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Research article

A national riparian restoration programme in New Zealand: Is it value for money?

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ABSTRACT

National scale initiatives are being attempted in New Zealand (NZ) to meet important environmental goals following land-use intensification over recent decades. Riparian restoration to filter agricultural spillover effects is currently the most widely practised mitigation measure but few studies have investigated the cumulative value of these practices at a national level. We use an applied economic land use model the benefits (GHG emissions, N leaching, P loss, sedimentation and biodiversity gain) and relevant costs (fencing, alternative stock water supplies, restoration planting and opportunity costs) of restoring riparian margins (5–50 m) on all streams in NZ flowing through current primary sector land. Extensive sensitivity analysis reveals that depending on margin width and cost assumptions, riparian margin restoration generates net benefits of between NZ$1.7 billion – $5.2 billion/yr and benefit-cost ratios ranging between 1.4 and 22.4. This suggests that even when not monetising the increase in biodiversity or components of stream ecosystem health and other benefits from planting riparian strips, the benefits to climate and freshwater are significantly greater than the implementation costs of riparian restoration.

1. Introduction

Governments are introducing national environmental policies that often struggle to achieve traction because the potential benefits and costs are rarely evaluated. However, demonstration of net benefits from implementation could foster support and drive local and regional initiatives. The large-scale restoration of riparian systems are emerging globally as national foci for policy and management because of their role in supporting large human populations, significant natural biodiversity and critical ecosystem services (Stella et al., 2013). An essential feature of riparian systems is their connectivity as part of larger watersheds and their interface with adjoining terrestrial environments. These features contribute to their functional importance for sustaining water quality and quantity, limiting soil erosion, maintaining in-stream biodiversity, sequestering nutrients and toxins derived from land use activities, and mitigating the impacts of climate change (Capon et al., 2013). However they also make restoration challenging as benefits are scale and context dependent, and often diffuse. Net positive outcomes are influenced by the location of impacts and benefits within the watershed. Additionally, terrestrial land use, human population pressures, and the typology of river networks are dynamic over different temporal and spatial scales making it difficult to evaluate the contributions to overall watershed health of either a single activity or management at one or a few locations.

Watersheds have multiple purposes and policy and management agencies are increasingly requiring models and frameworks that enable full evaluation of the economic and environmental outcomes of different options seeking to restore ecosystem functions (Burnett et al., 2017). This is to assist decision making where riparian restoration requires forgoing current or potential economic benefits from agricultural or urban activity in parts of the watershed. Moreover, outcome evaluation is increasingly recommended when multiple ecosystem services, derived from many natural sources, are required (Maseyk et al., 2016).

As ecologically diverse strips of vegetation along the riparian margin of waterways, riparian buffers can play a vital role in cleaning up waterways (Osborne and Kovacic, 1993; Naiman and

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Decamps, 1997; Duchemin and Hogue, 2009). Excluding stock from streams with fencing can greatly reduce sedimentation from bank erosion and stream contamination with N, P and pathogenic bacteria in dung (e.g., Di and Cameron, 2000; Nagles et al., 2002). Active or passive restoration of riparian vegetation will often add further benefits, particularly in capturing overland erosion flows, filtering unused nutrients and providing habitat and shading for both terrestrial and aquatic biota (e.g., Parkyn et al., 2003; Parkyn, 2004; Jowett et al., 2009; Zhang et al., 2010).

New Zealand has already implemented or is considering a range of major environmental policies nationally, including climate change mitigation (NZ Government, 2002) freshwater quality (MfE, 2014), and pest control (Russell et al., 2015). The latter has arisen in response to the expansion and intensification of the primary sector and the degraded quality of many waterways. In New Zealand, water quality limits are being set for each catchment in the country under the recently amended National Policy Statement for Freshwater Management (NPS-FM) of 2014. Through the NPS-FM, the agricultural sector will be required to take action to reduce their contribution to the degradation of water quality, particularly via nitrogen (N) and phosphorous (P) pollution, sediment deposition, and contamination by pathogenic bacteria. In addition, New Zealand has a domestic climate change mitigation policy that has been implemented through an emissions trading scheme since 2008. The scheme currently covers most sectors of the economy, including forestry, and has proposed to cover agricultural emissions at some point in the future.

Fencing stream banks and planting riparian buffers have been proposed in New Zealand as a key option to mitigate freshwater contaminants (LAWF, 2015; DairyNZ, 2013), with buffers also having the potential to reduce the country's GHG emissions (Vibart et al., 2015). Meurk and Swaffield (2000) even suggest targeted riparian restoration plans to help recreate the unique and culturally familiar landscapes of New Zealand. Despite the apparent value of buffers, riparian restoration programmes in New Zealand and elsewhere, tend to be piecemeal and to reflect individual industry or community actions. One key limitation is that unclear whether these initiatives will achieve the necessary environmental and biodiversity objectives for the nation. In addition, citizens are concerned that the benefits of implementing wide-scale restoration activities will outweigh the aggregate direct costs of developing riparian margins as well as the opportunity costs through lost agricultural revenues from reducing the area of productive land.

This objective of this paper is to assess the net benefits of uniformly implementing a national riparian restoration programme in New Zealand. We use an applied economic land use model to quantify the benefits and relevant costs of restoring riparian margins on all NZ streams flowing through land that is currently used for primary sector activities. The paper presents an analysis of the cumulative impact and costs of riparian restoration at different margin sizes, implementation costs, and mitigation effectiveness to estimate their net value in terms of enhancing water quality, carbon sequestration, and biodiversity. While the focus of the paper is on analysing the aggregate (i.e. nationwide) effects of a uniformly applied riparian restoration programme, we conduct extensive sensitivity analysis to determine where maximum net benefits could be attained depending on buffer width, primary sector, and spatial location across a total of 72 modelled scenarios. Our results support discussions of the value of having a riparian restoration network that effectively mitigates land-use impacts while restoring freshwater habitats and the multiple services they provide.

The foundation of our analytical model is similar to methods used in other analysis of policies in mixed agricultural-natural landscapes (e.g., Wätzold and Drechsler, 2005; de Bruin et al., 2009; Fernandez and Daigneault, 2016). That is, we integrate spatially explicit databases on land-use, farm profitability, and restoration costs with information on the impact-mitigating potential and biodiversity profiles of riparian margins. Our policy scenario approach is similar to landscape-scale studies focusing on valuing and analysing trade-offs of multiple ecosystem services that have recently emerged in the literature (e.g., Nelson et al., 2009). For example, Lawler et al. (2014) use analysed the impact of taxes, subsidies, and land use change restrictions on US carbon storage, food and timber production, and habitat provision, while Bateman et al. (2011) developed an integrated assessment model to analyse future oriented policy and decision-making in the UK. We build upon this literature by utilising a nationally comprehensive model of land use and various ecosystem services to estimate the potential benefits, costs, and trade-offs of uniformly applying a riparian restoration policy across all of New Zealand.

