Impact of greenhouse gas metrics on the quantification of agricultural emissions and farm-scale mitigation strategies: a New Zealand case study

Andy Reisinger and Stewart Ledgard

1 New Zealand Agricultural Greenhouse Gas Research Centre, AgResearch, Palmerston North, New Zealand
2 AgResearch, Hamilton, New Zealand

E-mail: andy.reisinger@nzagrc.org.nz

Received 14 January 2013
Accepted for publication 9 May 2013
Published 23 May 2013
Online at stacks.iop.org/ERL/8/025019

Abstract

Agriculture emits a range of greenhouse gases. Greenhouse gas metrics allow emissions of different gases to be reported in a common unit called CO$_2$-equivalent. This enables comparisons of the efficiency of different farms and production systems and of alternative mitigation strategies across all gases. The standard metric is the 100 year global warming potential (GWP), but alternative metrics have been proposed and could result in very different CO$_2$-equivalent emissions, particularly for CH$_4$. While significant effort has been made to reduce uncertainties in emissions estimates of individual gases, little effort has been spent on evaluating the implications of alternative metrics on overall agricultural emissions profiles and mitigation strategies. Here we assess, for a selection of New Zealand dairy farms, the effect of two alternative metrics (100 yr GWP and global temperature change potentials, GTP) on farm-scale emissions and apparent efficiency and cost effectiveness of alternative mitigation strategies. We find that alternative metrics significantly change the balance between CH$_4$ and N$_2$O; in some cases, alternative metrics even determine whether a specific management option would reduce or increase net farm-level emissions or emissions intensity. However, the relative ranking of different farms by profitability or emissions intensity, and the ranking of the most cost-effective mitigation options for each farm, are relatively unaffected by the metric. We conclude that alternative metrics would change the perceived significance of individual gases from agriculture and the overall cost to farmers if a price were applied to agricultural emissions, but the economically most effective response strategies are unaffected by the choice of metric.

Keywords: greenhouse gas metrics, agriculture, mitigation strategies, uncertainty, global warming potential, global temperature change potential

1. Introduction

Livestock agriculture emits a range of greenhouse gases, most notably CH$_4$ from enteric fermentation and manure treatment and N$_2$O from the use of synthetic fertilizers and deposition of urine and manure on land. Agriculture also emits CO$_2$ through fossil fuels use and can affect the amount of soil carbon stored in agricultural soils, but uncertainties are generally large (Smith et al 2007).

While knowledge of emissions of each gas from individual processes is obviously important, for many applications an aggregate measure of all greenhouse gas...
emissions is needed, e.g. to compare absolute net emissions or emissions intensity (i.e. emissions per unit of product) of different farms, or to evaluate the mitigation potential of different management strategies. This requires a metric that assigns a weighting factor to the emission of each gas. The most common metric is the global warming potential (GWP), which is used to convert non-CO\textsubscript{2} greenhouse gases into CO\textsubscript{2}-equivalent emissions. The 100 yr GWP is used to report and account for aggregate emissions under the UNFCCC and its Kyoto Protocol but also in scientific reporting of mitigation potentials by the IPCC (Smith et al. 2007, UNFCCC 2009a, 2009b).

The near-universal use of the GWP has been criticized on the grounds that it entails a number of important value judgements, such as the choice of a 100 yr time horizon, and its reliance on the integrated radiative forcing rather than a measure that might be closer to the issue of concern, such as actual temperature change. The GWP has also been criticized for not resulting in the most cost-effective mitigation pathway if used as the basis for prioritizing abatement options (Manne and Richels 2001, Manning and Reisinger 2011, Shine 2009, Manne and Wigley 2000).

