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Achieving ambitious climate targets: is it economical for New Zealand to invest in agricultural GHG mitigation?

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Abstract

Reducing agricultural greenhouse gas (GHG) emissions, which contribute approximately 24% of global emissions, is important to efficiently achieve the goals of the Paris Agreement; however, most mitigation options have focused on industrialized, not pastoral farming practices. New Zealand (NZ) has ambitious GHG reduction targets, but biogenic emissions from the agricultural sector are nearly half of total annual emissions and hence must be an integral part of the solution. We use a national-level economic land use model to estimate the benefits and costs of implementing land-based GHG emissions reduction practices that are currently available and/or under development. Results indicate the cost and effectiveness of modeled practices are highly variable, with individual practices capable of reducing gross GHGs by 2% to 62%. Methane inhibitors are estimated to be highly effective but costly, while targeted urine patch treatments are cheap but less effective. Afforestation and methane vaccines cost less than $50/tCO_2e$ and could reduce NZ's GHG emissions by at least 20%. Using a mix of current and emerging mitigation practices to achieve reduction targets ranging from 10% to 50% could cost an average of $14 to $76/tCO_2e$, potentially much less than estimates for achieving similar targets from NZ's energy and transportation sectors. Sensitivity analysis indicates that commercialization of an effective methane vaccine at a cost that is typical of other livestock vaccines is critical to achieving a 50% gross emissions reduction target. Without it, a large portion of land could be left fallow. The practices and technologies evaluated in this paper are not unique to New Zealand and could be adopted globally, thereby helping other nations achieve their climate mitigation goals more cost-effectively.

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions have already begun to cause impacts across all continents. Without additional mitigation and adaptation measures beyond current efforts, there is a high risk of irreversible impacts globally by 2100 (IPCC 2014c). Emissions from agriculture, forestry, and other land uses (primarily from crop and livestock cultivation and deforestation) contribute approximately 24% of global GHG emissions (IPCC 2014b). Current mitigation practices for the agricultural sector primarily focus on farm management practices and efficiency improvements, such as improved fertilizer

management, reduced stocking rates, and conservation tillage; carbon sequestration; afforestation; manure management through covered lagoons and anaerobic digesters; and antimethanogens (Moran *et al* 2011, Archibeque *et al* 2012, Hristov *et al* 2013, Whittle *et al* 2013, Beach *et al* 2015).

Observed climate change impacts in New Zealand (NZ) include melting glaciers, increasing sea and air temperatures, stresses on water supply, and drier soils (Barros *et al* 2014, Ministry for the Environment and Stats NZ 2017). As part of its nationally determined contribution to the Paris Agreement, New Zealand pledged to reduce its annual GHG emissions 30% below 2005 levels by 2030 (11% below 1990 levels)

(Government of New Zealand 2015). The government has also set a 2050 target of reducing emissions 50% below 1990 levels (Government of New Zealand 2011) and currently is considering an even more ambitious 2050 target (Ministry for the Environment 2018). Unusual for a developed country, emissions from the agricultural sector comprise approximately 48% of New Zealand's total GHG emissions (Ministry for the Environment 2019). Meeting the targeted emission reductions will be difficult to near impossible without steep reductions in agricultural emissions (Fernandez and Daigneault 2016).

To reduce GHG emissions, New Zealand implemented an Emissions Trading Scheme (ETS) in 2008 that covers all major sectors of the economy, including forestry (Ministry for the Environment 2009). Although methane (CH_4) and nitrous oxide (N_2O) emissions from agriculture were scheduled for inclusion in 2015, these biological emissions from the agricultural sector were indefinitely excluded in 2012 (Leining and Kerr 2016) amid strong opposition from stakeholders (Cooper and Rosin 2014) and ongoing discussions on how to balance meeting emissions reduction targets without overly burdening farmers or damaging the sector's global competitiveness. In response, the NZ government recently proposed a bill to reduce all GHG emissions (except biogenic methane) to net zero by 2050 and to reduce emissions of biogenic methane within the range of 24%–47% below 2017 levels by 2050, including to 10 per cent below 2017 levels by 2030 (Government of New Zealand 2019).

The agricultural sector is an integral component of the New Zealand economy; dairy, beef, and sheep farming contribute about 8% of the country's GDP and nearly 50% of its exports. (Ministry for Primary Industries 2019, Statistics NZ 2019). As New Zealand eliminated farm subsidies in 1984, the country is a price taker on the international marketplace and thereby particularly sensitive to cost increases and market fluctuations. Key objections to the inclusion of agricultural emissions in the ETS are the lack of effective mitigation technologies and the limited ability of farmers to pass the costs of compliance on to their predominately international customers (Kerr 2016).

Mitigation options for agricultural emissions currently available to New Zealand farmers include improving pastoral efficiency to maximize dry matter yield and quantity (Beukes *et al* 2010); restricting the amount of time animals graze during winter and early spring (Luo *et al* 2013, Romera *et al* 2017), optimized fertilizer use; improved animal health; and feed supplementation to balance diets (Reisinger *et al* 2017). A nitrogen inhibitor, dicyandiamide (DCD, $C_2H_4N_4$), had been available in New Zealand until 2013, when its use was suspended after trace quantities of the chemical were found in milk products. DCD had been applied to pastoral land to reduce both nitrous oxide emissions and nitrate leaching, while simultaneously promoting pasture growth (Gillingham *et al* 2012).