Extensive literature exists on the costs of restoration of riparian margins. Many of these studies estimated the construction, maintenance, and opportunity costs of riparian buffers applied to specific land uses such as agricultural crops (e.g., Nakao and Sohngen, 2000; Rickerl et al., 2000; Frimpong et al., 2007; Roberts et al., 2009; Sieber et al., 2010), and forestry (e.g., Carlén et al., 1999; Basnyat et al., 2000; LeDoux, 2006; Laurén et al., 2007). Other studies have looked at the impact to a watershed across several land uses (e.g., Chang et al., 2010; Trenholm et al., 2013). Watanabe et al. (2005) used an integrated bio-economic model to estimate the costs and benefits of passive versus active riparian restoration and found that the net benefits of each vary based on buffer width and the length of time since implementation. To our knowledge, no studies have analysed the benefits and costs of riparian restoration achieved via a uniform policy at the national-scale or over such a wide-range of land uses and environmental indicators, nor have they focused on the likely impacts of planting buffers in a livestock-dominant landscape such as New Zealand.

The paper is organised as follows. First, we present the theoretical foundation of the model and detail the data sources used for this study; next, we describe the mitigation potential from riparian planting options under consideration; following that, we present baseline land use, farm earnings, greenhouse gas (GHG) emissions, and other environmental outputs, followed by results from a series of riparian margin restoration scenarios; the final section provides a conclusion of our findings.

2. Model and parameterisation

2.1. Agri-environmental economic model

Our analysis uses a comparative-static agri-environmental economic model based on Daigneault et al. (2016) to estimate the benefits and costs of implementing a national riparian restoration programme along all permanent streams and rivers running through primary sector land. In the model, total economic returns from the New Zealand agriculture sector, calculated as annual net farm revenue (π), are measured as:

$$\pi = \sum_{r,s,l,e,m} \left\{ PA_{r,s,l,e,m} + Y_{r,s,l,e,m} - X_{r,s,l,e,m} \left[\omega^{live}_{r,s,l,e,m} + \omega^{vc}_{r,s,l,e,m} + \omega^{fc}_{r,s,l,e,m} \right] \right\} \quad (1)$$

where $\boldsymbol{P}$ is the product output price, $\boldsymbol{A}$ is the agricultural product output quantity, $\boldsymbol{Y}$ is other gross income earned by landowners (e.g., grazing fees), $\boldsymbol{X}$ is the area of specific farm-activity, and ω^{live}, ω^{vc}, ω^{fc} are the respective livestock, variable, and fixed input costs. 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. This parameter is used in our analysis to estimate the opportunity costs of riparian margin restoration. Methods for estimating other costs of implementing riparian buffers (e.g., planting, fencing) are described below.

To parameterise the baseline economic returns for the primary sector (and the potential opportunity costs of planting riparian buffers) in the model, we first input a farm boundary map of nearly 1 million individual land use parcels (Fig. 1) developed using Agribase and the NZ Land Cover Database (LCDBv4). Farm and regionally-distinct factors such as location, climate, soil fertility, and slope determine agricultural yields, input costs, and output prices for farms and thus their resulting net revenue (i.e. annual profit). Many of these data come primarily from national and regional-level policy and research reports produced for the New Zealand primary sector (MPI, 2015; MPI, 2013; Lincoln University, 2013, etc.). When required, figures were downscaled to the land block-level using farm-specific characteristics such as location and stock carrying capacity (Newsome et al., 2008). Daigneault et al. (2016) verified these block-level estimates with agricultural consultants and enterprise experts through semi-structured interviews. The full list of data sources used to populate the model for this analysis are presented in Table A1.

The model is also parameterised to track the flow of several environmental factors ($\boldsymbol{E}_i$). These include freshwater contaminants such as nutrient (N and P) loss and sediment deposited from overland and streambank erosion, gross and net GHG emissions, and biodiversity. Per hectare values are specified via the parameter γ^{env}, and as with economic returns, can vary by region, soil type,

