Zealand might gain from climate change policy settings, it gains by less under the GTP metric, but where it would lose, it would also lose by less. Overall though, whether or not other countries impose an explicit price on agricultural non-CO_2 emissions has a bigger effect on New Zealand's economic welfare than the choice of GHG exchange metrics, especially under higher GHG prices.

Only in the scenarios where agricultural non-CO_2 emissions are totally excluded is the effect of the timing difference (GHG prices) comparable to the effect of the choice of

GHG exchange metrics (Scenarios 4 & 4a for 2020 and 8 & 8a for 2050). One might argue that is a trivial result: if agricultural non-CO_2 emissions are excluded, their conversion factors into CO_2 equivalents are irrelevant. However, the conversion factors do affect the global price on CO_2 that is required to meet a given stabilisation target, and this price flows back into the New Zealand economy. However, our results demonstrate a relative insensitivity to that CO_2 price in 2020 (when prices are still moderate, less than \$100/tCO_2) in comparison with the other assumptions made in our study.

Figure 5.1: Changes in RGNDI



5.6 Summary

We analysed the macroeconomic effects on New Zealand of using alternative metrics to price different greenhouse gases (100-year GWPs and GTPs), for New Zealand net emissions responsibility targets of -15% and -50% in 2020 and 2050, respectively, relative to gross emissions in 1990, consistent with current government policy. We also assume that the current provisions of the New Zealand Emissions Trading Scheme remain in place until 2050.

The key conclusions from our analysis are:

- If agriculture is priced globally, then switching from Global Warming Potentials (GWP) to Global Temperature Change Potentials (GTP) would not benefit New Zealand economically. This is because the lower emissions liability under the GTP metric for New Zealand would be offset by smaller increases in commodity prices as agricultural production costs would be lowered globally.
- If commodity prices were not affected by a change in metric, then switching from GWP to GTP would also not benefit New Zealand in 2020 as the lower emissions liability is counterbalanced by declining terms of trade. However, New Zealand would benefit from such a switch in 2050 as the benefit from a reduced emissions liability under GTPs by then is much greater than the decline in the terms of trade.
- New Zealand economic welfare is higher if New Zealand is liable for its agricultural emissions (coupled with a relatively lower carbon price, high commodity prices and global participation), than if agriculture were excluded globally and New Zealand has to face a higher carbon price coupled with lower

commodity prices. This finding holds irrespective of the choice of GHG exchange metric for other non-CO_2 gases, although it is marginally stronger under the GWP metric than under the GTP metric. The strength of the finding also varies directly with the price on emissions.

- Worse for New Zealand than either of those situations is if all countries are nominally liable for agricultural non-CO_2 emissions, but all countries other than New Zealand choose to shelter them from a carbon price, because this reduces the increase in world agricultural commodity prices from which New Zealand would be a net beneficiary. The negative implications are significantly greater in 2050 than in 2020. GTP metrics would not alter these negative implications in 2020, but would reduce them significantly (by about 20%) in 2050.
- If a significant additional agricultural abatement technology for emissions of methane from enteric fermentation were to be developed, then New Zealand would derive greater economic benefit from this technology if agricultural non-CO_2 emissions are priced according to GWPs rather than GTPs.

As a very broad summary, whether switching from GWPs to GTPs is of benefit to New Zealand strongly depends on other climate policy assumptions. In scenarios where agriculture is exposed globally to the full costs of its non-CO_2 emissions, New Zealand stands to receive net economic gains due to increasing commodity prices and associated increased export earnings; switching from GWPs to GTPs would reduce those gains. In scenarios where New Zealand is the only country to expose its agriculture sector to the full costs of non-CO_2 emissions, it would experience net costs due to its reduced competitive advantage; in that case, switching from GWPs to GTPs would reduce those costs.