Recently, renewed interest emerged in potential alternatives to the GWP and many alternative metrics and approaches have been proposed. The most prominent alternative currently is the global temperature change potential (GTP), which can be used to compare the warming at a future point in time resulting from the emission of non-CO\textsubscript{2} gases at a specific point in time against that from an emission of CO\textsubscript{2} (Shine et al. 2007, 2005). Using a pulse-based GTP would, as the GWP, still allow the reporting of aggregate CO\textsubscript{2}-equivalent emissions for any given year, but the weighting assigned to non-CO\textsubscript{2} gases would potentially be very different, particularly for gases with a short lifetime such as CH\textsubscript{4} because the GTP ignores the integrated warming effect from short-lived warming agents for longer time horizons (see table 1).

The implications of alternative metrics for individual countries and sectors with large fractions of CH\textsubscript{4} emissions, in particular agriculture, have received surprisingly little attention in the scientific literature, even though alternative metrics could significantly change the perceived importance of different gases and would materially change emissions inventories at farm and national level. In the most extreme case, where mitigation entails increasing the emission of one gas to reduce emissions of another gas, one can even envisage situations where a specific action reduced net emissions under one metric but increases net emissions under another metric.

This study explores the implications of two alternative metrics, the 100 yr GWP and GTP, for the greenhouse gas emissions profile of a set of New Zealand dairy farms and the efficacy of different mitigation strategies at the farm level. We emphasize that there is no a priori scientific reason for a specific time horizon, and the most appropriate choice of metric depends strongly on policy goals (IPCC 2009, Shine 2009, Tol et al. 2012). The specific metrics and time horizons evaluated here should therefore be regarded as a sensitivity test of the influence of alternative metrics on apparent farm efficiency and the performance of mitigation strategies, not as the only or most plausible choices for metrics, as some other metrics choices could result in near zero weight given to CH\textsubscript{4} at least in the near term (see table 1; also Reisinger et al. 2012). To our knowledge, this is the first study to investigate the implications of metrics at the farm level quantitatively using detailed and realistic mitigation options.

### Table 1. Metric values for CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O for GWP and GTP and for a range of time horizons. Values are from Forster et al (2007) for GWP. GTP are from Fuglestvedt et al (2010) for 20 and 100 year horizons, and calculated for 500 year horizons based on Reisinger et al (2010). Only 100 year values are used in this study. Note that current UNFCCC reporting uses slightly different GWP values, based on IPCC (1996).

| Metric | Time horizon (yr) | CO\textsubscript{2} | CH\textsubscript{4} | N\textsubscript{2}O |
|--------|------------------|------------------|------------------|------------------|
|        | 20               | 100             | 500             | 20               | 100             | 500             |
| GWP    | 1                | 72              | 25              | 7.6             | 289             | 298             | 153             |
| GTP    | 1                | 57              | 4               | 0.7             | 303             | 265             | 37              |

2. Methods and models

We used emissions data and explored management options for 26 dairy farms in the Lake Rotorua catchment in the central North Island of New Zealand. The analysis was done originally as part of a project to examine options for reducing nutrient emissions from farms (Judge et al. 2010). These farms are on free-draining pumice soils in a relatively high rainfall area (1400–2500 mm yr\textsuperscript{-1}). They show a wide range in inputs (e.g. 0–277 kg fertilizer-N ha\textsuperscript{-1} year\textsuperscript{-1}; brought-in feed of 0–2577 kg dry matter-equivalent ha\textsuperscript{-1} year\textsuperscript{-1}), stocking rate (1.7–3.8 cows ha\textsuperscript{-1}) and milk production (270–1366 (kg milk solids) ha\textsuperscript{-1} year\textsuperscript{-1}). The average and range for these parameters is similar to that observed in other New Zealand regions, except that the average per-hectare N fertilizer input (168 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}) is about 40% higher than the New Zealand average (DairyNZ 2012).