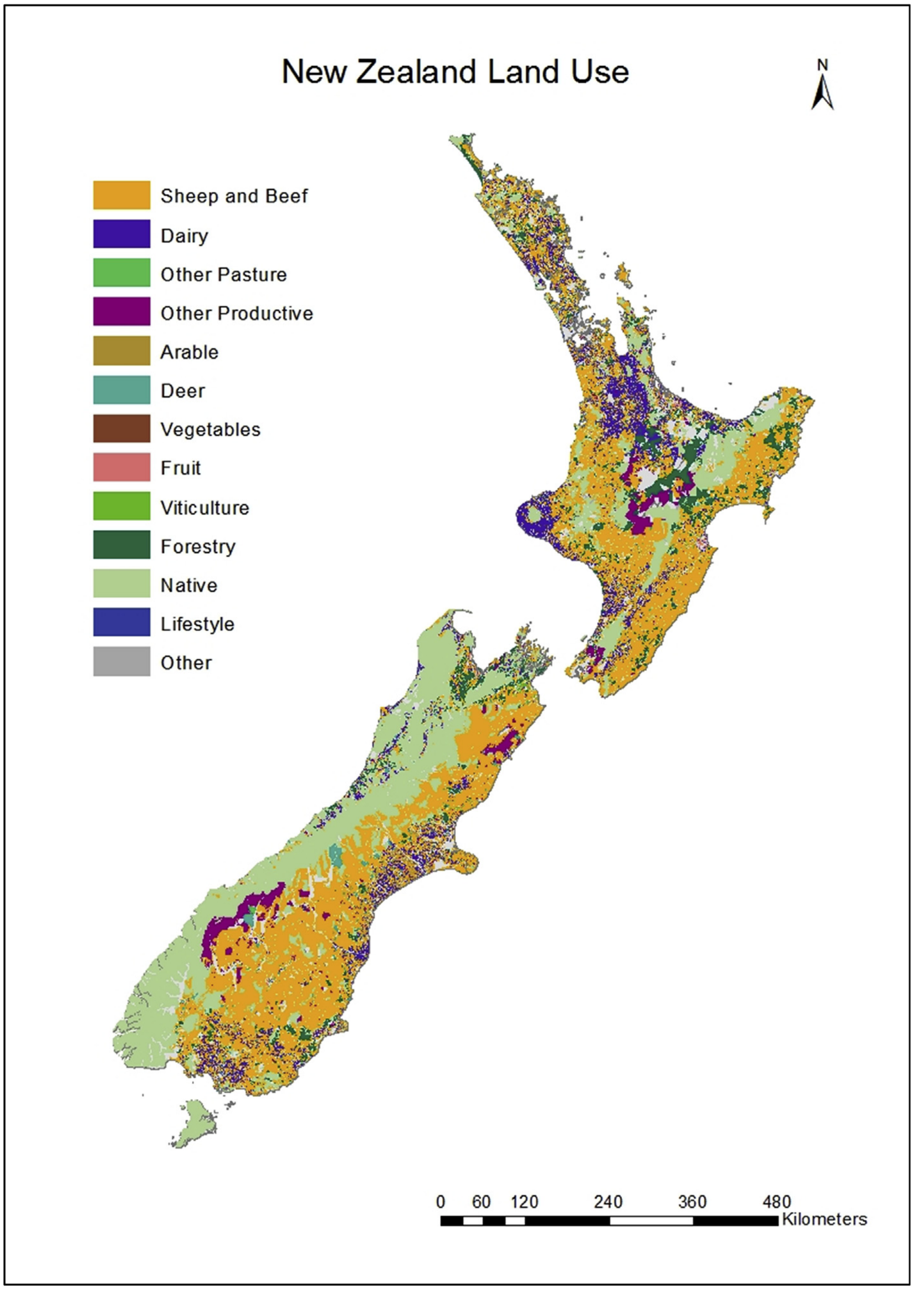

Fig. 1. Current land use in New Zealand.

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:

$$\sum_{r,s,l,e} \gamma^{env}_{i,r,s,l,e} X_{r,s,l,e} = E_i \tag{2}$$

Nutrient losses for pastoral enterprises, the largest primary sector area in New Zealand, are estimated using the OVERSEERv6 nutrient budgeting tool,[1] while N and P estimates for other land uses are derived from research reports for New Zealand (e.g. Lilburne et al., 2010; Parfitt et al., 1997). GHG emissions are derived using national GHG inventory methodologies (MfE, 2015). Sediment is estimated using soil loss from overland and stream bank erosion as a proxy, using methods developed by Dymond et al. (2010). Additional details on the data and methodology are provided in Appendix 1, Ausseil et al. (2013), and Fernandez and Daigneault (2016).

Eqn (2) specifies environmental impacts under current land use. In our analysis, we consider a policy of restoring riparian margins on all primary sector land. To describe environmental impacts under such a policy, we amend Eqn. (2) to:

$$\sum_{r,s,l,e,m} \gamma'_{i,r,s,l,e,m}\left(X_{r,s,l,e} - Z_{r,s,l,e}\right) + \psi^{env}_{i,r,s,l,e} Z_{r,s,l,e} = E'_i \tag{3}$$

where $\boldsymbol{Z}$ is the area of the restored riparian margin as a function of on-farm stream length and margin width. To determine the length of streams on individual parcels, we overlay a map of river centrelines (LINZ, 2011) on the land use maps and the buffer width is a policy parameter discussed below. The parameter γ' specifies the environmental impacts of land use after accounting for the width-dependent effects of riparian margins, while ψ^{env} describes the impact of riparian margins on the environmental factors. Following Parkyn 2004 and Zhang et al., 2010, we assume that $\gamma' \le \gamma^{env}$, as riparian margins reduce total environmental effects by a) decreasing the area of land use that causes environmental impacts, b) reducing impacts per unit of land use, and c) through their own biophysical processes that intercept freshwater contaminants, sequester carbon, or promote biodiversity. The environmental impact after restoring riparian margins, E'_i, is equal to or smaller than the impact without margins, E_i, so that the mitigation in impact i achieved by the riparian margin is $E_i - E'_i$. As $\mathbf{Z}$ represents the area that is converted to riparian and taken out of production and, it also has a non-positive effect on the net economic returns estimated in Eqn. (1).

Restoring riparian margins has many potential environmental and biodiversity benefits. Our analysis focuses on changes in N and P loss, sediment, and net GHG emissions, and improvements in biodiversity potential. To determine the reduction in N leaching, P loss, and sediment deposition, we use results from a global meta-analysis of riparian restoration studies by Zhang et al. (2010). As shown in Fig. 2, the loss-reducing effect of riparian margins are asymptotic with margin width, and thus γ' in Eqn. (2) also varies with margin width. The results from Zhang et al. (2010) are relatively high, even at widths as small as 5 m. Thus, we conduct sensitivity analysis to allow for the possibility that riparian margin restoration in New Zealand may be less effective (see, e.g., Wilcock et al., 2009) at reducing freshwater contaminants and GHGs than our initial assumption.

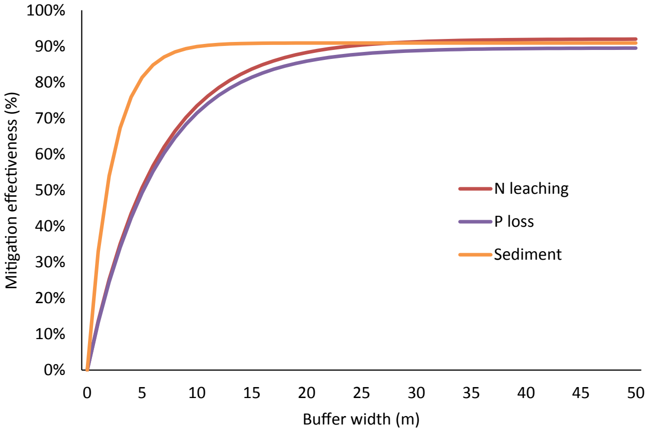

Fig. 2. Riparian buffer mitigation effectiveness, by width (based on Zhang et al., 2010).

GHG benefits were estimated using a combination of the MfE GHG inventories for emissions from productive land and results from Carswell et al. (2015), who develop a model to predict carbon storage in woody biomass when productive land is allowed to go through a process of passive afforestation. With this, they generate a map of additional carbon captured, which we use to determine the contribution of riparian margins on these environmental variables to carbon gain. Under the assumption that our comparative-static analysis covers approximately 20 years, we convert total carbon from Carswell et al. (2015) to an annual flow of carbon dioxide-equivalent (CO_2-e) captured. We also consider the option of revegetating riparian margins with a recommended planting regime of mānuka trees. When mānuka trees are planted with 10-m spacing, the mean annual carbon sequestration is approximately 5 MtCO2e/ha/yr over a 20 year period (Funk et al., 2014).