In conclusion, whether or not other countries impose an explicit and full price on all agricultural non-CO_2 emissions (or impose other mitigation requirements of equal stringency to those emissions) has a much bigger effect on New Zealand's economic welfare than the choice of greenhouse gas exchange metrics, especially under higher greenhouse gas prices.

6. Discussion and conclusions for climate policy

6.1 Global-level considerations and implications

6.1.1 Uncertainty and change over time

Our analysis of alternative bio-physical metrics (GWPs and GTPs) makes it clear that exchange rates between different greenhouse gases are uncertain and hence may change over time due to predictable and unpredictable changes in the physical climate system. In addition, exchange rates could change either due to one-off policy decisions either to change metrics or their time horizons, or to adopt a metric that is in itself designed to generate time-dependent exchange rates. This resulting overall uncertainty about future values in exchange rates matters for climate policy because such changes could imply significant shifts in the composition of greenhouse gases at a national level and thus introduce uncertainties and potential costs regarding the optimal balance of national mitigation efforts across a range of different sectors.

The intersection of policy choices and scientific uncertainty implies that there is limited justification for updating 100-year GWPs over time. Considering the multitude of goals that international climate policy seeks to achieve, maintaining at least for the time being the current exchange rates would appear equally justified, as would a discussion about changing metrics altogether as envisaged under the UNFCCC SBSTA work programme (which implies the potential for a much larger change in exchange rates, and one that would potentially go in the opposite direction to updating 100-year GWPs). On the other hand, including additional feedback processes in the calculation of 100-year GWPs would increase their values significantly more than a mere updating of their values based on the limited range of processes that are currently included in their calculation.

Altogether, this analysis underscores that exchange rates between gases are essentially conventions that are informed by science but rely heavily on additional judgements and policy goals. Consideration of other issues, such as cost-effectiveness and broader economic, environmental and social impacts of mitigation requirements on specific sectors, regions and countries under alternative metrics forms an essential input to ultimate decisions regarding the choice and/or regular updating of metrics.

6.1.2 Cost-effectiveness of alternative metrics

Using fixed 100-year GTPs instead of 100-year GWPs would give lesser weight to abatement of CH_4 compared to CO_2. At the global level, this results in higher total global mitigation costs (expressed in aggregated net present value of abatement activities across all sectors over the 21st century) mainly because changes to long-lived capital infrastructure associated with CO_2 emissions from energy supply systems would need to be taken earlier and more rapidly to meet the same long-term stabilisation target.

Using time-dependent GTPs give less weight to CH_4 initially than under GWPs but much more weight towards the end of the 21st century. This would reduce total global mitigation costs because abatement of CH_4 in the near term contributes very little to radiative forcing in 2100, which was adopted as target year in this study. The much more stringent abatement requirements for CH_4 under time-dependent GTPs towards the end of the 21st century would reduce radiative forcing rapidly towards the target year 2100 and hence leave somewhat greater room for CO_2 emissions, resulting in a slight reduction in the urgency of costly near-term CO_2 reductions.

Purely from a global cost-effectiveness perspective then, and looking only at radiative forcing in the target year 2100, time-dependent GTPs would appear to be a ‘better’ metric than GWPs or GTPs. However, several important caveats need to be considered before this conclusion is translated into a policy recommendation, namely:

- the practical feasibility and likelihood of implementing and maintaining time-dependent GTPs over the course of the 21st century
- the risks to achieving agreed long-term goals if a time-dependent GTP metric were to be abandoned at some stage during the 21st century
- the relative orders of magnitude of global cost savings under alternative metrics compared to cost differences arising from other assumptions and policy choices.

Overall mitigation costs under time-dependent GTPs are lower only because of discounting. GDP losses in 2100 relative to business-as-usual are significantly greater under time-dependent GTPs than under GWPs. The steady increase in mitigation costs for non-CO_2 emissions, particularly agriculture and waste management, raise significant questions whether time-dependent GTPs could realistically and reliably be implemented by climate policy, and whether future generations would be prepared to accept the higher cost on their shoulders based on a discounting argument.