The New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC) in collaboration with the Pastoral Greenhouse Gas Research Consortium (PGgRc) is investing in the research and development of new technologies and practices to reduce methane and nitrous oxide emissions and enhance soil carbon retention. Commercialization and adoption of new mitigation options in New Zealand is expected to occur over the next two to ten years. The mitigation solutions under development include the identification and selective breeding of lower emitting animals (Jonker *et al* 2017); slow-release methane inhibitors (Hristov *et al* 2015, Vyas *et al* 2016) that target methane-producing microbes in the rumen while maintaining efficacy in a pastoral context; and a methane vaccine (NZAGRC 2017, Reisinger *et al* 2018). Another technology under commercial development is the mechanical application of nitrogen inhibitors to urine patches (Bates *et al* 2015).

The purpose of this paper is to establish New Zealand's current agricultural GHG mitigation capacity and examine the potential for emerging technologies to achieve the country's GHG reduction targets. Recent research has been conducted in NZ on farm-scale to national-level mitigation potential (e.g., Smeaton *et al* 2011, Reisinger and Ledgard 2013, Vibart *et al* 2015, Dorner and Kerr 2017, BERG 2018, Dynes *et al* 2018). This paper extends the work by using a dynamic model capable of evaluating the impact of technological innovations on NZ's rural incomes and emissions for a wide array of enterprises.

The issues discussed in this paper extend well beyond NZ and build upon literature on the costs and efficacies of agricultural mitigation across the globe. For example, Lobell *et al* (2013) investigate the impact of agricultural investment on emissons and find that investing in high yielding regions is more effective in mitigation. Valin *et al* (2013) evaluate the effect of crop yields and livestock efficiency in developing countries and conclude that improving livestock productivity could lead to greater reductions in GHGs. Olander *et al* (2013) argue that finding more cost-effective ways to quantify agricultural emissions and abatement will help facilitate the policy discussion on how the sector can better contribute to countries achieving their climate change mitigation targets. Concerns have also been raised about whether targeting the agricultural sector emissions could impact food security (Frank *et al* 2017). This suggests that preferred mitigation practices should ideally be cost-effective and capable of maintaining or enhancing agricultural and animal productivity.

2. Methods

2.1. Agri-environmental land use model
Our analysis uses an agri-environmental economic model based on Daigneault *et al* (2018) to estimate the

economic costs of implementing land-based GHG emissions reduction practices at the national scale in New Zealand between 2015 and 2050. The spatially explicit model is a nonlinear mathematical programming model of New Zealand land use that is delineated at the farm-parcel level. Similar versions of the model have been used to assess GHG mitigation policy (Daigneault *et al* 2018), climate change impacts (Monge *et al* 2018), land restoration (Daigneault *et al* 2017b), erosion control (Fernandez and Daigneault 2017), and nutrient management (Daigneault *et al* 2017a).

In the model, total economic returns from the New Zealand agriculture sector, calculated as annual net farm revenue (π), are measured as:

$$\pi = \sum_{r,s,l,e,m} \{ PA_{r,s,l,e,m} + Y_{r,s,l,e,m} - X_{r,s,l,e,m} \\ \times 3[\omega^{live}_{r,s,l,e,m} + \omega^{vc}_{r,s,l,e,m} + \omega^{fc}_{r,s,l,e,m} + \tau\gamma^{env}_{i,r,s,l,e}] \},$$

$$(1)$$

where **P** is the product output price, **A** is the agricultural product output quantity, **Y** is other gross income earned by landowners (e.g. grazing fees), **X** is the area of specific farm-activity, and ω^{live}, ω^{vc}, ω^{fc} are the respective livestock, variable, and fixed input costs, τ is an environmental tax (if applicable), and γ^{env} is an environmental output coefficient. Summing the revenue and costs of production across all regions (r), soil types (s), land covers (l), enterprises (e), and land management options (m) yields the total net revue for the geographical area of concern. Methods for estimating other costs of implementing land-based GHG mitigation practices are described below.

The model tracks the flow of several environmental factors ($\mathbf{E}_i$) from more than a dozen different land uses, including GHG emissions and sequestration, and freshwater contaminants. Per hectare values are specified via the parameter γ^{env}, and as with economic returns, can vary by region, soil type, land cover, and enterprise. Summing over the area of all land use activities yields the aggregate environmental output from land-based activities for New Zealand:

$$\sum_{r,s,l,e,m} \gamma^{env}_{i,r,s,l,e,m} X_{r,s,l,e,m} = E_i.$$

$$(2)$$

Equation (2) specifies environmental impacts under current land use. In our analysis, we consider applying a range of GHG mitigation practices and/or emissions reduction targets on agricultural sector land. To describe environmental impacts under such a policy, we amend equation (2) to:

$$\sum_{r,s,l,e,m} \{ \gamma'_{i,r,s,l,e,m} (X_{r,s,l,e,m} - Z_{r,s,l,e,m}) \\ + \psi^{env}_{i,r,s,l,e,m} Z_{r,s,l,e,m} \} = E'_i,$$

