A double win: new pathways to reduce greenhouse gas emissions and improve water quality in New Zealand

Mario A Fernandez1,2 and Adam J Daigneault3

1 Research and Monitoring Unit, Auckland Council, Auckland, New Zealand
2 ESAl Business School, Universidad Espiritu Santo, Guayaquil, Ecuador
3 School of Forest Resources, University of Maine, Orono, ME, United States of America

E-mail: adam.daigneault@maine.edu

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Abstract

This paper explores potential land-sector policies and practices that could help meet New Zealand’s 2030 Paris Agreement target of reducing their greenhouse gas emissions by 30% from 2005 levels while simultaneously achieving improvements in freshwater quality. We use an integrated model of the country’s agricultural and forestry sectors to explore the economic and environmental outcomes for 21 freshwater and climate change policy alternatives and mitigation target scenarios. The agri-environmental model estimates are then included in a multidimensional decision space framework that incorporates the risk attitude of policy-makers and uses an ordered weighting average model to evaluate potential policy pathways. We find policies that feature afforestation of marginal land are often preferred over because they provide a range of co-benefits such as carbon sequestration and reduced sedimentation and nutrient loss at relatively low cost. On the contrary, policies that only target a specific practice or pollutant are often less preferred because they fail to provide ample spill overs relative to their cost savings.

1. Introduction

It can be costly and complex for nations to achieve the greenhouse gas (GHG) reduction commitments of the Paris Agreement (PA). Though the range of GHG mitigation alternatives may appear broad in principle (Grassi et al. 2017), policy-making in practice reveals that transaction, coordination and operation costs may outweigh the benefits of achieving GHG reductions or other environmental goals. In addition there is often a lag associated with policy implementation and operation (Brown et al. 2019).

Emissions markets have been championed as the leading cost-efficient mitigation alternative (Reeling et al. 2018), where their expansion and linking with foreign emissions markets may open the door to an even greater pool of mitigation alternatives to non-energy sectors in particular (Doda and Taschini 2017). Despite promises of cost minimization and flexibility, emissions markets may not necessarily be welfare-enhancing for all countries because of market distortions, terms-of-trade effects, and imported volatility (Anger 2008, Flachsland et al. 2009, Fernandez and Daigneault 2018, Schneider and La Hoz Theuer 2019). Additionally, the diversity of nationally determined contributions (NDC) targets and lack of international oversight could pose challenges that may increase the range and complexity of emissions market mechanisms (Schneider and La Hoz Theuer 2019). Moreover, the sharing of the burden of mitigation efforts may not be equitable (conditional on the economic composition of a country), and political opposition may rise against climate policies seeking to meet the PA commitments.

New Zealand (NZ) is an open and small economy that committed to a reduction target of 30% below 2005 levels by 2030, (i.e. 34.9 million metric tonnes of carbon dioxide equivalent (MtCO2e)) (Ministry for the Environment 2015), and 80% or more by 2050 (Ministry for the Environment 2019b). The country has a unique profile amongst developed countries because agriculture contributes to nearly 15% of GDP (Ministry for Primary Industries 2019) and is responsible for nearly 50% of NZ’s gross emissions (Ministry for the Environment 2019a). Land use, land use change and forestry sequesters 1 to
24 MtCO$_2$e yr$^{-1}$, thereby offsetting about 30% of NZ's gross emissions (Ministry for the Environment 2019a). A large share of electricity generation (nearly 80%) comes from renewable sources, and agriculture is currently not covered by the domestic emissions market. Therefore, the burden of the GHG mitigation effort is carried by the energy and manufacturing sectors with limited flexibility to introduce further mitigation potential (Ministry for the Environment 2019a).

Natural climate solutions (NCS) and improved land stewardship are mentioned as alternatives to overcome ineflexibilities and to increase the likelihood of meeting the PA commitments (Griscom et al. 2017, Anderson et al. 2019). The NCS may operate in tandem with emissions markets and add value to climate policy because of their associated secondary benefits (e.g. water filtration, flood buffering, soil health, and biodiversity habitat) (Townsend et al. 2012, Griscom et al. 2017, Turner 2018). For example, in addition to reducing agricultural GHG emissions and enhancing forest carbon sequestration (FCS), NZ is also designing strategies to limit freshwater contaminants—specifically nitrogen (N), phosphorous (P), E.coli and sediment (S)—in catchments throughout the country. Some of those strategies include some degree of tree-planting, which opens the door for the simultaneous management of air and freshwater pollutants (Reeling et al. 2018). While FCS may contribute a significantly to reducing NZ's freshwater contaminants and ability to cost-effectively meet the PA target by 2030, tree-planting becomes even more relevant as it can potentially reduce the reliance on linking NZ's domestic emissions market with foreign ones (Fernandez and Daigneault 2018). This approach can also help avoid the price volatility of the emissions permits that has recently affected the profitability of commercial forestry (Adams and Turner, 2012; Bryan et al. 2015, Evison 2017, Manley 2017).