Food security concerns for the poorest parts of global society are very unlikely to disappear by 2050 but rather could intensify as population increases and the effects of climate change become more and more tangible. Such concerns make it rather implausible that costs in the order of US$100,000 per tonne of CH_4 would indeed be imposed globally on all sources of agricultural greenhouse gas emissions in the second half of the 21st century. However, if those costs are not imposed, then this effectively means that the time-dependent GTP metric would not in fact be applied. This in turn would result in the need to place more emphasis on abatement of CO_2 emissions instead.

This raises the real risk that a time-dependent GTP metric could be adopted in the near term but then abandoned by 2050 due to mounting concerns about its costs for agricultural mitigation. While a revision of earlier decisions is not uncommon in climate policy and may in fact be necessary as new information comes to light, it would imply an increasing risk that long-term goals of climate policy (such as limiting warming to less than 2°C) will not be achieved even if global actions appear on track over the next few decades. This risk is smaller though than the much bigger issue that near term actions are already not on track to deliver the agreed long-term goal of limiting warming to 2°C, regardless of the metric used to treat non-CO_2 gases (Rogelj et al. 2010).

Within this discussion, it is important not to lose sight of orders of magnitude: the relative cost savings that could be achieved globally by using time-dependent GTPs rather than GWPs are much smaller than cost differences arising from alternative long-term stabilisation targets and alternative assumptions about agricultural mitigation potential (see results in this study), and the costs arising from delays in near-term mitigation actions to reduce CO_2 emissions and lock-in to carbon intensive capital infrastructure (Bosetti et al. 2009; Calvin et al. 2009; den Elzen et al. 2010; Krey and Riahi 2009; van Vliet et al. 2009; Vaughan et al. 2009). Such comparisons can, and perhaps should, temper the emphasis that is placed on the search for and implementation of an 'optimal' metric compared to the current arrangements, at least from a global perspective.

6.1.3 Weak equivalence of outcomes under alternative scenarios

Another important caveat regarding the attractiveness of time-dependent GTPs would be that even though our analysis ensures the same radiative forcing is achieved in all scenarios in 2100, the emissions pathways and forcing outcomes under alternative scenarios are not environmentally equivalent in two other important aspects.

One non-equivalence is that the intermediate forcing during the middle of the 21st century would be greater under time-dependent GTPs than under GWPs. This would result in greater intermediate warming and slightly greater near-term rate of warming, which could result in higher impacts and increases the risk of irreversible impacts such as species extinctions and thresholds (O'Neill and Oppenheimer 2004). Similar to the caveat above though, the differences in those intermediate warming levels are much smaller than differences that would be associated with different stabilisation levels. The degree of overshoot also depends on assumptions about the availability and timing of additional mitigation options for agricultural non-CO_2 gases.

A second non-equivalence is that even though our scenarios are all designed to result in the same radiative forcing in 2100, they imply different long-term risk levels as a greater or lesser share of the forcing in 2100 comes from CO_2 or CH_4.

Under scenarios that use the GWP metric and assume a constant mitigation potential for agriculture, radiative forcing from CH_4 in 2100 constitutes 22% of the total forcing. If agriculture were excluded from all mitigation obligations it would be as high as 24-25%. By contrast, under scenarios that assume time-dependent GTPs and assume an increasing agricultural abatement potential, CH_4 constitutes only 16% of the total forcing in 2100. If an additional mitigation technology were developed, then the share of CH_4 in the total forcing could drop as low as 11-12%. Because CO_2 remains in the atmosphere for many centuries, a greater share of CO_2 in the total forcing in 2100 implies a greater commitment to on-going climate change, whereas the forcing from CH_4 would disappear within about 50 years if all emissions were to cease hypothetically.