Carswell et al. (2015) also provide estimates of biodiversity gain (measured as restored significance, Mason et al., 2012) through passive afforestation. This measure records the national-scale benefit to environmental representation (Pressey et al., 1993; Overton et al., 2015) of indigenous afforestation. This map represents an ideal state with maximally achievable biodiversity outcome if active management and current land use in New Zealand were stopped entirely. We determine the biodiversity gain on riparian margins and assess the contribution of margin restoration to the ideal state.

2.2. Costs and benefits of riparian planting

Restoring riparian margins on agricultural land involves several costs. In our model, we include the cost of fence construction, vegetation planting (unless passive afforestation is assumed, which has zero planting cost), and construction of alternative stock water supplies, as well as the opportunity costs of taking land out of current production. We establish a range of costs, shown in Table 1, from a variety of sources (Taranaki Regional Council, 2016; Journeaux, 2014; DairyNZ, 2015; WET, 2011). To consistently compare costs on an annual basis, the costs of planting and constructing fencing and alternative water supplies were annualised

Table 1
Estimated costs of riparian planting (NZ$).

Cost Component	Low	Medium	High
Fencing (per m)[a]	\$2	\$8	\$16
Alternative Water Supply (per ha)[a]	\$50	\$250	\$500
Vegetation planting (per ha)	\$0	\$1000	\$5000
Opportunity (% of farm earnings)	0%	50%	100%

[a] Only applies to pastoral land uses, i.e. farms with livestock.

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[1] http://overseer.org.nz/ [accessed April 1, 2016].

over 25 years at rate of 5%. These figures are further converted to a per hectare basis for consistent comparison across all major New Zealand land uses.

The opportunity costs of taking land out of production are equal to net farm revenue, which varies depending on the type, size, and location of the farm (see Eqn. (1) and Daigneault et al., 2016). We include the construction of fencing because the riparian margin and vegetation need protection from livestock. Fencing costs therefore only apply to pastoral types of land use, i.e., all enterprises with livestock. Similarly, the cost of constructing alternative stock water supplies also only applies to pastoral land use. For this cost, we use cost estimates for an alternative water system for a 50-ha farm, which approximately corresponds to the median farm size in our land use data (Darran Austin, pers comm). We conduct sensitivity analysis of the literature-based cost data by modelling low and high cost settings that have also been cited in the literature.

The cost of vegetating riparian margins can vary significantly depending on the species planted and level of effort required. For example, our low-cost scenario assumes the buffer vegetation is established through natural processes (e.g. passive afforestation) and thus faces zero planting cost. Costs for the medium scenario ($1000/ha) are for planting mānuka at the recommended density and the high-cost analysis ($5000/ha) includes the services of landscape planning, contracting and planting (e.g., Taranaki Regional Council, 2016; DairyNZ).

The sensitivity analysis of opportunity costs was varied to assume that land directly adjacent to a stream produces lower economic returns than the farm average or that adding riparian buffers could provide production benefits to offset some of the opportunity costs such as reducing soil loss, preventing stock from drowning, and improved stock health from drinking clean reticulated water (Beef + Lamb NZ, 2016). Hence, the scenarios assume the land taken out of production was either 0% (low-cost), 50% (medium-cost) or 100% (high-cost).

To facilitate a comparison of the costs and benefits of riparian margin restoration, we estimate the monetary value of the increases in environmental benefits, $E_i - E_i'$. Specifically, we calculate the monetary value of reducing N leaching, P and sediment loss, and GHG emissions as a result of implementing the riparian restoration policy. This approach is similar to many other ecosystem service valuation studies that use market prices and benefits transfer techniques and constant prices to monetise the value of reducing an environmental contaminant or enhancing ecosystem services (see Nelson and Kennedy, 2009 for examples). While the approach has its limitations due to the uncertainty surrounding the application of an estimated value outside of the original context, it is a useful tool for researchers and policy-makers facing time and budget constraints or wishing to conduct large-scale studies such as this one (Costanza et al., 2014).

The values we use for our study are based on current market prices N and GHG emissions in NZ and values transfer from other relevant studies that have investigated the benefit of reducing P and sediment loss in the country (Table 2). Prices can fluctuate over time, and the value of reducing freshwater contaminants is likely to vary depending on the state of a given waterways, and as a result we explore the sensitivity of low and high values in addition to our core scenario analysis that assumes the medium values.

For the biodiversity gains of passive afforestation, we have no monetary value estimates. Thus, we assess this environmental improvement as the biodiversity gain on riparian margins as a percentage of an ideal state with maximal biodiversity outcomes, in which passive afforestation is allowed to occur on all of New Zealand soil.

2.3. Policy scenarios analysis

Our analysis includes a baseline with no riparian restoration and multiple policy scenarios that iterate across a wide set of assumptions. As mentioned above, there is potential uncertainty around the cost of riparian restoration, the effectiveness of the buffer to mitigate freshwater contaminants and GHG emissions, and the value of reducing environmental outputs to New Zealand society. As a result we conduct extensive scenario analysis that varies by:

- Buffer width: 5, 10, 20 and 50 m on each side of waterway
- Riparian costs: low, medium, high
- Buffer effectiveness: low, high
- Monetized value of environmental benefits: low, medium, high

The core policy analysis assumes all buffer widths face medium costs, high effectiveness, and medium benefit values as this combination is best supported by the current literature. However, for the sensitivity analysis, we also iterate across all of the above combinations to create a total of 72 scenarios in which the benefits and costs of riparian restoration can be measured relative to the no-policy baseline.

3. Results

3.1. Baseline

The reference state or baseline for land use and environmental impacts describes current land use, shown in Fig. 1. Indicators for the baseline scenario are summarised in Table 3, against which riparian restoration options are compared below. Table 3 excludes biodiversity gains, however, which are zero in the baseline because the baseline scenario does not include the restoration of any riparian margins.

New Zealand has a land area of approximately 27 Million hectares (Mha), which comprises mainly sheep and beef farms (11 Mha) and native vegetation (8.7 Mha) such as forest, scrub and tussock. In the baseline scenario with no new riparian margins being set aside and restored, dairy and forestry each take up circa 2 Mha, as do all other land uses not explicitly mentioned in Table 3. Dairy farms generate by far the highest net revenue (NZ$7.1 billion), however, which is approximately five times the revenue from the next-largest sector in terms of total net revenue, sheep and beef farming. Arable and horticultural crops are comparatively

Table 2
Estimated monetary value of units of environmental effects.