Decision-making with respect to land management can become complex given the diverse goals of broad environmental and land use policy; e.g. mitigating GHG emissions and/or any (combination) of the freshwater contaminants. Hence, the purpose of this paper is twofold: First, to utilize an economic land use model to assess the market and environmental outcomes from 21 distinct policies intended to mitigate the flow of non-point source contaminants to NZ's waterways and/or reduce the country's land-based GHG emissions. Second, to use a quantitative framework to construct and evaluate the multidimensional policy decision space focusing on improving land management. This methodology can assist decision-makers in selecting the ‘most appropriate’ policy approach, even when there is policy uncertainty or individual goals may vary. The key contribution of this paper is to provide economic and decision-making inputs for the design of climate and freshwater policy packages that support NZ on cost-effectively meeting its PA commitments. While the application is specific to NZ, the methodology and implications are applicable to evaluating the efficiency and effectiveness of implementing multi-objective environmental policies across the globe.

2. Methods

We use an integrated NZ-wide land use sector model to estimate the economic and environmental impacts of policy options (scenarios) in table 1, which can be achieved through a broad set land-based mitigation practices ranging from afforestation to improved effluent management. The policy options simulated in this paper have been historically adopted by NZ farmers to minimise compliance costs with environmental regulations (Vibart et al. 2015, Shephard et al. 2016, Fernandez 2017, Fernandez and Daigneault 2017, BERG 2018). Table S1 (stacks.iop.org/ERL/15/074004/mmmedia) in the supplementary material shows the annualized costs and effectiveness rates of those policies by contaminant and agricultural enterprise. The model tracks changes in land cover, enterprise distribution, and land management for more than 20 different land uses, cost of policy scenarios (calculated as the difference between net farm revenue under the baseline and each scenario), GHG mitigation from agriculture and FCS (in MtCO$_2$e), and percentage changes on N leaching, P losses, E.coli loads and sediment runoff to waterways (Daigneault et al. 2018). The policy options are established at a national level and modelled at the catchment-scale for all of NZ.

Target-based scenarios in table 1 set a reduction target on at least one of the water contaminants and/or GHG emissions. Some of these scenarios vary with regards to whether afforestation can be undertaken as a specific mitigation alternative. Other mitigation alternatives consist of a range of on-farm practices such as stock exclusion, wetland construction, or planting riparian buffers (table S2). Afforestation involves the conversion of baseline land use to pine plantations, estimated to be feasible up to 2 million additional hectares, or about double what is currently planted in NZ (BERG 2018). Erosion-based scenarios (focused on sedimentation) consist of the adoption of management plans for HEL with erosion rates greater than specific thresholds that range in severity (table S3). Lastly, the stock-management scenarios consist of excluding stock by fencing of all pastoral streams, where fencing may be expanded with 5 m of riparian planting with native vegetation along stream banks.

For meaningful interpretations of our scenarios analysis, we use the analysis of Fernandez and Daigneault (2018) as a reference of the cost to achieve NZ’s 2030 PA target. In this context, we assume that the NZ emissions market is a purely domestic policy (i.e. no international trading of GHG permits or offsets) to achieve a PA target of reducing net emissions
Table 1. Policy alternatives (scenarios) to improve freshwater quality.

| Approach            | Scenario | Scenario description                                      |
|---------------------|----------|----------------------------------------------------------|
| A                   | Reduce gross GHGs by 30%—mitigation + afforestation |
| B                   | Reduce gross GHGs by 30%—mitigation only               |
| C                   | Reduce all four contaminants by 30%—mitigation + afforestation |
| D                   | Reduce all four contaminants by 30%—mitigation only   |
| E                   | Reduce gross GHGs and all 4 contaminants by 30%—mitigation + afforestation |
| F                   | Reduce gross GHGs and all 4 contaminants by 30%—mitigation only |
| G                   | Reduce N by 30%—all mitigation + afforestation         |
| H                   | Reduce N by 30%—all mitigation                         |
| I                   | Reduce P by 30%—all mitigation + afforestation         |
| J                   | Reduce P by 30%—all mitigation                         |
| K                   | Reduce sediment by 30%—all mitigation + afforestation  |
| L                   | Reduce sediment by 30%—all mitigation                  |
| M                   | Reduce E. coli by 30%—all mitigation + Afforestation   |
| N                   | Reduce E. coli by 30%—all mitigation                    |
| O                   | Highly Erodible Land (HEL) Management Plan 1 t ha\(^{-1}\) |
| P                   | HEL Management Plan 3 t ha\(^{-1}\)                    |
| Q                   | HEL Management Plan 5 t ha\(^{-1}\)                    |
| R                   | HEL Management Plan 10 t ha\(^{-1}\)                   |
| S                   | HEL Management Plan 20 t ha\(^{-1}\)                   |
| T                   | Stock exclusion with 1 m stream buffer                  |
| U                   | Stock exclusion with 5 m riparian planting              |