$$(3)$$

where **Z** is the area of the land in which specific GHG mitigation practices are applied. The parameter γ' specifies the environmental impacts of land use after accounting for the mitigation, while ψ^{env} describes the impact of the practices on the environmental factors. In this paper, we assume that $\gamma' \leqslant \gamma^{env}$, as GHG mitigation practices reduce total environmental effects

by (a) reducing impacts per unit of land use, and (b) through their own biophysical processes that reduce GHG emissions or sequester carbon. The environmental impact after implementing mitigation practices, E'_i, is equal to or smaller than the impact without these practices, E_i, so that the mitigation in impact i achieved by implementing a specified set of mitigation practices is $E_i - E'_i$. As **Z** represents the area that implements on-farm GHG mitigation production, which is typically at an increased cost relative to the industry standard practices, it also has a non-positive effect on the net economic returns estimated in equation (1).

The mitigation potential of implementing farm-specific GHG mitigation is quantified as a percentage change in GHG emissions (or sequestration) relative to a base case in which farms implement the regional industry standard practices for their enterprise (not all practices are suitable for all farms based on their current land use and farming system). There has been extensive research on the range of practices and level of effectiveness of such farm-specific mitigation options in New Zealand for both GHG emissions (Adler *et al* 2013, Reisinger and Ledgard 2013, Vibart *et al* 2015, Dorner and Kerr 2017, Daigneault *et al* 2017b) as well as freshwater contaminants (Manderson *et al* 2007, Monaghan *et al* 2007, Daigneault and Elliot 2017) in addition to the more detailed and updated set presented in this analysis. Most of this literature indicates that effectiveness of a given GHG mitigation practice will depend on factors such as the farm's physical characteristics (e.g. soil, slope, and rainfall), specific practices implemented (e.g. fertilizer regime, stocking, and planting type), and technical expertise. A more detailed description of the model's mathematical formulation, data, and calibration procedure is in the supplementary material, available online at stacks.iop.org/ERL/14/124064/mmedia.

2.2. Mitigation options

This analysis attempts to determine how well New Zealand can meet its emission reduction goals through adopting agricultural mitigation options that are currently available and/or that are under development. Implementing the mitigation options will impose costs on the agricultural sector, and those costs may not be born evenly across farming enterprises. The impact of each option on greenhouse gas emissions are depicted in table 1, and more details on the assumptions related to each are provided in section 2 of the supplementary material. The descriptions include both the effectiveness and costs of each practice to explore the trade-off between achieving mitigation goals and the economic impacts on the agricultural sector.

The practice-based scenarios include each practice individually, and then we bundled practices into three broader categories: (1) mitigation options currently available; (2) emerging mitigation technologies; and

Table 1. Summary of potential agricultural GHG mitigation options.

Mitigation Option	Description	Adoption Challenge	Gross GHG Impact (%/yr)	Average Cost ($/tCO$_2$e)
Base efficiency	Historical trend of improved GHG efficiency of farm management practices by ~1%/year	Very low	−1%	$0
Stock reduction	Reduce herd size by 15% but maintain productivity per hectare because of increased productivity per animal	Very low	−8%	$738
Supplemental feed	Grazing supplemented with low-nitrogen feed such as fodder beet or maize silage	Medium	−2%	$161
Selective breeding	Breed lower emitting animals over time to reduce overall herd GHGs	Medium	−3%	$231
Once-a-day milking	Milk cows only once rather than twice per day, which reduces feed intake and animal productivity	Very low	−2%	$77
N inhibitor	Treat grazed pasture soils with chemical compound that slows conversion of urine to N$_2$O	Low	−8%	$396
CH$_4$ inhibitor	Administer compound via a bolus to lock a portion of enzymatic pathway to restrict methane production	High	−38%	$220
CH$_4$ inhibitor - high eff	Administer with a slow release mechanism that enables greater reduction in methane production than standard inhibitor	Very high	−46%	$219
Urine patch treatment	Mechanically treat grazed pasture with application of a nitrogen inhibitor to urine patches	Very low	−2%	$2
CH$_4$ vaccine	Administer vaccine that induces antibodies to suppress methanogen growth	Very high	−20%	$20
Organic conversion	Convert using practices that restrict fertilizer application, establishes riparian setbacks, and improves animal productivity	Medium	−19%	$82
Afforestation − 0.5 Mha	Plant trees on marginal land; limited to 0.5 Mha across NZ	Very low	−3%	$15
Afforestation − 1.0 Mha	Plant trees on marginal land; limited to 1.0 Mha across NZ	Low	−7%	$15
Current combo	Jointly implement the current mitigation practices: supplemental feed, selective breeding, and N inhibitors	Low	−20%	$94
Future combo 1	Jointly implement a combination of future mitigation practices: CH$_4$ inhibitor, CH$_4$ vaccine, and N inhibitor	Med-high	−51%	$204
Future combo 2	Same as 'Future Combo 1' mitigation bundle but excludes the costly CH$_4$ inhibitor	Medium	−31%	$68
Future combo 1–high efficiency (HE)	Jointly implement CH$_4$ inhibitor, CH$_4$ vaccine, and N inhibitor that have the theoretically maximum mitigation potential but a higher cost	Very high	−62%	$338
Future combo 2–high efficiency (HE)	Same as 'Future Combo 1–HE' mitigation bundle but excludes the costly CH$_4$ inhibitor	High	−55%	$145

(3) emerging mitigation technologies that achieve high effectiveness. Table 1 identifies the practices considered in this analysis, summarized by ease of adoption, maximum mitigation potential if adopted by all eligible farms in NZ, and the average mitigation cost.