The Udder model (Larcombe 1999) was used to model monthly animal productivity in relation to the known average pasture production profile for the area and to calculate farm profitability based on a gross margin analysis (accounting for gross income less fixed and variable input costs, excluding labour and debt servicing). A carbon footprint model (Flysjö et al. 2011, Ledgard et al. 2008) based on life cycle assessment was used to estimate total annual greenhouse gas emissions for all farms and scenario analyses to ensure that all on- and off-farm contributions of various management strategies were included. The model is based on a tier-2 energy-based feed intake model (Clark et al. 2003) and NZ-specific CH\textsubscript{4} and N\textsubscript{2}O emission factors (MfE 2012a). It accounts for all animals
(dairy cows and replacement animals whether grazed on or off-farm), enteric, effluent and dung-based CH\textsubscript{4} emissions, direct and indirect N\textsubscript{2}O emissions from excreta, effluent and N fertilizer, refrigerant emissions, and total embodied CO\textsubscript{2} emissions from all inputs (including feed and fertilizer production) and energy sources. Emissions associated with infrastructure and soil carbon sequestration were excluded. Greenhouse gas emissions were allocated between milk and meat on a biophysical basis according to relative energy requirements for each product (Flysjö \textit{et al.} 2011), with an average value of 86\% to milk.

Data are for 2005 and a price to farmers of NZS\(5.20\) kg\textsuperscript{-1} of milk solids was used. Farm profitability (gross margin) varied widely between the farms, at NZS\(7–23\) ha\textsuperscript{-1} yr\textsuperscript{-1}. We evaluated both absolute emissions (per hectare) and emissions intensity (emissions per unit of product, in this case, per unit of milk solids produced) of farms since both measures are relevant for different policy contexts. Absolute emissions can be used to determine the contribution of farms to national gross emissions, whereas emissions intensity may be more useful in international comparisons and product labelling to support consumer decisions, and to determine changes in absolute emissions for any given product demand. Total greenhouse gas emissions, expressed on a dairy farm area basis and using GWP, ranged from 5030 to 16 800 kg CO\textsubscript{2}-equivalents ha\textsuperscript{-1} year\textsuperscript{-1}, and the carbon footprint of milk ranged from 11.8 to 18.7 kg CO\textsubscript{2}-equivalents kg\textsuperscript{-1} milk solids.

A subset of 6 farms was selected for more analysis of the potential effects of management options specific to each farm on total annual greenhouse gas emissions, productivity and profitability. This subset of farms was selected to cover a similarly wide range from low to high inputs (40–277 kg fertilizer-N ha\textsuperscript{-1} year\textsuperscript{-1}), productivity (649–1366 (kg milk solids) ha\textsuperscript{-1} year\textsuperscript{-1}) and profitability (NZS\(665–2344\) ha\textsuperscript{-1} yr\textsuperscript{-1}, but excludes the economically marginal farms. This subset was used in section 4 to assess detailed and farm-specific mitigation or management options.

Options included reducing or eliminating the use of N fertilizer; increasing N fertilizer rate associated with increasing milk production/cow; decreasing stocking rate and increasing per-cow milk production; decreasing replacement rate (to 19\%); and increasing cows ha\textsuperscript{-1}; grazing a proportion of the cows off-farm over winter and increasing cows ha\textsuperscript{-1}; and accounting for improved feed conversion efficiency based on the equivalent of a 10 yr genetic gain. A key assumption for N fertilizer scenarios was that pasture growth changed by 10 kg dry matter per kg fertilizer-N (a typical value from New Zealand research). The magnitude of change with the various scenarios depended on the specific current baseline farm practices (e.g. N rate, per-cow production, replacement rate) and what appeared realistically achievable. In all cases, changes under any specific management strategy were modelled using Udder to account for effects on pasture growth and cow feed requirements over the course of a year; resulting changes in annual emissions were then calculated for each greenhouse gas using the full carbon footprint model, and aggregated into CO\textsubscript{2}-equivalents using either GWP or GTP as the metric.

The strategies were not applied uniformly to all farms but selected for each farm using expert judgement, based on their specific operating conditions and performance in the baseline year. The number of strategies evaluated for each farm ranged from 10 to 18 for the different farms. Some strategies target improved profitability via increased farm intensity and hence increase absolute emissions but reduce emissions intensity, while some even increase both absolute emissions and emissions intensity. These strategies were included because farmers might use increased profitability to offset increased operating costs if a price on emissions were applied.