*Afforestation is only a mitigation option in scenarios that clearly list it in the scenario description.*

(gross GHGs less sequestration) by 34.9 MtCO\(_2\)e. GHG abatement can be achieved through a mix of reductions in all sectors of NZ’s economy, including land use. Nonetheless, agricultural GHGs are not priced in the emissions market. Based on this approach, Fernandez and Daigneault (2018) estimate that 13.2 MtCO\(_2\)e could be abated from domestic sources (8.6 from energy and transport, 0.1 from agriculture and 4.5 from value-added sectors), with the remaining 21.7 MtCO\(_2\)e occurring through additional forestry sequestration.

There are seven dimensions to consider in each policy scenario: policy costs, agricultural GHG emissions, freshwater contaminants (sedimentation, E. Coli, N leaching, and P loss), and FCS. As decision-making about the most appropriate policy package becomes complex, we link the land use model output with an ordered weighting average (OWA) model, which summarizes the multidimensionality of the problem at hand and incorporates the risk attitude of policy-makers toward the set of choices (Yäger 1988, Javidi Sabbaghian et al 2016, Machado and Ratick 2017, Runfola et al 2017). The purpose of the modelling exercise is to identify which of the policies in table 1 are more convenient to address environmental targets at a national level.

2.1. Agri-environmental land use model

We use an agri-environmental economic model based on Daigneault et al (2018) to estimate the GHG and freshwater benefits as well as the economic costs of implementing land-based emissions reduction practices at the national scale in NZ. The spatially explicit model is a non-linear, partial equilibrium mathematical programming model that is spatially delineated at the farm-parcel level. Similar versions of the model have been used to assess GHG mitigation policy (Carroll and Daigneault 2019), climate-change impacts (Monge et al 2018), land restoration (Daigneault and Elliot 2017), erosion control (Fernandez and Daigneault 2017), and nutrient management (Daigneault et al 2017).

In the model, total economic returns from the NZ land-use sector, calculated as annual net farm revenue (\(\pi\)), are measured as:

\[
\pi = \sum_{r,s,l,e,m} \left\{ PA_{r,s,l,e,m} + Y_{r,s,l,e,m} - X_{r,s,l,e,m} \left[ \omega_{lw} \right] + \omega_{lw} \right\} \tag{1}
\]

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 \(\omega_{lw}, \omega_{lw}, \omega_{lw}\) are the respective livestock, variable, and fixed input costs, \(\tau\) is an environmental tax (if applicable), and \(\gamma_{mw}\) 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 revenue 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 (E) (i = N leaching, P loss, E. Coli, erosion and GHG emissions) from 20 different land uses. Per hectare values are specified via the parameter
γ_{env}^\gamma\text{, 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:}

\[ \sum_{r,s,l,e,m} \gamma_{i,r,s,l,e,m} X_{r,s,l,e,m} = E_i \]  

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

\[ \sum_{r,s,l,e,m} \gamma'_{i,r,s,l,e,m} (X_{r,s,l,e,m} - Z_{r,s,l,e,m}) + \psi_{i,r,s,l,e,m} Z_{r,s,l,e,m} = E_i' \]  

(3)

where \( Z \) is the area of the land in which specific mitigation practices are applied. The parameter \( \gamma' \) specifies the environmental impacts of land use after accounting for the mitigation, while \( \psi_{env}' \) describes the impact of the practices on the environmental factors. In this paper, we assume that \( \gamma' \leq \gamma_{env} \), as mitigation practices reduce environmental effects by a) reducing impacts per unit of land use, and b) through their own biophysical processes that reduce 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 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 potential of implementing farm-specific mitigation is quantified as a percentage change in GHG, freshwater contaminants, and FCS relative to a base case in which farms implement the regional industry standard practices for their enterprise (table S2). There has been in NZ extensive research on mitigation practices and their effectiveness for both GHG emissions (Adler et al 2013, Reisinger and Ledgard 2013, Vibart et al 2015, Daigneault et al 2017, Dorner and Kerr 2017) and freshwater contaminants (Monaghan et al 2007, Manderson et al 2007, Daigneault and Elliot 2017). The model in our analysis develops a detailed and updated set of practices where their effectiveness vary accordingly to 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.

2.2. The ordered weighting approach

Selecting the optimal or most cost-effective policy is complex because of the seven dimensions of concern, which are summarised in the 21 policy scenarios in Table 1. The perspective of the paper may be viewed as a decision-maker having to optimize the allocation of a limited budget across a set of environmental goals, conditional to the economic structure of the country and the availability of policy instruments. Decision-making may then rely on choosing the policy package with the lowest cost, or the highest GHG mitigation or any other combination of policy goals. To address such multidimensionality and to narrow down the decision space, we feed the output (from the agri-environmental model) of the seven policy dimensions in the 21 scenarios into the OWA model.