2.3. Policy scenarios

This analysis investigates a range of policy scenarios that were compared against a no mitigation baseline land use and emissions scenario to assess both how the costs to New Zealand varied with different domestic GHG emissions reduction targets and the optimal mix of practices to achieve that target. The first set of scenarios are practice-based, which estimate the technical potential that each individual practice could achieve. The second set are target-based, where the agri-environmental model is constrained to achieve a gross GHG limit at least cost in 10% reduction increments.

2.4. Sensitivity analysis

As the emerging technologies are still under development and will not likely be commercialized for at least 7–10 years, there is high uncertainty about both the overall effectiveness they achieve and their cost. To address this uncertainty, we performed a sensitivity analysis for the methane inhibitor and vaccine that includes a range of efficacies and costs, which are listed in table S3. These ranges are based on values currently found in published literature (e.g. Cotter *et al* 2015, Reisinger *et al* 2018). Note that most of the baseline assumptions fall into the mid-range of estimates, with the exception of the CH_4 vaccine cost, which is based on recent research specifically from the region (Cotter *et al* 2015). In addition, we performed sensitivity analyzes to isolate the potential effect that excluding afforestation and the composition of the future mitigation bundles may have on the cost of meeting mitigation targets.

3. Results

3.1. Baseline

The agri-environmental land use model baseline is calibrated to empirical estimates of NZ land use, stock numbers, productivity, net farm returns, and GHG emissions from 2015. The recursive-dynamic model is then run to 2050 in 5 year time steps, following historical trends in land productivity, animal numbers, and GHG emission intensities but holding land use area and financial returns fixed. As a result, we estimate that in 2050, NZ's 26.3 Mha will produce $11.7 billion of net farm returns, 34.2 $MtCO_2e$ of gross GHG emissions, and 24.8 $MtCO_2e$ of forest carbon sequestration, thereby resulting in 9.4 $MtCO_2e$ of net GHG emissions (table 2). A bulk of the economic returns and gross emissions are estimated to be produced by the dairy, sheep, and beef sectors (80%

Table 2. New Zealand 2050 baseline estimates by major land use.

Land use	Area (Mha)	Net revenue (Mil $)	Gross GHG ($MtCO_2e$)	Net GHG ($MtCO_2$-e)
Dairy	1.7	$6374	12.8	12.8
Sheep-Beef	8.6	$3007	20.1	20.1
Deer	0.2	$237	0.8	0.8
Forest	2.1	$833	0.0	−19.1
Arable + Hort	0.4	$1198	0.5	0.5
Native	7.4	$0	0.0	−3.2
Other	5.9	$66	0.0	−2.5
NZ Total	26.3	$11 715	34.2	9.4

and 96%, respectively). All of the mitigation scenarios are measured against this no mitigation baseline.

3.2. Practice-based scenarios

The practice based scenarios focused on estimating the relative cost and effectiveness if all eligible landowners implemented a specific set of GHG mitigation practices. Results indicate that there is a large spread in both the cost and effectiveness of various practices modeled for this analysis (table 3), with practices producing total gross GHG mitigation estimates ranging from 0.5 to 21.0 $MtCO_2e$/yr, or a 2% to 62% reduction from the baseline. However, the cost of individual practices can vary in magnitude, thereby having an important effect on likelihood of implementation. For example, CH_4 inhibitors are estimated to be highly effective as they could reduce agricultural GHGs by 38%–46%, but at an average cost of $220/$tCO_2e$, they are more expensive than 75% of the options considered. On the other hand, using targeted urine patch treatments on flat pasture only costs $2/$tCO_2e$ but has a minimal impact on total agricultural GHGs because it can only mitigate N_2O from dairy farms. Practices with costs of $50/$tCO_2e$ or less that could reduce NZ's GHG emissions by at least 20% compared to the baseline include afforestation and the methane vaccine. Furthermore, we estimate that organic farming and all of the mitigation practice combination bundles that do not include the CH_4 inhibitor could reduce emissions by at least another 20% but cost in the range of $50 to $100/$tCO_2e$. All of the other practices are estimated to cost more than $100/$tCO_2e$ or are not large enough in scope to reduce agricultural emissions by more than 5%. However, collectively, if farmers implement several practices on their land with abatement costs of under $100/$tCO_2e$, then they have the potential to reduce nearly all of the country's baseline GHG emissions (figure 1).

Additional analysis indicates that the sheep and beef sector would bear the majority of estimated costs from the mitigation options (figure S1 is available online at stacks.iop.org/ERL/14/124064/mmedia). While this is logical given the total area and emissions that the sector produces, it is also not nearly as profitable as the dairy or deer sectors. Thus, many New

Table 3. Estimated impacts of NZ practice-based scenarios relative to no mitigation baseline, 2050.