Environmental effect	Unit	Baseline monetary value (NZ$)			Sources
		Low	Medium (base)	High	
GHG emissions	tCO_2-e	$10	$20	$40	NZ Government (2015); Commtrade (2016)
N leaching	kgN	$10	$20	$40	Daigneault et al. (2016); Duhon et al. (2015); Monge et al. (2016)
P loss	kgP	$50	$100	$200	McDowell and Nash (2012); Daigneault et al. (2016)
Soil loss	t sediment	$1.50	$3	$6	Forgie and McDonald (2013); Fernandez and Daigneault (2016)
Biodiversity gain	%	n/a	n/a	n/a	Mason et al. (2012); Carswell et al. (2015)

Table 3
New Zealand baseline indicators by aggregate land use.[a]

Land use	Area (Kha)	Net farm revenue (mil NZ$)	Net GHG (MtCO$_2$e)	N leach (kt)	P loss (kt)	Sediment (Mt)	Stream length (km)
Dairy	2085	7128	13.3	79.2	1.8	8.8	31,802
Sheep & Beef	11,025	1403	21.9	112.6	5.7	137.0	226,909
Other Pasture	1263	417	1.6	7.7	0.5	10.4	22,027
Arable & Hort	341	1057	0.4	5.9	0.1	0.5	2709
Forestry	1926	991	−21.7	3.9	0.4	6.2	36,486
Native	8698	0	−5.2	10.4	0.9	23.0	160,233
Other Land	2028	22	0.4	2.0	0.1	27.7	28,505
NZ Total	27,367	11,018	10.7	221.7	9.5	213.6	508,672

[a] Based on assumption that no streams have riparian planting.

profitable, contributing NZ$1 billion from only 341,000 ha. In total, the primary sector produces NZ$11 billion in net farm revenue per annum.

The total net GHG emissions (gross agricultural emissions less carbon sequestration) produced by these sectors are 10.7 million tonnes of CO$_2$ equivalent (MtCO$_2$e) for New Zealand. The main emitters are sheep and beef and dairy farming, which together account for around 35 MtCO$_2$e annually. The forestry sector and native vegetation act as important carbon sinks, respectively sequestering 21 and 5 MtCO$_2$e/yr.

The sheep and beef and dairy sectors are also the major sources of N and P, leaching 190 kilotonnes (kt) from a total of 221 kt of N, and losing 7.5 kt out of 9.5 kt of P annually to streams. With an annual (overland and stream bank) sediment loss of 136 million tonnes (Mt), sheep and beef farms are also the main contributor to the 214 Mt total annual sediment loss. These farms are generally large and located in hilly country, which makes pastures particularly susceptible to soil loss. Forestry is another significant contributor to sediment loss (23 Mt), as wind and rain wash away the bare soil that remains after plantation forest is harvested, particularly from stands located on steep slopes. Remaining native vegetation is generally located on very steep land with high rainfall, which explains the relatively high sediment loss from this land cover class. The totals of N leaching, P and sediment loss estimated by our model are in range of other national-level studies (Parfitt et al., 2012; Dymond et al., 2010, 2013).

The final column in Table 3 shows the length of on-farm streams aggregated for each of the primary sectors we consider. The total length of streams and waterways in New Zealand is more than 508,000 km. Native land cover contains approximately 160,000 km, leaving 348,000 km of streams on land that is used for production, cities or other infrastructure. Due to its extent, the sheep and beef sector contains by far the largest share (ca 227,000 km) of New Zealand's streams, followed by forestry (ca 36,500 km) and the dairy sector (ca 32,000 km).

3.2. *Riparian scenario analysis*

The costs and benefits of a national-level riparian margin restoration policy are estimated as a result of assuming that the buffers are implemented along all streams running through primary sector land. We consider four different buffed widths, with set-aside of riparian margins of 5, 10, 20, and 50 m wide on each side of a stream, which corresponds to between 0.5 and 6.0 million ha of riparian planting across the country, or between approximately 2% and 22% of the total area of New Zealand. The relative cost and effectiveness of riparian buffers is likely to vary spatially and by sector. To account for these uncertainties in our estimates, we conducted extensive sensitivity analysis to quantify the likely envelope of valued net benefits (and associated benefit-cost ratios) that would result from adjusting both the level of effectiveness of riparian buffers to mitigate freshwater contaminants and GHG emissions (base/high v. low), as well as the cost of doing so (low, base/medium, high).

The relative change in environmental outputs as a result implementing the national riparian restoration policy is listed in Table 4. Estimates indicate that the annual net GHG emissions differ for all buffer widths between the low-cost scenario with natural revegetation and the medium and high-cost scenarios in which riparian margins are planted with native trees. Carbon sequestration is lower under natural revegetation, because grasses, weeds and shrubs are more likely to revegetate riparian margins on dairy farms and on sheep and beef farms that are distant from areas with (semi-) natural vegetation (Carswell et al., 2015). Revegetating riparian margins with native tree plantations is between 1.6 and 2.1 times more effective at reducing emissions than natural revegetation for the 20 years period we assume for full establishment under our comparative-static analysis. Eventually (after ca 100 years), vegetation growth and carbon sequestration stabilise and the net GHG difference between revegetation options disappears. With active revegetation, New Zealand's land use sector becomes GHG negative (i.e. a carbon sink) within 20 years when riparian margins are approximately 20 m wide on each side of the stream, whereas 50 m wide margins are needed to achieve that under a policy of natural revegetation.

With the available information, both active and natural revegetation of the riparian zone reduces N leaching and P and soil loss to the same degree. Narrow 5 m margins are sufficient to reduce N and P loss by 50%, and 10 m margins achieve ca. 73% reductions in both N leaching and P loss. Wider riparian margins achieve smaller additional improvements in these environmental impacts. Riparian margins of only 5 m wide already cause an 80% decrease in sediment loss, and wider margins contribute up to 15% additional reductions. While fencing strongly reduces stream bank erosion, in New Zealand a significantly larger share of stream sedimentation originates from overland erosion flows (Dymond et al., 2010).

The biodiversity gains that can be expected from natural revegetation of riparian margins appear to be limited. Riparian margins of 5 m on either side of streams attain 2% of the maximal biodiversity gains that can be expected from allowing passive afforestation to occur on all of New Zealand. This biodiversity gain increases linearly with margin width except at very wide margins, where there is a 23% increase in biodiversity relative to the baseline. As riparian margins become wider, margin area available for passive afforestation increases non-linearly with stream length as stream paths are smoothed out.