The OWA is a parameterized family of aggregation operators that incorporates the risk attitude of decision-makers and the trade-off between dimensions (or decision criteria) (Yager 1988, Jiang and Eastman 2006; Romano et al, 2015). The trade-off represents the degree to which a weak performance in any dimension can be upgraded or compensated by other stronger ones (Majlender, 2005). The OWA, rather than attributing importance weights, estimates weights for the rank order of the dimensions (from largest to smallest) in each unit of interest or policy option (Yager 1988).

For each value of trade-off, derived from the ORness value, the OWA involves a nonlinear constrained optimization as follows:

Objective function:

$$\text{Maximize Dispersion} = -1 \times \sum_k \left( W_k(d) \times \ln (W_k(d)) \right)$$

subject to:

$$\text{ORness} = 1 - \left( \frac{1}{n-1} \right) \sum (n - dW_k(d))$$

where \(W_k(d)\) are the variables of interest, the order weight assigned to order \(k(d)\) that maximize the Shannon’s entropy measure in the objective function to account for the maximum information available in the dimensions \((d)\) of each policy scenario \((j)\), and for any ORness value (Malczewski et al 2003, Malczewski 2006, Runfola et al 2017). The order weights are then used to construct a composite index, \(I_j\), for each policy scenario as follows:

$$I_j = \sum_{k(d) \in A} W_k(d) Y_{k(d)j}$$

where \(\sum_{k(d)} = 1\), \(k(d) j\) represents the order of each normalized indicator, \(Y_{k(d)j}\), for every dimension \(d\) and scenario \(j\), where \(A\) is the set of indicators for which the order weight is different from zero. For each ORness value the composite indices are ordered from largest to smallest in order to rank the policy scenarios and identify the most preferred.

For the purpose of this paper, importance weights of the dimensions are all equal to 0.143 \((= \frac{1}{7}; n = 7)\) (Fernandez et al 2017). We focus only on the order weights and the effects of changing the assumed ORness values on the selection of the optimal policy package.

In the OWA context, risk is understood as the degree by which each dimension affects the decision-making outcome and, consequently, the likelihood that any decision selected may be wrong (Jiang and Eastman 2000, Malczewski 2006, Mianabadi et al 2014, Feizizadeh and Kienberger 2017). The risk attitude of the policy-maker is explored through the ORness value, which ranges from 0 to 1 and any particular value carries a different interpretation. An ORness value equal to 0.5 represents full compensation or substitutability between dimensions, which is interpreted as the policy-maker being risk neutral. In turn, an ORness value equal to 0 implies that the composite index, \(I_j\), is determined solely by the dimension with the smallest value, which is equivalent to an optimistic or risk taking attitude. And, an ORness value equal to 1 implies that the composite index is determined (solely) by the dimension with the highest value, equivalent to a pessimistic or risk averse attitude (Javidi Sabbaghian et al 2016, Machado and Ratick 2017).

The decision space for the policy-maker is depicted in Figure 1. The x-axis is the ORness value and represents the continuum from a risk-taking attitude (risk is completely accepted) to the point of maximum caution. The y-axis represents the continuum from no trade-off between the dimensions to the point of maximum trade-off (Jiang and Eastman 2000). Thus, trade-off \((= \left( \frac{1}{n-1} \right) \sum (n - iW_k(d))\) is determined by the relative distribution of the order weights among the seven dimensions. Therefore, high trade-off values may imply optimistic assessments potentially overlooking policy scenarios (or alternatives) because their high constituent dimension values have been averaged out (traded-off or compensated for) by lower values of other dimensions (Runfola et al 2017). Thus, an optimistic attitude implies that the decision-maker focuses more on the desirable dimensions of policy scenarios. In turn, trade-off values approaching zero imply that low dimension values cannot average out (traded-off or compensated for) higher values of other dimensions, and lead to pessimistic assessments, that focus more on dimensions with negative aspects (Mianabadi et al 2014).
Table 2. Environmental outcomes and costs of policy scenarios.