Practice	Annual Mit. Cost (mil $)	Gross GHG Mit. (MtCO$_2$e)	Average Mit. Cost ($/tCO$_2$e)
Stock reduction	$1893	2.56	$738
Supplemental feed	$88	0.55	$161
Selective breeding	$259	1.12	$231
Once a day milking	$63	0.82	$77
N inhibitor	$1137	2.87	$396
CH$_4$ inhibitor	$2826	12.87	$220
CH$_4$ inhibitor - hi eff	$3445	15.74	$219
Urine patch treatment	$1	0.61	$2
CH$_4$ vaccine	$136	6.74	$20
Organic conversion	$526	6.44	$82
Afforestation — 0.5 Mha	$17	8.67	$15
Afforestation — 1.0 Mha	$34	17.34	$15
Current combo	$638	6.75	$94
Future combo 1	$3546	17.35	$204
Future combo 2	$719	10.53	$68
Future combo 1 + high Efficiency	$7117	21.03	$338
Future combo 2 + high Efficiency	$2740	18.88	$145

Zealand farmers could find it difficult to remain viable without additional compensation.

3.3. Target-based scenarios

The target-based scenarios analyzed the potential impacts of achieving specific GHG reduction goals but allowed farmers to collectively select the optimal mix of practices at least possible cost. To estimate this, we ran the model at 10% reduction increments, up until gross agricultural GHG emission targets were 90% below the 2050 baseline.

Average and marginal abatement costs increase nonlinearly with more stringent targets, as expected (table 4, figure 2). The degree that practices are implemented also closely follows findings from the practice-based scenarios: low-cost options such as afforestation, organic farming and administering the CH$_4$ vaccine to dairy cows are implemented until their total mitigation potential is exhausted (up to 30% reduction). After that, more farmers move towards administering the vaccine to sheep and beef; adopting bundles of mitigation practices on dairy farms, specifically the high efficiency combination of the CH$_4$ vaccine and N inhibitor; and leaving some of the least productive pasture fallow (40%–60% reduction). For a 70% reduction in gross GHGs, a majority of the target could be achieved if all pastoral farmers adopted a mix of high efficiency combinations of future practices, afforestation, or stock exclusion; however about 5.5 Mha

of pasture would also have to be left fallow. Once the target reaches 80% reduction below the baseline, at least 7 Mha of NZ's pasture used for sheep and beef may become fallow because all of the more cost-effective options are exhausted. Interestingly, dairy farmers only adopt the more costly but effective mitigation combo that includes both the vaccine and CH$_4$ inhibitor for the most stringent target (90% reduction). As with the practice-based scenarios, at least two-thirds of the costs, on average, are incurred by sheep and beef farmers.

The average costs of achieving a gross GHG reduction target of 10% to 50% range from $14 to $76/tCO$_2$e, while the marginal costs for the same targets are between $15 and $162/tCO$_2$e. These figures are well within the range of estimates of achieving low emissions pathways and arguably are on the lower side of estimated costs for NZ's energy and transportation costs to meet similar GHG targets (Ballingall and Pambudi 2018, Vivid Economics *et al* 2018). Thus, it appears that if emerging mitigation technologies realize their potential in the next 30 years, then NZ agriculture could be a major source of mitigation.

Setting national targets that focus on reducing gross agricultural GHG emission also has a strong effect on net GHGs. This is because afforestation of a mix of pine plantations and native trees has the potential to increase forest carbon sequestration by an average of 17 tCO$_2$e/ha/yr, and nearly all scenarios result in planting the maximum 1 Mha on marginal pasture land. As a result, NZ's land use sector could have net zero GHG emissions even if gross agricultural GHG mitigation targets are relatively low.

3.4. Sensitivity analysis

Detailed sensitivity analysis highlights the relative effect that key assumptions such as the cost and effectiveness (C/E) of emerging technologies have on the results. For this study, we conducted the following scenarios to evaluate the potential range of impacts of achieving a 50% agricultural GHG reduction target:

- Scen 0: Original assumptions.

- Scen 1: No Highly Effective combo.

- Scen 2: Current practices only.

- Scen 3: Low CH$_4$ inhibitor and vaccine C/E.

- Scen 4: Medium CH$_4$ inhibitor and vaccine C/E.

- Scen 5: High CH$_4$ inhibitor and vaccine C/E

- Scen 6: High CH$_4$ inhibitor and vaccine C, low E.

- Scen 7: Low CH$_4$ inhibitor and vaccine C, high E.

- Scen 8: No afforestation.