The outcomes of the various policies in aggregate monetary values, broken down by cost item and monetized environmental benefit E_i are presented in Fig. 3. The costs of constructing fencing and alternative water supplies vary according to the assumptions of the sensitivity analysis, but are not largely affected by the width of riparian margins. Planting and opportunity costs of riparian margins rise non-linearly as the margin width increases and greater areas are being restored.

Table 4
Estimated environmental impacts from national riparian restoration policy.

Scenario	Buffer width	Net GHG (MtCO2e)[a]	N leach (kt)	P loss (kt)	Sediment (Mt)	Biodiversity (% potential of ideal)
Baseline		10.7	221.7	9.5	213.6	0
% Change from baseline						
Low cost	5 m	−16	−51	−50	−82	2
(passive afforestation)	10 m	−26	−74	−73	−90	4
	20 m	−54	−88	−87	−92	8
	50 m	−147	−90	−92	−93	23
Medium & high cost	5 m	−26	−51	−50	−82	0
(active revegetation)	10 m	−54	−74	−73	−90	0
	20 m	−112	−88	−87	−92	0
	50 m	−306	−90	−92	−93	0

[a] Changes greater than 100% indicate that annual land use emissions are a net sink.

Under the high-cost assumption, opportunity costs constitute the major share of total policy cost when riparian margins are 20 m or wider. Otherwise, the construction of fences is the major cost component. We also provide a sector-level of cost, broken down by NZ land uses in Table A2 of the Appendix. Sheep and beef farms generally face the highest costs as they include the largest stream length (6.3%), and hence riparian area in the country. When 50 m riparian margins are set aside, however, the dairy sector carries the main cost, which is a result of the high opportunity costs of taking dairy pastures out of production.

The additional value of higher carbon sequestration from replanted riparian margins is lower than the increased total costs under all cost scenarios. Holding all costs other than the planting cost constant, however, the benefits from higher carbon sequestration are multiples of planting costs under the medium-cost assumption. Under the high-cost assumption, only 20 m and 50 m replanted riparian margins sequester sufficient carbon to compensate the cost of planting. This suggests that the biodiversity gains of natural re-vegetation have a significant cost in terms of lost potential carbon sequestration for the 20 years following implementation.

Riparian margin restoration generates net benefits of between NZ$1.7 billion – $5.2 billion per annum, resulting in benefit-cost ratios (BCR) ranging between 1.4 and 22.4 (see Table A3). This suggests that even when not monetising the value of the increase in biodiversity or other benefits from planting riparian strips, the benefits to climate and freshwater are greater than the implementation costs of riparian restoration. The valued benefit of reducing N leaching is the largest contribution to this result. Overall, the low-cost assumption generates the highest cost-benefit ratio, but even under the high-cost assumption benefits are twice as high as the costs.

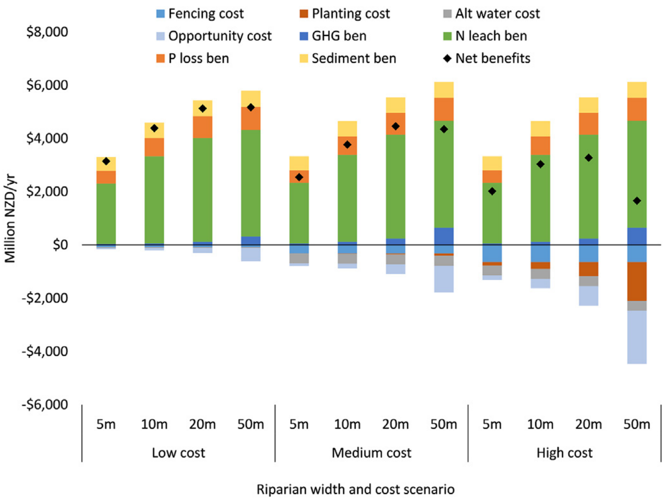

Fig. 3. Estimated net benefits (million NZD/yr) for national riparian restoration.

The estimates shown in Fig. 3 can be interpolated to approximate an optimal width that would maximize the net benefits of riparian restoration. Under the low-cost assumption, net benefits increase rapidly up to NZ$5.5 billion annually at a margin width of 30 m. Further widening riparian margins adds further net benefits, but these increases are comparatively small. Assuming medium-level costs, net benefits peak at NZ$4.5 billion per year when margins are 27 m wide, and decline in slowly as riparian margins are widened further. When we assume costs to be high, there is a clear optimal width for riparian margins at 17 m, where annual net benefits are NZ$3.4 billion. These results indicate that regardless of the cost structure, New Zealand society faces a net benefit from riparian restoration at the national scale, provided it is correctly implemented and along all waterways.

We estimate that large-scale riparian restoration provides an aggregate net benefit to NZ for all buffer widths under the core assumptions, but with notable spatial variation. Fig. 4 displays the net benefit figures on a per hectare basis at the Territorial Authority (TA) level for ease of comparison. The most positive estimates for most areas are still estimated to accrue at around 20 m buffer margin, with values ranging from about $50 to more than $500/ha/yr. TAs with a high proportion of dairy are estimated on average to experience greater net benefits from riparian restoration due to the high level of mitigation that the buffers can create. On the other hand, TAs with low proportions of intensely farmed land and/or low baseline environmental outputs are estimated to have low or even potentially negative net benefits regardless of the specified buffer width. This suggests that in the presence of a budget constraint, a riparian restoration program wishing to maximize net monetized benefits should initially target rivers and streams flowing through the intensely farmed areas located in the North Island.

Fig. 5 shows the comparative BCRs for combinations of the sensitivity analyses for cost levels (low, medium, high), valuation of benefits (low, medium/base, high) and the effectiveness of riparian margin in reducing environmental impacts (low, high/base). We provide the corresponding estimates of net present value in Table A4. For the low and medium cost scenarios, the BCR values are greater than 1 for all of the sensitivity analyses, indicating that the initiative would provide net benefits to society. In most cases, the ratios are at least 3:1, indicating that every dollar invested in riparian planting is likely to create $3 or more in monetized benefits. The high cost scenarios do not produce positive net benefits ($BCR < 1$) when the buffers have low effectiveness and the monetary values of environmental benefits used above are halved. However, in the case where one of the key assumptions was specified as low, only the wide 50 m buffer was estimated to have a