Concerns about the commitment to long-term climate change from a higher fraction of radiative forcing from CO_2 may be tempered somewhat though by two additional considerations. One consideration is that the absolute differences in the forcing contribution from CH_4 are mostly smaller than from different stabilisation targets, which again emphasises that critical policy choices have a bigger impact than the choice of metric. The second consideration is that the pathways consistent with stabilisation at 450ppm CO_2-eq all assume the wide use of bioenergy or free air carbon capture in conjunction with carbon capture and storage, resulting in net negative CO_2 emissions towards the year 2100. The presence and use of this negative emissions technology implies that the millennial-scale commitment to on-going climate change from CO_2 emissions is not in fact an irreversible commitment, but could be managed by upscaling this negative emissions technology that could actively remove CO_2 from the atmosphere. Whether this technology can in fact be implemented at the necessary scales can be doubted (Dessler 2009; Marland and Obersteiner 2008), but this is a question that applies to the feasibility of all the scenarios run in this study.

6.1.4 Summary of global issues

In summary, it appears that at a global level, the choice of alternative metrics is not irrelevant but is outweighed under almost all scenarios by uncertainties and the potential for different choices with regard to long-term stabilisation targets and assumptions about the availability, cost and potential of different mitigation options. In other words, collective choices of what to aim for in the long term, and collective efforts in technological development and implementation of mitigation technologies and policies matter much more at a global level than how specific emissions are compared.

Our analysis showed that enhancing agricultural mitigation potential, and its effective application globally, would have major economic benefits not just for agricultural economies but for all economies, because it reduces the pressure for near-term and costly emissions reductions of CO_2. The associated cost savings are much greater than savings that would result from a change from GWPs to time-dependent GTPs. The same applies, conversely, if agriculture were excluded entirely from mitigation obligations out of concerns e.g. over food security. Excluding agriculture entirely would raise global mitigation costs substantially, regardless of metric, particularly if it is assumed that agricultural mitigation potential could have improved over time but did not because it was excluded from any mitigation obligations.

It is worth re-emphasising that we tested metrics only in a *cost-effectiveness* framework, i.e. with regard to the question of what metrics result in lowest net present value mitigation costs aggregated over the 21st century, for a pre-determined goal of a given radiative forcing in the year 2100. An alternative approach would be to determine what metrics deliver the greatest *cost-benefit* (Hammitt et al. 1996), taking into account actual damages from climate change over time, and potential co-benefits of reducing various emissions on health and other environmental issues such as surface ozone pollution (Cox and Jeffery 2010; Shindell et al. 2012). However, evaluating these issues within a rigorous economic modelling approach must be left to future study and would require a different model design to take adequate account of climate damages.

The analysis in this report proceeded on the basis that future agreements will use some form of emissions trading amongst a basket of gases. However, this in itself is a policy choice and not a scientific or economic necessity. The fundamental differences between greenhouse gases make full emissions trading between short- and long-lived greenhouse gases only weakly justifiable from a physical science perspective, given their very different long-term impacts on the climate system and the potential for some gases to affect atmospheric chemistry in ways that are as yet only poorly understood (Manning and Reisinger 2011).

No developed country to date has made active use of the fungibility between gases offered by the concept of metrics (other than through participation in the Clean Development Mechanism). New Zealand is an exception in that it has included non-CO_2 emissions (maonly CH_4) from landfills, and currently intends to include agricultural non-CO_2 emissions in its ETS from 2015. However, this plan is subject to a review taking into consideration whether other countries are taking similar action. This very limited trading of different gases raises the question whether a single basket approach is indeed a necessary or even useful way for international climate policy to proceed (Johansson and Persson 2005).

However, the alternative of having separate baskets or emissions targets for individual gases is not necessarily more attractive, as it could multiply the obstacles faced by international negotiations to reach agreement. In addition, it could also heighten the issues that New Zealand faces in terms of its emissions profile being unique in the developed world. Most other developed countries are likely to have access to a greater range of mitigation options even for CH_4 emissions from agriculture, given the typically more intense farming systems that offer greater opportunities for intervention via feed additives, housing and manure management than in New Zealand. Hence an emissions reductions target specifically for CH_4 emissions from developed countries could result in even greater pressures on New Zealand, unless such a discussion were coupled with a very open disclosure, analysis and comparison of actual mitigation potentials and costs from different sectors in each country. If such a disclosure were to take place, then this information could equally inform different national targets set under a basket of gases, without having to resort to setting targets for individual gases.