An additional scenario tested was a hypothetical vaccine (Attwood \textit{et al.} 2010, McAllister \textit{et al.} 2011) that would reduce enteric CH\textsubscript{4} emissions by 50\% and assuming no effect on milk production or N\textsubscript{2}O emissions, for two different hypothetical cost levels (zero and NZS\(50\) ha\textsuperscript{-1} cost). While the specific assumptions around the effectiveness and cost of a vaccine are obviously arbitrary at this stage, they can serve as a sensitivity test of the relative role of technological mitigation solutions and changes in farm management practices.

Effects on profitability under management options, including the vaccine, were modelled using the Udder model, for three different carbon prices (NZS\(0, NZS\(25\) and NZS\(50\) per tonne CO\textsubscript{2}-eq) and the full carbon footprint (i.e. both on- and off-farm) emissions.

3. Implications of metrics for baseline emissions profiles of farms

3.1. Relative importance of different gases

The use of alternative metrics has some predictable but nonetheless striking implications for the apparent emissions profile of the 26 farms. While CH\textsubscript{4} is the most important gas under GWP, N\textsubscript{2}O is dominant under GTP, and overall emissions are much lower (figure 1). For a country like New Zealand, where agriculture forms a large part of the national inventory, changing the metric from GWP to GTP would significantly reduce the relative importance of agriculture in the national emissions profile: under GWP, agriculture is the most important emissions source at 47\% of the total (which is unique for a developed country), whereas under GTP, agriculture emissions would drop to 29\% and become smaller than energy emissions at 60\% (based on emissions data for 2010, from MfE 2012a).

Farms differed in emissions intensity compared to absolute emissions per hectare. The least productive farm (number 18) had a high emissions intensity but low emissions ha\textsuperscript{-1}, whereas farm 7 with the highest absolute emissions had one of the lowest emission intensities. These qualitative results hold under both metrics, but the ranking differs for some farms.

The change in the balance between CH\textsubscript{4} and N\textsubscript{2}O emissions from farms could affect directions of mitigation research and climate policy. The current lack of mitigation
options (particularly for enteric \( \text{CH}_4 \) from grazing cattle) is one of the main reasons why agriculture to date has not been included in a price-based climate policies in New Zealand (e.g. MfE 2012b). By contrast, some mitigation options exist for \( \text{N}_2\text{O} \) and emissions reductions would have co-benefits of reduced nitrate leaching and reduced freshwater pollution (e.g. Ledgard et al 2009, Yeo et al 2012). Thus alternative metrics could affect whether greenhouse gas mitigation is seen as distinct from or a core part of environmental sustainability of agriculture.

3.2. Economic performance and its relationship to emissions intensity

In the absence of climate policies targeting agricultural emissions, the main reason for changing farm-level emissions comes from economic pressures on farmers to increase their profitability per hectare, which is correlated with a reduction in emissions intensity (see figure 2(a)). This negative correlation is preserved when GTP instead of GWP is used as metric, suggesting that greenhouse gas intensity can be a useful predictor for the ranking of farms in terms of profitability even in the absence of a carbon price.

Greenhouse gas emissions intensity is also a robust predictor of the potential loss of profitability if these farms were exposed to a price on their greenhouse gas emissions. Figure 2(b) shows the relative reduction of gross margin under a carbon price of NZ$25 \( \text{tCO}_2\text{-eq}^{-1} \). Assuming no change in farm management, the farms with lower emissions intensity would experience lower relative reductions in their gross margins. This result holds for both GWP and GTP, and the correlation is very similar for carbon prices up to at least NZ$50 \( \text{tCO}_2\text{-eq}^{-1} \). The main difference between metrics is the overall economic impact: under GWP, the profit margin of the farms would reduce on average by 28% (14%–77%) under a price of NZ$25 \( \text{tCO}_2\text{-eq}^{-1} \), whereas under GTP the reduction would be roughly halved to 13% (6%–37%) for the same price. The two marginal farms would start to make economic losses under either metric at this price.