- Scen 9: Future practices only.
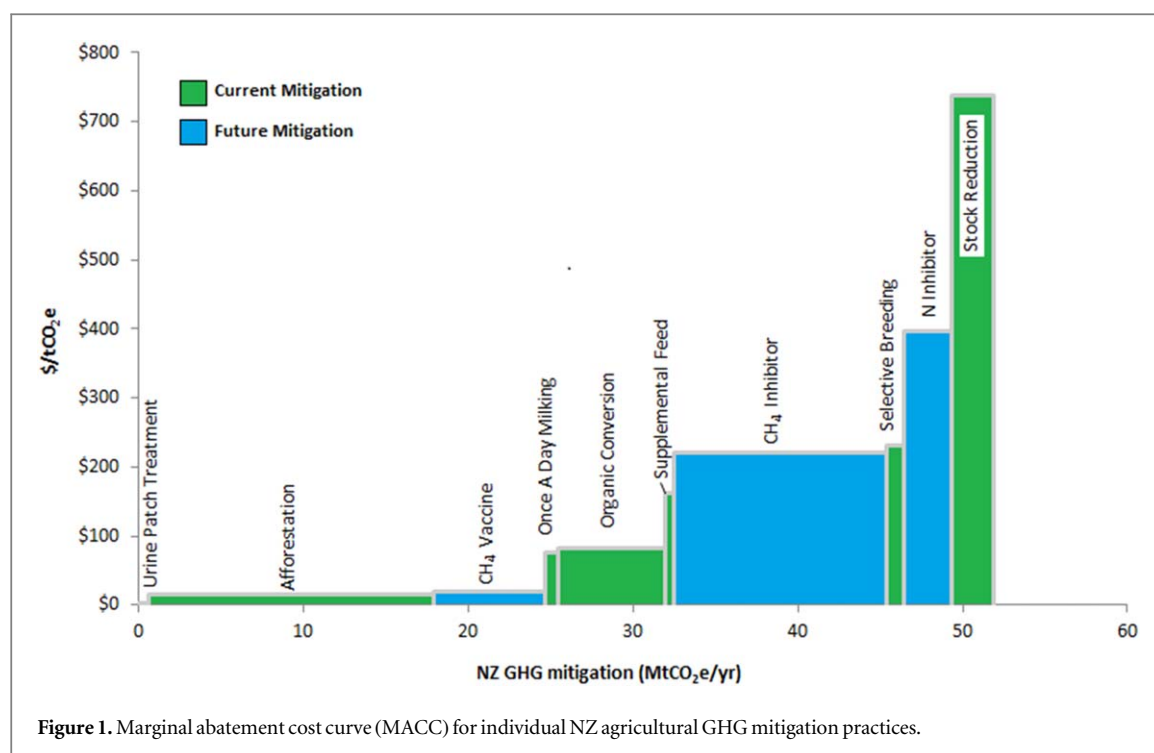
- Scen 10: Fallow land only.

Figure 1. Marginal abatement cost curve (MACC) for individual NZ agricultural GHG mitigation practices.

Note that all but Scen 0 excluded the 'future with high efficiency' mitigation combinations because of the large uncertainty about whether the optimistic reduction potential could technically be achieved. Estimates indicate that both the total cost of the policy and the distribution of practices employed to achieve the target are indeed sensitive to the model assumptions, particularly if the CH_4 vaccine costs are closer to the medium to high range (figure 3, table S4). In this case, landowners would no longer choose to administer the vaccine but instead would convert to organic, employ more costly mitigation combos, or let some of their land go fallow. In addition, if afforestation is not considered a feasible option but the CH_4 vaccine was still relatively cheap (Scen 8), then farmers would likely administer a mix of emerging mitigation options to achieve the 50% target. Encouraging farmers to implement a suite of current and emerging practices will reduce the cost of meeting a 50% reduction target by at least 31% ($790 million yr^{-1}) compared to the scenario where the only option is to let land go fallow (Scen 10). Interestingly, restricting mitigation practices to just emerging technologies could actually cost more than all other sensitivity cases (Scen 9), primarily because of the high cost of the CH_4 inhibitor. However, if these options can be develeloped at relatively low cost and be highly efficient (Scen 7), then the 50% GHG reduction target could be achieved for about $375 million yr^{-1}, equivalent to a 3% reduction from the baseline, and 71% less costly than Scen 0.
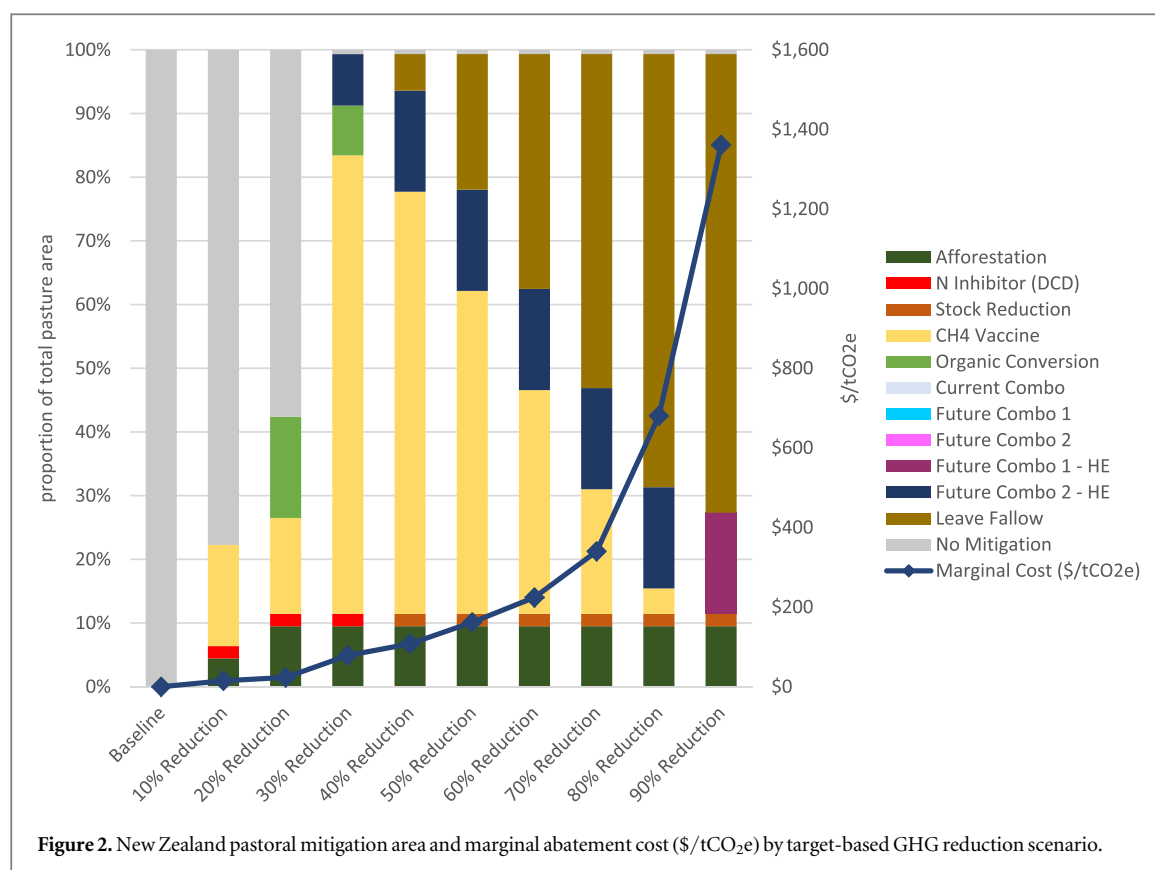
4. Discussion and policy implications