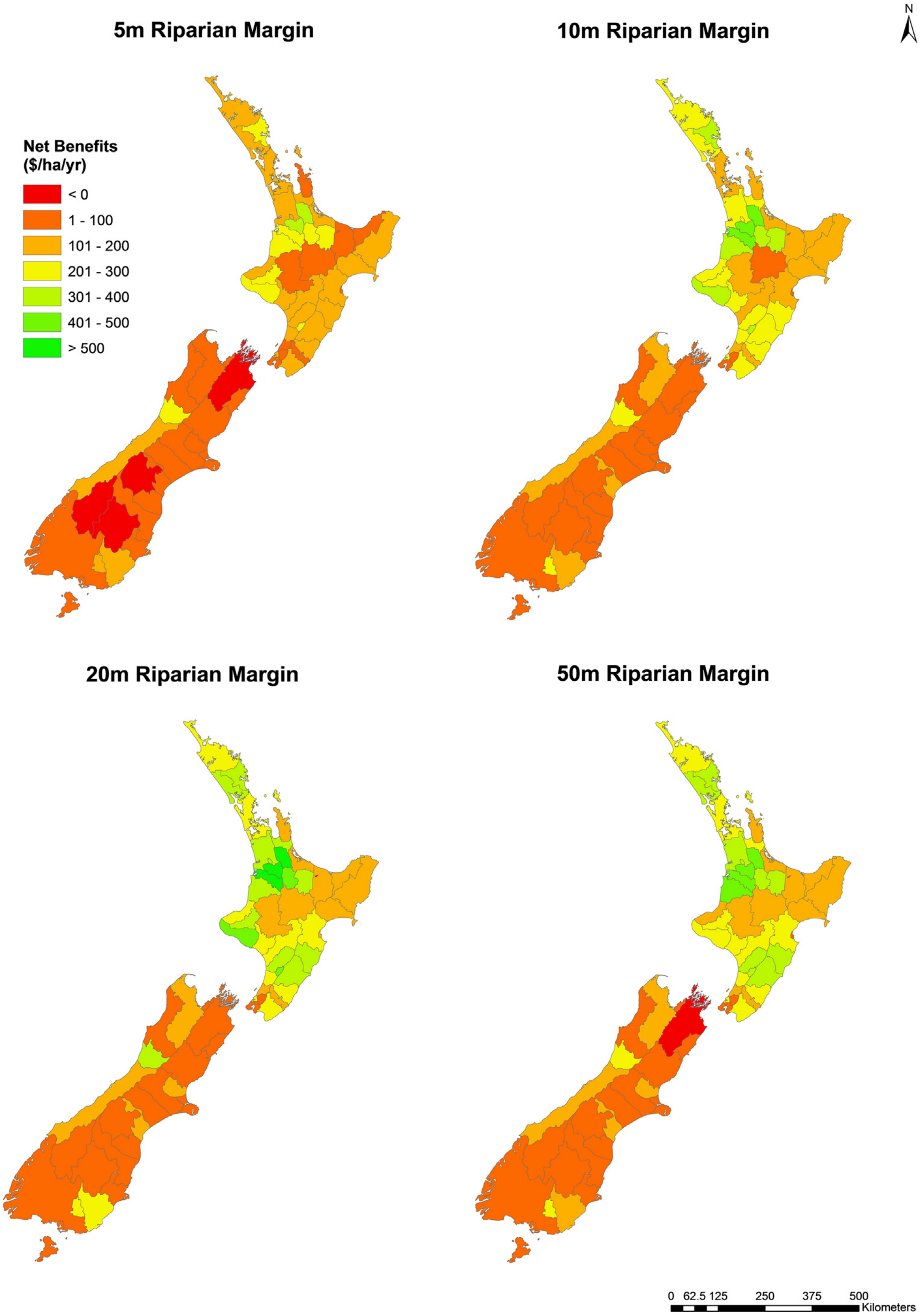

Fig. 4. Net benefits ($/ha/yr) of varying riparian margin widths by New Zealand Territorial Authority, baseline cost and effectiveness assumptions.

BCR less than 1 and create a net welfare loss. This suggests that, unless extreme conditions prevail in New Zealand, a national initiative to set aside and restore riparian margins will provide positive economic outcomes. Further benefits from riparian margin restoration can be expected, however, as we discuss below.

4. Discussion and conclusions

Agricultural expansion and intensification are compromising the water quality in New Zealand's extensive network of streams. Excluding stock from streams and restoring riparian margins is being widely undertaken to improve water quality, but no assessment exists of the cost of implementing such a policy at larger scales. We develop a model for a comparative-static analysis of the benefits (GHG emissions, N leaching, P loss, sedimentation and biodiversity gain) and relevant costs (fencing, alternative stock water supplies, planting and opportunity costs) of restoring riparian margins (5 m, 10 m, 20 m, 50 m) on all streams located on land that is currently used for primary sector activities. We conduct sensitivity analysis on the cost and benefit values as well as on the effectiveness of riparian margins in reducing environmental impacts of land use.

Our analysis suggests that restoring riparian margins on productive lands is a cost-effective approach to improve water quality

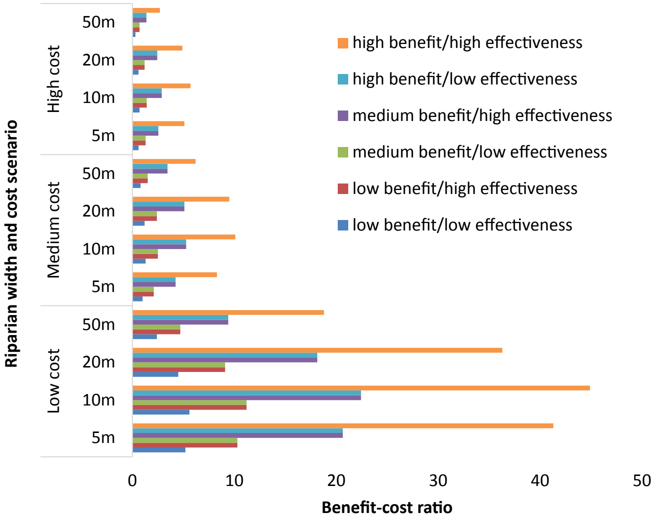

Fig. 5. Benefit-cost ratio for riparian margin widths for cost and effectiveness assumptions.

and mitigate climate change in New Zealand. For the medium and high cost levels assumed in the analysis, setting aside and restoring riparian margins of 20 m wide generates the highest annual net benefits of NZ$4.5 billion and NZ$3.3 billion, respectively. When costs are assumed to be low, margins of 50 m width produce the highest annual net benefits of NZ$5.2 billion. However, across all cost levels and margins widths, the range of annual net benefits is between NZ$1.7 billion and NZ$5.2 billion, or equivalent to about 5–15% of NZ's agricultural GDP. An interpolation of these results suggests that there is an optimum margin width of 30 m or more for the low cost assumption, 27 m for medium costs, and 17 m when costs are assumed to be high.