4. Performance of mitigation strategies under alternative metrics

We now investigate potential strategies to reduce either absolute emissions or the emissions intensity of the six subset farms, and explore their robustness under alternative metrics and for different carbon prices. We included strategies that would reduce neither absolute emissions nor emissions intensity but bolster profitability, since most farmers would aim to maximize their profit margin, accounting for the costs associated with emissions but not focusing on emissions reductions per se.

4.1. Elimination of nitrogen fertilizer inputs

In all dairy farms, the most straightforward currently available mitigation strategy is to eliminate all nitrogen (N) fertilizer inputs. This approach would have significant co-benefits through reduced nitrate leaching and improved water quality. Figure 3(a) shows that the net \( \text{CO}_2\text{-eq} \) emissions reductions achieved for the different farms (including adjustments to stocking rates and per-cow production to match the changed pasture production) would be greater if emissions are measured by GTP than GWP, because most of the reduction applies to decreased \( \text{N}_2\text{O} \) emissions, which is given greater weight under GTP. The total effect of this mitigation strategy on \( \text{CO}_2\text{-eq} \) emissions varies strongly between farms, reflecting their different levels of N fertilizer inputs in the base case. The change in total \( \text{CO}_2\text{-eq} \) emissions also depends on whether stocking rates are optimized for profitability after elimination of N fertilizer inputs, or simply adjusted from the base case to reflect the changed pasture production, which does not necessarily achieve optimum production per cow. Both management choices in responses to elimination of N fertilizer inputs were modelled and included in figure 3.

Figure 3(a) demonstrates that avoiding N fertilizer inputs would also reduce the emissions intensity of all farms. The extent of reduction is strongly correlated with but generally lower than absolute emissions reductions, because eliminating...
N fertilizer inputs generally results in less productive animals and hence a higher \( \text{CH}_4 \) emissions intensity of milk production, which partially offsets the gain from reduced N losses. The relationship between absolute emissions and emission intensity is closer to the 1:1 ratio under GTP, because the compensating effect of increased \( \text{CH}_4 \) emissions intensity is given a lesser weight under GTP than under GWP.

4.2. Farm management strategies that balance economic and environmental outcomes

Eliminating N fertilizer inputs results in a strong reduction of absolute \( \text{CO}_2\text{-eq} \) emissions but in almost all farms (with one exception) is also associated with a significant drop in profitability even if stocking rates are optimized, with reductions of up to 30% for the most input-intensive farms (see figure 3(b)). We therefore also explored more balanced strategies that seek to only moderately reduce GHG emissions, or emissions intensity, via a combination of measures such as reducing but not eliminating N fertilizer inputs, optimizing stocking rates, off-farm grazing etc (see section 2).

We found that in most cases, the relative change in net absolute emissions or emissions intensity was only little affected by the choice of metric (figure 4). However, in a few cases discussed below, the estimated mitigation effect,
Figure 4. Comparison of change in absolute emissions (a) and emissions intensity (b) under GWP and GTP, for a range of different mitigation strategies applied to the six farms investigated in detail. The dotted lines indicate a perfect agreement in emissions change between the two metrics. Red circles denote mitigation strategies where the sign of the change differs depending on whether emissions are reported in GWP or GTP; green/blue circles denote strategies where emissions reduce/increase noticeably more under GTP than under GWP.

particularly emissions intensity, depends markedly on whether GWP or GTP are used to report aggregated emissions.

The three cases with markedly greater reductions in absolute emissions under GTP than under GWP all occurred on farm 24, which is a farm with high N fertilizer inputs (highlighted by a green oval in figure 4(a)). In these three cases, the mitigation strategy is to significantly reduce (but not eliminate) N inputs and hence N\textsubscript{2}O emissions, which results in lesser reductions of CH\textsubscript{4} emissions due to reduced production efficiency. Weighting emissions by GTP give greater emphasis to the N\textsubscript{2}O mitigation effect and hence greater relative reductions absolute net emissions than under GWP. In one specific strategy and farm (highlighted by a red circle in figure 4(a)), net absolute emissions reduce by 5% if reported using GTP but increase by 3% if reported using GWP.