New Zealand's government currently has a goal of reducing total net emissions 50% below 1990 levels by 2050 and is considering a bill that reduces all GHG emissions (except biogenic methane) to net zero by 2050. We estimate that New Zealand's agricultural sector can contribute to meeting these emissions reduction goals, even with the currently available mitigation options, particularly if afforestation of 1 Mha is included and large areas of marginal land are left fallow. Afforestation combined with a 10% reduction in gross agricultural GHG could also result in net zero emissions, suggesting that NZ's land use sector can make a strong contribution to the country's aggregate mitigation targets. However, the costs of achieving this policy are not spread evenly across landowners. Net revenue remains relatively steady for the dairy industry until an 80% emission reduction target (after which more expensive but highly effective options are necessary), but the policy could have a more profound negative economic impact on the sheep and beef industries.

Our modeled scenarios demonstrate that emerging technologies whose development is currently funded by the government are critical to achieving significant reductions at reasonable costs. As the inhibitor and vaccines are still under development, there is considerable uncertainty about their market prices. The sensitivity analysis indicates that commercialization of an effective methane vaccine at a cost that is typical of other livestock vaccines can greatly reduce costs in the sheep and beef industries and is critical to achieving a 50% reduction target. A rush to commerciicialization of less effective technolgies could preclude achieving the substantial cost-savings of these more ambitious technologies. If cost-effective technolgies are not developed, a large portion of land could be left fallow. Moreover, the costs could more than double,
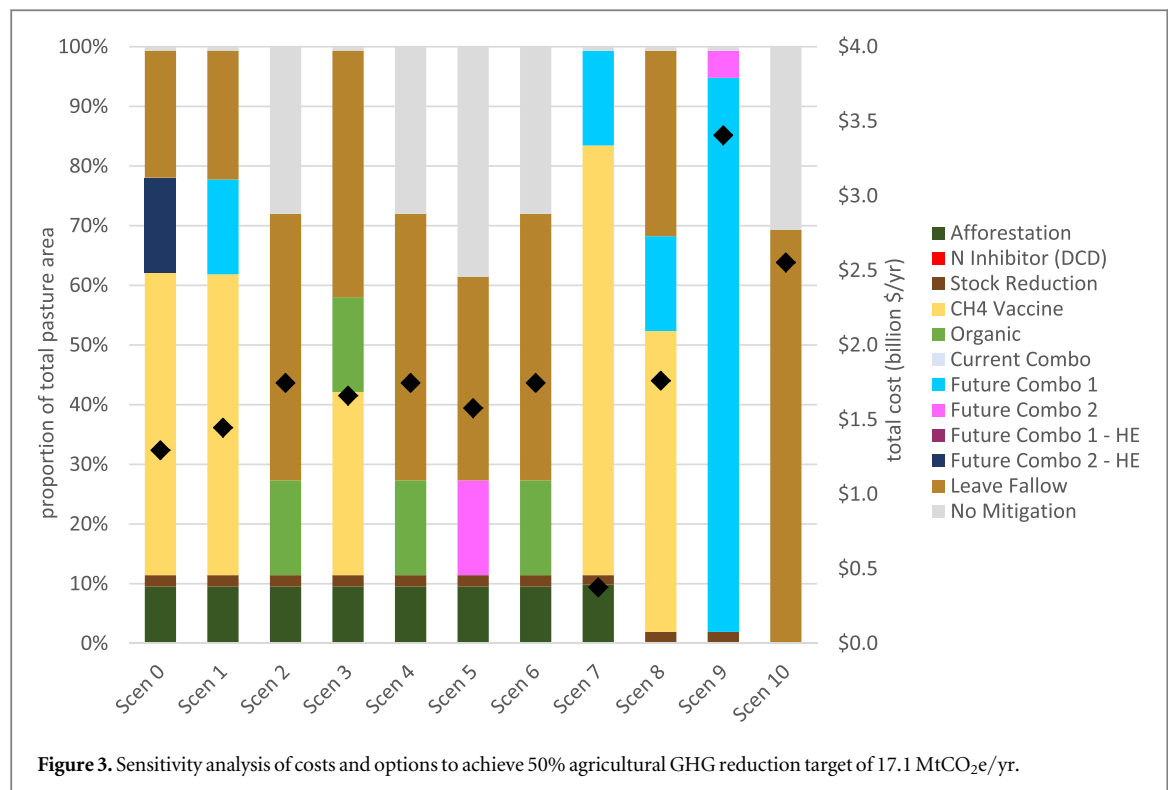
Figure 2. New Zealand pastoral mitigation area and marginal abatement cost ($/tCO₂e) by target-based GHG reduction scenario.