| Scenario | Policy cost (Mil NZ$ yr$^{-1}$) | Sediment reduction (% change) | E. Coli reduction (% change) | N Leaching reduction (% change) | P Loss reduction (% change) | Agricultural GHG Mitigation (MtCO$_2$e yr$^{-1}$) | Forest GHG Mitigation (MtCO$_2$e yr$^{-1}$) | Gross GHG mitigation (MtCO$_2$e yr$^{-1}$) |
|----------|---------------------------------|------------------------------|-----------------------------|-------------------------------|----------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------|
| A*       | 351                             | 1.3%                         | 13.0%                       | 10.4%                         | 3.9%                       | 10.25                                         | 30.14                                         | 40.40                                   |
| B        | 981                             | 1.4%                         | 12.9%                       | 11.8%                         | 5.3%                       | 10.25                                         | 0.14                                          | 10.40                                   |
| C*       | 440                             | 30.0%                        | 53.2%                       | 30.0%                         | 30.0%                      | 4.99                                          | 30.55                                         | 35.54                                   |
| D        | 1331                            | 30.0%                        | 57.3%                       | 32.1%                         | 30.0%                      | 5.96                                          | 0.26                                          | 6.21                                    |
| E*       | 839                             | 30.0%                        | 52.9%                       | 30.0%                         | 30.0%                      | 10.25                                         | 30.83                                         | 41.09                                   |
| F        | 1585                            | 30.0%                        | 54.6%                       | 30.6%                         | 30.0%                      | 10.25                                         | 0.80                                          | 11.06                                   |
| G*       | 390                             | 15.1%                        | 45.9%                       | 30.0%                         | 23.9%                      | 5.05                                          | 30.64                                         | 35.69                                   |
| H        | 599                             | 18.9%                        | 47.2%                       | 30.0%                         | 22.1%                      | 0.54                                          | 1.01                                          | 1.55                                    |
| I*       | 341                             | 19.4%                        | 49.6%                       | 24.7%                         | 30.0%                      | 4.98                                          | 30.46                                         | 35.43                                   |
| J        | 1310                            | 17.9%                        | 57.3%                       | 32.0%                         | 30.0%                      | 5.93                                          | 0.23                                          | 6.16                                    |
| K        | 86                              | 30.0%                        | 7.6%                        | 2.8%                          | 7.9%                       | 1.12                                          | 6.50                                          | 7.62                                    |
| L        | 93                              | 30.0%                        | 3.1%                        | 1.4%                          | 4.5%                       | 0.17                                          | 0.34                                          | 0.51                                    |
| M*       | 42                              | 5.6%                         | 30.0%                       | 6.6%                          | 6.8%                       | 2.67                                          | 13.52                                         | 16.19                                   |
| N        | 92                              | 5.3%                         | 30.0%                       | 6.5%                          | 5.7%                       | 0.82                                          | 0.00                                          | 0.82                                    |
| O        | 2671                            | 24.1%                        | 31.5%                       | 17.0%                         | 23.3%                      | 8.60                                          | 0.84                                          | 9.44                                    |
| P        | 1339                            | 22.2%                        | 13.3%                       | 8.7%                          | 15.7%                      | 3.18                                          | 0.64                                          | 3.83                                    |
| Q        | 844                             | 20.4%                        | 6.1%                        | 3.0%                          | 10.2%                      | 2.03                                          | 0.48                                          | 2.51                                    |
| R        | 346                             | 17.8%                        | 6.1%                        | 2.4%                          | 6.6%                       | 0.74                                          | 0.24                                          | 0.98                                    |
| S        | 254                             | 14.1%                        | 3.3%                        | 0.9%                          | 2.9%                       | 0.67                                          | 0.12                                          | 0.79                                    |
| T        | 1524                            | 25.4%                        | 77.4%                       | 36.3%                         | 31.3%                      | 0.00                                          | 0.00                                          | 0.00                                    |
| U        | 2289                            | 25.6%                        | 77.2%                       | 47.5%                         | 38.2%                      | 0.65                                          | 1.30                                          | 1.95                                    |

*Full compliance with PA—abatement above 34.9 MtCO$_2$e

*Partial compliance with PA—abatement above 13.2 MtCO$_2$e (required from domestic sources)

$^2$Gross GHG mitigation = Agricultural mitigation + forest mitigation
Table 3. Ranking positions of policy alternatives under different policy attitudes (ORness values). Full set of policy alternatives.