Four cases show markedly greater increases in absolute emissions under GTP than under GWP (blue oval). In these cases, the mitigation strategy is to increase farm productivity by increasing N inputs, resulting in increased N\textsubscript{2}O emissions but a much lesser increase in CH\textsubscript{4} due to increased efficiency of milk production. GTP give greater weight to the increased N\textsubscript{2}O emissions than CH\textsubscript{4}.

The same principles explain the more marked differences in reported changes in emissions intensity under alternative metrics (figure 4(b)). Strategies that involve significantly reducing N inputs from N-intensive farms tend to reduce N\textsubscript{2}O emissions intensity more than CH\textsubscript{4} emissions intensity, and hence the net reduction in emissions intensity is greater under GTP (green oval). The reverse applies, even more poignantly, in a few cases to strategies that increase profitability on low-intensity farms by increasing N inputs (blue oval). This significantly increases N\textsubscript{2}O emissions intensity but simultaneously decreases CH\textsubscript{4} emissions intensity due to the greater productivity per cow. In many cases this results in increased net emissions intensity under both metrics, but the increase is much more pronounced if emissions are weighted using GTP. In some cases, net emissions intensity would appear to decrease if reported using GWP, due to the significant decrease in CH\textsubscript{4} emissions intensity, but would increase if reported using GTP as greater weight is given to the increasing N\textsubscript{2}O emissions intensity (red circle).

4.3. Economic performance under an emissions price

The effect of metric choices on reported emissions, and differing preferences for focusing on reductions of CH\textsubscript{4} or N\textsubscript{2}O, could potentially be amplified if a price was applied to all agricultural greenhouse gas emissions as a policy measure to stimulate abatement. This is in principle considered in the New Zealand Emissions Trading Scheme, although entry of agriculture into the scheme has recently been deferred indefinitely (MfE 2012b).

To test the implications of alternative metrics under an emissions price, we modelled the estimated gross profit margin under carbon prices of NZ$0, 25 and 50 t\textsuperscript{-1} of CO\textsubscript{2}-eq under GWP and GTP, for the six farms studied.

Table 2 shows the relative change in emissions and profitability averaged over the six farms for some example options. Different mitigation strategies have markedly different effects on profit margins and emissions. Eliminating N fertilizer inputs delivers the largest emission reductions under either metric, but in the absence of a carbon price, this also results in the economically worst outcomes. Eliminating N fertilizers becomes economically more effective than maintaining current operations (doing nothing) for carbon prices NZ$25 and NZ$50 per tonne CO\textsubscript{2}-eq, but other mitigation strategies appear much more profitable under any carbon price.
The model suggests that on average across the six farms, profitability could be lifted most significantly by increasing N fertilizer inputs and increasing per-cow milk production. Even though this results in increased greenhouse gas emissions (under either metric), this remains the economically most beneficial ‘mitigation’ strategy at the farm level even if an emissions price as high as NZS50 tCO$_2$-eq$^{-1}$ were applied, in the sense that it results in lowest costs (or greatest gains) to farmers. This holds true independent of the metric. However, the absolute change in profits very clearly depends on the metric: under GTP, increasing N inputs would deliver increased profits even at NZS50 tCO$_2$-eq$^{-1}$, whereas under GWP, profitability would fall below that in the baseline once carbon prices exceed about NZS25 tCO$_2$-eq$^{-1}$.

A similar picture arises from an alternative strategy of reducing the replacement rate of cows, which generally reduces CH$_4$ emissions but has little effect on N$_2$O emissions. However, the average increase in profitability under this management option is lower, and losses start to arise earlier as carbon prices increase. Note that these conclusions apply only to the average across the six case study farms, but do not necessarily hold for each individual farm.