6.2 New Zealand-specific considerations

The global perspectives highlighted above provide important context for New Zealand-specific considerations. Metrics for comparing greenhouse gases would very likely be set by international agreement and from such agreements flow through to New Zealand. In addition, global mitigation responses and agreed emissions or concentrations targets will flow back to New Zealand via the prices established for emissions trading and through changes in the prices of key commodities.

Our analysis shows that, perhaps contrary to intuitive assumptions, New Zealand would not necessarily benefit if GTPs were chosen as metric instead of GWPs. Instead, the net effect on New Zealand's economy depends heavily on other assumptions, mainly the degree of participation by other countries in agricultural mitigation activities and the consequential effects on global carbon and commodity prices.

Overall, our study found that New Zealand would see significant economic benefits if all countries undertook stringent agricultural mitigation measures, and in that case, New Zealand would benefit more from GWPs than from GTPs. This benefit is because the increasing commodity prices would outweigh the costs associated with meeting emissions targets, at least for the targets currently accepted by the New Zealand government. New Zealand would also benefit more under GWPs than GTPs if an additional agricultural mitigation technology were developed.

The worst outcome for New Zealand is if other countries take no actions to reduce agricultural emissions even though all countries are nominally liable for them. In that case, New Zealand is worse off. It is noteworthy though that even in this scenario the costs relative to business-as-usual are very small (0.2% of RNGDI or less) by 2020, given the expected increase in global commodity prices even if no agricultural mitigation takes place elsewhere, mainly through increased biofuel demands limiting the expansion of land for livestock production. Only in 2050, if all other countries continue to exclude all agricultural emissions from stringent mitigation requirements, would New Zealand see a more significant economic loss (of -5.6% relative to BAU). In this case, GTPs would temper this loss by about 20% to -4.5% but would not radically alter the situation.

The larger effect in 2050 compared to 2020 is because New Zealand has accepted an aspirational emissions target of -50% by 2050 (relative to 1990). Given the large fraction of agricultural emissions and the assumed absence of mitigation options, meeting this long-term target is only possible at high costs, but switching to GTPs would reduce the fraction of agricultural emissions and allow a greater emphasis on mitigation of CO_2 for which at least in principle more technological mitigation options exist.

This analysis indicates that alternative metrics do not appear to make a radical difference to economic implications for New Zealand, and that (as in the global picture) other assumptions about climate policy have a much bigger effect. In addition, benefits for New Zealand arising from reduced liabilities under GTPs are counterbalanced by changes in terms of trade.

As in all modelling studies, we had to make some idealising assumptions about global and domestic climate policies and their effectiveness in achieving mitigation outcomes, as well as the degree of foresight that is employed in adopting mitigation practices and targets and associated emissions prices. Our model assumes full foresight and a globally optimal distribution of mitigation efforts to achieve emissions reductions at least cost across all world regions. A more detailed and realistic modelling of the implications of policy choices, including the implications of graduated, delayed and inefficient participation by key trading partners and economic competitors to New Zealand under different metrics, and the implications of limited or lack of foresight by individual actors affecting carbon and commodity prices and their changes over time, may be desirable to further test and refine these conclusions.

The limited modelling tools available and increasing assumptions that must be made at a national level mean that we had to rely on inferences made from several different models that do not all share the same assumptions. Enhancement of New Zealand's capacity to conduct such modelling studies appears as a significant priority for future work, and is in fact being progressed through a parallel research effort conducted under the Sustainable Land Management and Adaptation to Climate Change programme.

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