| ORness values | Ranking position |
|--------------|-----------------|
|              | 0   | 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.5  | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | 1   |
| 1            | E   | E    | E    | E    | E    | E    | E    | E    | E    | E    | E    | E    | E   |
| 2            | G   | C    | C    | C    | C    | C    | C    | C    | C    | U    | C    | C    | U   |
| 3            | C   | I    | I    | I    | I    | I    | I    | I    | U    | I    | U    | C    | F   |
| 4            | I   | G    | G    | G    | G    | G    | F    | F    | F    | F    | F    | F    | E   |
| 5            | M   | D    | D    | D    | D    | D    | G    | U    | I    | I    | A    | A    | A   |
| 6            | K   | J    | F    | D    | D    | D    | D    | D    | G    | G    | G    | A    | T   |
| 7            | U   | F    | J    | J    | J    | J    | U    | U    | D    | T    | T    | I    | L   |
| 8            | H   | M    | H    | U    | U    | J    | T    | T    | T    | D    | G    | K    | T   |
| 9            | F   | H    | T    | T    | T    | J    | J    | A    | A    | D    | D    | G    | D   |
| 10           | P   | U    | M    | H    | H    | H    | A    | J    | J    | K    | L    | B    | C   |
| 11           | Q   | P    | T    | O    | O    | A    | A    | H    | H    | K    | L    | D    | M   |
| 12           | D   | K    | O    | M    | A    | O    | O    | O    | O    | O    | B    | G    | E   |
| 13           | R   | T    | P    | A    | M    | K    | K    | K    | H    | J    | M    | I    | I   |
| 14           | J   | O    | K    | P    | P    | M    | M    | M    | M    | L    | B    | N    | N   |
| 15           | B   | Q    | A    | K    | K    | P    | P    | P    | L    | B    | M    | O    | S   |
| 16           | A   | N    | Q    | Q    | B    | B    | B    | L    | B    | M    | H    | S    | R   |
| 17           | N   | A    | N    | B    | Q    | L    | L    | B    | P    | P    | N    | R    | O   |
| 18           | T   | R    | B    | N    | L    | Q    | Q    | Q    | Q    | N    | R    | J    | H   |
| 19           | O   | B    | R    | R    | N    | N    | N    | N    | N    | R    | S    | H    | J   |
| 20           | L   | L    | L    | L    | R    | R    | R    | R    | R    | Q    | P    | P    | P   |
| 21           | S   | S    | S    | S    | S    | S    | S    | S    | S    | S    | Q    | Q    | Q   |

Note: Colours track the ranking changes of particular policies across the ORness values. Policy U (Policies I and G) moves upward (downward) in the ordering as risk aversion attitudes becomes more pronounced. Table 3 shows that policies E and C are dominant regardless risk attitudes, depicting preferences toward simultaneous management of freshwater contaminants and GHG emissions.

3. Results

3.1. Freshwater mitigation and GHG mitigation policy analysis

This paper explores policy scenarios for NZ to meet their 2030 PA target of reducing GHG emissions by 30% from 2005 levels (i.e. 34.9 MtCO₂e) while simultaneously achieving improvements in freshwater quality. Policies A, C, I, G and E over comply with the PA commitment (table 2). Those policies are all target-based scenarios, including afforestation, and their costs range between $340 and 838 million (−3% to −7% from the no-policy baseline). The variation of costs sources from the policies definitions, while G and I focus only on the reduction of a single contaminant (N leaching or P loss); A, C and E focus on the simultaneous reductions of all four freshwater contaminants and/or GHGs. But the contribution of forest GHG to gross GHG mitigation ranges between 75% and 86%, implying that the mitigation burden for agriculture and other energy, transport and value-added sectors are reduced significantly. Therefore, the FCS strategy directly addresses GHG emissions by not relying solely on increased investments in renewable energy sources or shifts in the production mix of non-agricultural sectors (Martin and Saikawa 2017).

Policy M, focused on a 30% reduction on E.coli and allowing afforestation, partially complies with the PA by reaching a reduction of 16.2 MtCO₂e, which covers the required domestic mitigation (13.2 MtCO₂e). Interestingly, Policy M is the least expensive out of all policy scenarios ($42.4 million). The most expensive (costing above $2 billion) are policies O: mitigation of sediments from highly erodible land (HEL) (on only 8.6 Mha of farmland with erosion rates of 1 t ha⁻¹ yr⁻¹ or higher—table 54), and U: mandatory stock exclusion and 5 m riparian planting along all of NZ’s permanent waterways. Other policies costing between $1 and $2 billion are characterised by having a target reduction either on P loss (Policy J), GHGs and the 4 contaminants (Policy F), erosion/sediments management (Policy P: HEL plan at 3 t/ha/yr or higher), or stock exclusion (Policy T). None of these relatively costly alternatives include afforestation, further highlighting the cost-effectiveness of FCS.

Results reveal that afforestation and FCS play a significant role on introducing a wide pool to relieve mitigation burdens. Policy A (focused on a 30% reduction of GHGs and allowing afforestation) costs about $351 million, but the cost of the same policy goal triples when afforestation is not a permissible mitigation option -Policy B. Likewise, not having afforestation increases costs by 50% for stock exclusion policies and 10% for policies targeting erosion management (i.e. sediment reduction).