A hypothetical vaccine to reduce enteric CH$_4$ emissions would lower profits by 0–4% in the absence of a carbon price, depending on the cost of the vaccine itself. At a price of NZS50 tCO$_2$-eq$^{-1}$, the vaccine would become more cost effective than doing nothing under GWP for both vaccine cost assumptions. Under GTP, only the cost-free vaccine would be more cost effective than doing nothing, whereas at a cost of NZS50 ha$^{-1}$ yr$^{-1}$ it would as effective as doing nothing, given the lower value placed on avoided CH$_4$ emissions under GTP. These results show that management changes could play at least as important a role in farm-level responses to greenhouse gas pricing as technological mitigation solutions.

In summary, the results shown in table 2 suggest that while different metric choices would significantly impact on overall economic performance of farms, the best management strategies to minimize the effect of an emissions price are virtually independent of the choice of metric. This was confirmed by a detailed analysis of the most profitable mitigation strategy for each individual farm. For five out of six farms, the top most profitable mitigation strategies differed between farms but for each individual farm were independent of the use of GWP or GTP even at an emissions price of NZS50 tCO$_2$-eq$^{-1}$. For the sixth farm, the most profitable mitigation strategy remained unchanged, but the mitigation strategy that was second most profitable under GWP at NZS50 tCO$_2$-eq$^{-1}$ swapped places with the fifth most effective strategy under GTP. Obviously, these results apply only to the six farms studied and implications could differ for other farms in New Zealand. However, given the high robustness of economically optimal mitigation choices both for the average across those six farms and for the farms individually, with their wide range of inputs, productivity and profitability, one may draw some confidence that these results may indeed hold more broadly.

5. Implications and conclusions

The results of our study suggest that alternative greenhouse gas metrics could significantly alter the contribution of different gases to overall (CO$_2$-equivalent) greenhouse gas emissions from current dairy farms, affect the perceived priorities and opportunities for mitigation actions, and the overall cost to farmers if a price were applied to non-CO$_2$ emissions.

Despite these significant implications, most mitigation strategies tested in this study for the six farms change absolute emissions or emissions intensity by only a few percentage points depending on whether GWP or GTP is used to report emissions. In a few cases though, mainly those that reduce N fertilizer inputs from high-intensity farms or that increase N inputs in low-intensity farms, alternative metrics give markedly different results in terms of the scale, and in a few cases even the sign, of the reported change.

The choice of most profitable management strategies, both without and with a price on CO$_2$-equivalent emissions, is surprisingly robust against the choice of metric for each of those six farms. Ironically, the most profitable changes in management for the farms studied here tend to be measures that increase absolute emissions through increased N fertilizer use to increase milk per cow, while emissions intensity is reduced in most but not all of these strategies (and in some cases only if GWP is used, while emissions intensity increases
under GTP). The profitability of a hypothetical vaccine to reduce emissions of enteric CH\textsubscript{4} clearly depends on the relative importance assigned to CH\textsubscript{4} and hence the greenhouse gas metric, but its performance relative to other management strategies across the six farms did not depend on the metric over a wide range of carbon prices.

This study demonstrates that while accurate quantification of greenhouse gas emissions from agriculture is clearly important to ensure accurate inventories, the choice of greenhouse gas metric has a fundamental and in many cases stronger influence on net farm-level emissions when reported as CO\textsubscript{2}-equivalents than the uncertainty in individual emissions factors. However, additional farm systems should be analysed before our conclusions can be scaled up to national or regional levels.

Acknowledgments

This study used data that were originally developed under a Sustainable Farming Fund project, funded by the Ministry for Primary Industries. We are grateful to three anonymous reviewers whose comments helped clarify key points and assumptions.