Table 4. Estimated impacts of NZ target-based scenarios relative to no mitigation baseline, 2050.

Target Scenario	Annual GHG Mit. Cost (mil $)	Gross GHGs (MtCO₂e)	Net GHGs (MtCO₂e)	Average Gross GHG Mit. Cost ($/tCO₂e)
Baseline	$0	34.2	9.4	$0
10% Reduction	$48	30.8	−1.1	$14
20% Reduction	$116	27.3	−12.5	$17
30% Reduction	$367	23.9	−14.8	$36
40% Reduction	$741	20.5	−19.3	$54
50% Reduction	$1295	17.1	−22.7	$76
60% Reduction	$1848	13.7	−26.1	$90
70% Reduction	$2402	10.3	−29.5	$100
80% Reduction	$2956	6.8	−33.0	$108
90% Reduction	$4922	3.4	−36.4	$160

and technological development would become more imperative if afforestation is not included as a mitigation option. Continued investment by the government in research and development can translate into substantial cost reduction for the agricultural sector if those efforts are successful.

Although successful research and development could lead to substantial cost savings in achieving New Zealand's ambitious targets, there are numerous challenges. The emerging technologies have shown promise in early trials; nonetheless, important questions remain about the potential health impacts of altering the gut microbiome of ruminants, the delivery mechanism for a slow-release inhibitor, whether the higher theoretical efficacies can be achieved, and if the policy environment will be conducive to widespread uptake.

Similarly important is the necessity of these technologies achieving full market penetration. Corner solutions such as the unwillingness of farmers to adopt new and unfamiliar practices are belied by the results of Brown and Roper (2017) who found that New Zealand farmers are more willing to adopt new technologies if they are demonstrated within farmer networks. Gawith (2018) further proposed potential remediation tools to addresss the adaptation constraints faced by New Zealand farmers, such as addressing the minimum cash flow constraint by providing public and/or private finance schemes for new forestry enterprises and using estabished fora to transfer new technological information. Additional research explores methods to empirically quantify these constraints during the policy-making process (Gawith and

Figure 3. Sensitivity analysis of costs and options to achieve 50% agricultural GHG reduction target of 17.1 $MtCO_2e$/yr.

Hodge 2018). Moreover, the government may wish to promote the public's acceptance of the ambitious targets by pursuing policies that alleviate some of the economic burden born by sheep and beef farmers.

Methane and nitrous oxide emissions from livestock production globally must be reduced to achieve the goals of the Paris Agreement (Wollenberg *et al* 2016); however, most mitigation options have been developed for industrialized farming practices (Hristov *et al* 2013, Herrero *et al* 2016) that are typical of the United States and Europe. Our abatement costs—which range from $10 to 200/$MtCO_2e$ depending on the mitigation target and mitigation practices included in the anlaysis—are within the range of similar studies (Vermont and De Cara 2010). These include MACC-based studies from Ireland (O'Brien *et al* 2014), the United Kingdom (Moran *et al* 2011), France (Pellerin *et al* 2017), and the world (Beach *et al* 2015) as well as model-based studies from the United States (Schneider and McCarl 2006), France (Mosnier *et al* 2019), Europe (Bellarby *et al* 2013), and NZ (Reisinger *et al* 2017, Djanibekov *et al* 2018). However, nearly all of these studies only assumed that current mitigation technologies were available, and thus achieved a lower percentage of total GHG abatement relative to our analysis.

Despite the minimal effect New Zealand reaching its targets will have on the global carbon budget, the country can serve as a model for reducing agricultural emissions in a pastoral context through its successful development of mitigation technologies. These effective technologies could be adopted in primarily developing economics whose agricultural system is also pastoral but that have higher total biological agricultural emissions, such as Brazil, Argentina, and India, as well as elsewhere in the developed world (Caro *et al* 2014). The continued investment of the New Zealand government in research and development could therefore play a much larger role in realizing the ambition of the Paris Agreement.

Author contributions

JC developed the research idea. JC and AD developed the methodological framework. AD conducted the model simulations. JC and AD drafted the manuscript.

Data Availability

Any data that support the findings of this study are included within the article. Additional data and model code related to this paper are available from the corresponding author upon reasonable request.

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