Stock exclusion with riparian planting (Policy U) has a slight effect on GHG emissions and it results in large reductions in N leaching (47%), P loss (38%), and E. coli (77%). However, riparian planting also results in an additional cost of about $764 million relative to a stock exclusion-only policy (Policy T),
Table 4. Ranking positions of Policy Alternatives under different policy attitudes (ORness values). Restricted set of policy alternatives.

| ORness values | Ranking position |
|---------------|------------------|
|               | 0    | 0.05 | 0.15 | 0.25 | 0.35 | 0.45 | 0.5  | 0.55 | 0.65 | 0.75 | 0.85 | 0.95 | 1   |
| 1             | G    | I    | I    | I    | I    | I    | I    | U    | U    | U    | U    | U    | U    |
| 2             | G    | G    | G    | G    | G    | G    | G    | U    | I    | I    | A    | A    |
| 3             | M    | J    | J    | J    | U    | U    | U    | G    | G    | A    | T    | K    |
| 4             | K    | M    | H    | U    | U    | J    | T    | T    | T    | T    | I    | L    |
| 5             | U    | H    | U    | T    | T    | T    | J    | J    | A    | A    | G    | K    |
| 6             | H    | U    | M    | H    | H    | H    | H    | A    | J    | J    | K    | G    |
| 7             | P    | P    | T    | O    | O    | A    | A    | H    | H    | K    | L    | L    |
| 8             | Q    | K    | O    | M    | A    | O    | O    | O    | O    | O    | B    | G    |
| 9             | R    | T    | P    | A    | M    | K    | K    | K    | H    | J    | M    |
| 10            | J    | O    | K    | P    | P    | M    | M    | M    | L    | B    | N    | N    |
| 11            | B    | Q    | A    | K    | K    | P    | P    | P    | L    | B    | M    | O    |
| 12            | A    | N    | Q    | Q    | B    | B    | B    | L    | B    | M    | H    | S    |
| 13            | N    | A    | N    | B    | Q    | L    | L    | B    | P    | P    | N    | R    |
| 14            | T    | R    | B    | N    | L    | Q    | Q    | Q    | Q    | Q    | N    | R    |
| 15            | O    | B    | R    | R    | N    | N    | N    | N    | N    | N    | R    | S    |
| 16            | L    | L    | L    | R    | R    | R    | R    | Q    | P    | P    | P    |
| 17            | S    | S    | S    | S    | S    | S    | S    | S    | S    | S    | Q    | Q    |

Notes: Colours track the ranking changes of particular policies across the ORness values. Policies in this subset do not allow joint targets for GHG emissions and water contaminants. As ORness increases there is a switch from the Policy I to U as the most preferred, revealing the contrast between a moderately costly policy that complies with the PA and associated with moderate mitigation of contaminants, and an exceedingly costly policy with negligible abatement of GHGs but achieving high mitigation of contaminants.

3.2. Policy assessment

The output of the agri-environmental model feed the OWA approach to develop the ranking positions in table 3. Policy E (focused on reductions of 30% on GHG emissions and water contaminants) is dominant across all ORness values, followed by Policy C (focused on reductions on water contaminants). While both Policy C and E allow afforestation as a mitigation option and achieve similar reduction of water contaminants, Policy E reduces GHG emissions by 5 MtCO₂ (17.5%) more than Policy C. However, this additional GHG mitigation comes at a price: Policy E costs almost double Policy C. The decision-maker then has to select between complying (or over complying) with the PA while improving freshwater quality, and at a minimum cost. Our results would then suggest that Policy C should be selected.

The OWA results also show that the HEL management plans are consistently ranked as the least preferred alternatives for meeting multiple environmental objectives regardless the risk attitude of the policy-maker (Policies O-S). While these policies may achieve moderate reductions on sediments, and can easily be measured on a farm-by-farm basis, they may be costly to implement on a wide-scale. Furthermore, it highlights that a policies that only target a specific practice could be less preferred because it fails to provide ample spill overs relative to the estimated cost savings.

Nonetheless, it could be reasonably assumed that simultaneous management of GHG and contaminants is not (politically or economically) feasible, for which we remove scenarios C, D, E and F from the OWA simulations (table 4). Under a risk-taking strategy, Policy G (30% reductions on N leaching) is ranked as the preferable option, but for increasing levels of the ORness value—reflecting risk neutrality (ORness = 0.5) and moderate risk taking behaviour—Policy I (30% reduction on P loss) becomes the preferable option. Though not explicit in the policy definition, both policies operate jointly because of the common mitigation practices in addition to afforestation. Though Policy I results in slightly greater reductions of sediments and E. coli, Policy G costs $49 million more. For ORness = 0, N leaching is not compensated by further reductions in other water contaminants despite the higher cost. Therefore, for ORness values reflecting moderate risk aversion and risk neutrality, there appears to be an inclination toward a more balanced combination of reductions on GHG and water contaminants (Policy I).

Additionally, in a risk averse decision strategy, Policy U (stock exclusion with riparian planting) is ranked as the top choice despite its large cost. Policy U achieves the largest reductions on E. Coli, N leaching and P loss, and moderate reductions on sediments, but negligible reductions on GHG emissions. That is, risk aversion implies a greater focus on water contaminants. Nonetheless, under extreme risk aversion (ORness = 0.95 to 1), Policy A (30% reduction on GHG) is ranked second-best. Therefore, risk aversion implies focusing either on GHGs or a bundle of water contaminants, where each approach is considered as...
a secondary benefit of the other and may not be an explicit part of the policy design.