References

Attwood G T et al 2011 Exploring rumen methanogen genomes to identify targets for methane mitigation strategies Anim. Feed Sci. Technol. 166/167 65–75

Clark H, Brooks I and Walcroft A 2003 Enteric Methane Emissions from New Zealand Ruminants 1990 and 2001 Calculated Using an IPCC Tier 2 Approach (Wellington: Ministry of Agriculture and Forestry)

DairyNZ 2012 DairyBase Statistics (www.dairybase.co.nz, cited December 2012)

Flysjø A et al 2011 The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden Agric. Syst. 104 459–69

Forster P et al 2007 Changes in atmospheric constituents and radiative forcing Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon et al (Cambridge: Cambridge University Press)

Fuglestvedt J S et al 2010 Transport impacts on atmosphere and climate: metrics Atmos. Environ. 44 4648–77

IPCC 1996 Climate Change 1995: The Science of Climate Change. Contribution of WG I to the Second Assessment Report of the Intergovernmental Panel on Climate Change ed J T Houghton et al (Cambridge: Cambridge University Press)

IPCC 2009 Meeting Report of the Expert Meeting on the Science of Alternative Metrics ed G-K Plattner et al (Bern: IPCC WGI Technical Support Unit) p 75

Judge A et al 2010 Greenhouse Gas Emissions from Rotorua Dairy Farms (Wellington: Ministry of Agriculture and Forestry) p 120

Larcombe M T 1999 UDDEr for Windows: A Desktop Dairy Farm for Extension and Research—Operating Manual (Victoria: Maffra Herd Improvement Co-op, Maffra)

Ledgard S F et al 2008 Carbon footprint measurement: carbon footprint for a range of milk suppliers in New Zealand Report to Fonterra (Hamilton: AgResearch) p 41

Ledgard S F et al 2009 Environmental impacts of grazed clover/grass pastures Irish J. Agric. Food Res. 48 209–26

Manne A S and Richels R G 2001 An alternative approach to establishing trade-offs among greenhouse gases Nature 410 675–7

Manning M and Reisinger A 2011 Broader perspectives for comparing different greenhouse gases Proc. R. Soc. A 369 1891–905

McAllister T A et al 2011 Greenhouse gases in animal agriculture—finding a balance between food production and emissions Anim. Feed Sci. Technol. 166/167 1–6

MfE 2012a New Zealand’S Greenhouse Gas Inventory 1990–2010. Submitted to the United Nations Framework Convention on Climate Change (Wellington: Ministry for the Environment) p 408

MfE 2012b Updating the New Zealand Emissions Trading Scheme: A Consultation Document INFO 646 (Wellington: Ministry for the Environment) p 12

Reisinger A et al 2010 Uncertainties of global warming metrics: CO\textsubscript{2} and CH\textsubscript{4} Geophys. Res. Lett. 37 L14707

Reisinger A et al 2012 Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture Clim. Change 117 677–90

Shine K et al 2007 Comparing the climate effect of emissions of short- and long-lived climate agents Phil. Trans. R. Soc. A 365 1903–14

Shine K 2009 The global warming potential—the need for an interdisciplinary retrial Clim. Change 96 467–72

Shine K et al 2005 Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases Clim. Change 68 281–302

Smith P et al 2007 Agriculture Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed B Metz et al (Cambridge: Cambridge University Press)

Smith S J and Wigley M L 2000 Global warming potentials: 1. Climatic implications of emissions reductions Clim. Change 44 445–57

Tol R S J et al 2012 A unifying framework for metrics for aggregating the climate effect of different emissions Environ. Res. Lett. 7 044006

UNFCCC 2009a The Kyoto Protocol (Bonn: Secretariat of the United Nations Framework Convention on Climate Change) (http://unfccc.int/kyoto_protocol/items/2830.php)

UNFCCC 2009b The United Nations Framework Convention on Climate Change (Bonn: Secretariat of the United Nations Framework Convention on Climate Change) (http://unfccc.int/essential_background/convention/items/2627.php)

Yeo B-L et al 2012 Synergies between nutrient and greenhouse gas regulation in the Lake Rotorua Catchment Motu Working Paper (Draft) (Wellington: Motu Economic and Public Policy Research) p 32