Hence, the OWA constructs the decision space conditional to the risk profile of the decision-maker. The decision space is illustrated in figure 2, which is based on the subset of policy options in table 4. The figure indicates that decisions for the entire risk-taking space are inclined toward mitigating freshwater contaminants (N leaching in particular) with afforestation included as a mitigation alternative. This decision environment holds even for moderate values within the risk averse space. In turn, risk aversion implies that policy decisions may place more emphasis on management via stock exclusion with riparian planting in order to achieve the largest reductions of E. Coli, but at the expense of GHG mitigation and high policy costs. Figure 2 then exemplifies how the regions (of the decision space) for risk taking or risk averse strategies are populated by the outcome of the simulated policies, and develops a greater level of generality by focusing on the variables or dimensions of interest rather than on a specific policy scenario. A greater level of generality serves to address debates where specificities of policy packages are still under discussion. Furthermore, figure 2 may even work as a displaying device during policy workshops as a roadmap for policy design or stakeholders’ involvement.

4. Discussion and conclusions

The PA has changed the spectrum of policy alternatives and calls for countries to develop a wider range of creative land-based mitigation options (Grassi et al 2017). Though emissions markets introduce certainty on the reductions target to be reached, they have proven to be challenging to implement because of a range of political and practical issues. Many NCS allow the simultaneous (or integrated) management of GHG emissions and freshwater contaminants in addition to providing greater flexibility on policy design. These mitigation practices also provide an avenue for the better coordination and implementation of development and conservation goals (Miteva 2019). Therefore, the efficiency of policy-making may improve as implementation in one area supports a policy goal in another (Townsend et al 2012, Howells et al 2013, Shephard et al 2016), while also creating positive planning synergies (Howells et al 2013, Smith et al 2019).

The model simulations and results in this paper suggest that through land use changes, NZ could greatly reduce GHG emissions while simultaneously improve freshwater quality. NZ’s primary sector has a significant role on relieving the country’s GHG mitigation burden from the energy and manufacturing sectors. Focusing on practices that improve land
management can contribute to emission reductions by 2030 and provide a more sustainable alternative approach to achieving the PA commitments of NZ (Fee 2019) without disregarding further action on advancing other clean energy solutions (Griscom et al 2019). Furthermore, land management objectives focused on improving freshwater quality in the country are highly relevant in the near term for NZ to shift toward a carbon neutral economy. Results in this paper are policy-relevant given the current scale of NZ’s agricultural emissions, dependence on renewable (carbon-free) sources for electricity generation, and the risk of relying heavily on negative emissions technologies that are not yet commercially viable and may not necessarily be more efficient relative to FCS (Griscom et al 2017, Harper et al 2018). The novelty of this paper relies on the linking between an agri-environmental model and a decision-making approach to identify those policy scenarios that meet multiple environmental goals under different profiles of risk attitudes. This modelling framework serves not only to inform decision-makers but also to address debates on policy design and to involve stakeholders.

The assumptions and limitations in this paper could be further refined and potentially improved in future research in the following ways. First, the seven dimensions analysed in this paper could be combined in many other ways to span a wider range of policy alternatives, albeit at the expense of model tractability. Second, we focus on the order weights of dimensions and assume equal importance weights; however, enhancing the importance weights through qualitative research or expert panels may expand the model’s capabilities and make it more practical. Further modelling efforts should consider this added layer of complexity and potential non-robustness of results (Fernandez et al 2017). Third, results may change when new data on mitigation practices or policy packages become available, although the current model includes a suite of practices that encompass a wide range of costs and effectiveness (table S2). Finally, some of the simulated policy alternatives are associated with implementing practices aimed at the restoration of degraded areas via afforestation, which cascades into side benefits such as increased production potential for food or biodiversity (Pasini et al 2018). The analysis limits afforestation as a viable mitigation alternative to only pine plantations, because it currently represents about 90% of the country’s currently planted forests. Arguably, results in this paper therefore represent a lower bound of potential ecological benefits provided by afforestation. This analysis thus provides an indication of the direction that other potential NCS may take, particularly if we include more diverse species-rich resilient ecosystems in future iterations of this research (Seddon et al 2019).

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Author contributions

M F developed the research idea. M F and A D developed the methodological framework. A D conducted the land use model simulations. M F conducted the OWA simulations. M F and A D drafted the manuscript.

Data availability

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

ORCID iDs

Mario A Fernandez https://orcid.org/0000-0002-1390-2375
Adam J Daigneault https://orcid.org/0000-0002-8287-8727

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