The findings that a uniformly applied riparian restoration programme provides net benefits to NZ society generally holds across most of New Zealand, However, even within a given policy scenario, the net benefits estimated at the Territorial Authority-level can vary by a magnitude or more, and are sometimes negative. We suggest that in the presence of a budget constraint, a riparian restoration should initially target rivers and streams flowing through the intensely farmed areas located on the country's North Island.

To account for uncertainty in the monetary value of environmental benefits and the effectiveness of riparian margins in reducing environmental impacts, we conducted a sensitivity analysis on the key parameters. This analysis confirms that setting aside and restoring riparian margins on productive land is a cost-effective policy for improving water quality in New Zealand under most assumptions. Only when values of benefits and margin effectiveness are both low and the cost level is high does riparian margin restoration produce annual net losses for all margin widths analysed. Even for the most pessimistic scenario assumptions, BCRs are greater than 1 for all but the buffers planted under the high cost scenarios. Otherwise, only 50 m-wide margins generate net losses under unfavourable combinations of costs, benefits and effectiveness. Overall, only 7 out of 72 combinations of parameter assumptions lead to annual net losses.

Our findings are aligned with other studies that riparian buffers generally provide a net benefit, even when taking into account the significant costs of implementation. For example, Holmes et al. (2004) estimated that BCRs for riparian planting in the Little Tennessee River, USA ranged from 3.3 to 15.7, while Loomis et al. (2000) reported a value of 5.2 for restoring a section of the Platte River, USA. In New Zealand, Monge et al. (2016) reported that when accounting for the value of multiple ecosystem services, some forested areas could be more valuable than dairy land. Large-scale multi-landscape studies like ours also indicated that in aggregate, there are inevitable trade-offs between agricultural production and other ecosystem services related to regulating climate and freshwater (e.g., Lawler et al., 2014; Nelson et al., 2009). When also taking into account the biodiversity benefits that continuous stretches of buffers can provide in addition to improvements in climate and water, there is a strong support for more conservation policies that encourage riparian restoration (e.g., Naidoo et al., 2006; Lovell and Sullivan, 2006).

There are a few issues to consider with respect to our results. First, the lack of nationally consistent data on existing riparian margin limits our model from accounting for riparian margins on productive lands that have already been restored. Including these buffers in the baseline would reduce costs, but also the potential benefits. Secondly, our model does not yet correct the effectiveness of riparian margin restoration for geological conditions such as slope steepness and soil type or for the ability of different vegetation types to absorb overland and groundwater flows of the various environmental impacts. Including these factors would allow us to select specific parcels of productive lands where costs are likely to be relatively low or effectiveness could be comparatively high. Ultimately, this could produce a spatially-explicit optimum that generates the highest net benefit for New Zealand. It could identify, for instance, the best way to use the National Party's pledge of NZ$100 million to implement a nation-wide stock exclusion policy that includes retiring agricultural fields adjacent to important waterways.

Other considerations may be more difficult to model. Our results suggest that the biodiversity gains of allowing passive afforestation to occur on riparian margins increase strongly only when margins are 20 m–50 m wide. This benefit is difficult to include in a cost-benefit analysis, but it should be a criterion by which to evaluate policies aiming for representativeness or complementarity in the conservation protection system. Riparian margins buffers are likely to provide several other benefits that were not accounted for in the study. Some of these physical attributes include bank stabilisation, overland flow filtering, and flood control. Many riparian species can provide wood and leaf litter input and/or shade for temperature control, which can enhance the abundance of freshwater species and stream ecosystems generally. Finally, riparian margins can provide recreational, aesthetic and cultural benefits that were not included in our analysis. New Zealand increasingly recognises Māori cultural values in policy making, requiring councils to work with indigenous people to protect significant biota, sites, activities and ecosystems. A policy assessment of riparian margins ideally considers such non-monetary effects along with net monetary benefits.

While the analysis found that a national riparian planting initiative is likely to provide positive net benefits to New Zealand, implementation will require significant costs, coordination and policy development to provide enduring environmental advantages.

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Appendix

Table A1
Description of data used to develop land block-level inputs for riparian buffer analysis.

Variable	Description	Data scale[a]	Source
Land use	GIS-based file of baseline land use across nearly 1 million land blocks.	Land block	AsureQuality (2015); LRIS (2015); LINZ. (2011)
River network	GIS-based file tracking centerlines totaling about 500,000 km of streams	Land block	LINZ (2011)
Farm Production	Annual on-farm commodity output, including milk solids, meat, wool, venison, logs, grain, fruit, vegetables, etc.	Regional, national	Kirshbaum and Watt (2011); MPI (2013); Lincoln University (2013); Statistics NZ (2013)
Stocking rates	Average land carrying capacity to estimate livestock production	Land block	Newsome et al. (2008)
Commodity Prices	5-year average farm-gate prices for product outputs	National	MPI (2015); Statistics NZ (2013)
Input costs	Annual on-farm operating and capital costs, including stock purchases, fertiliser, labour, grazing fees, energy, etc.	Regional	MPI (2013); Lincoln University (2013), MPI (2015), Olssen et al. (2012)
Riparian Costs	Fencing, planting, water reticulation, and opportunity	National	DairyNZ (2015), WET (2011), TRC (2016), Beef + Lamb NZ (2016); Journeaux (2014)
Environmental indicators	GHG emissions, carbon sequestration, nitrate leaching, phosphorus loss, sediment loss, biodiversity	Land block, regional, national	MfE (2015); Overseer (2016); Ausseil et al. (2013), Carswell et al. (2015); Kirshbaum and Watt (2011)
Riparian Effectiveness	Percent reduction from no buffer baseline if fully established	National	Zhang et al. (2010); Parkyn (2004)

[a] Scale determined by best available data source(s). All figures are downscaled to the land block-level for the analysis.

Table A2
Annual costs of riparian buffers by aggregate land use (NZ$).

Land Use	Buffer width			
	5 m	10 m	20 m	50 m
		Low Costs		
Dairy	$42,354,420	$70,974,739	$131,177,531	$333,496,108
Sheep & Beef	$99,972,324	$106,726,139	$120,934,996	$168,681,634
Other Pasture	$10,455,606	$12,246,479	$16,014,786	$28,619,615
Arable & Hort	$2,498,480	$5,092,065	$10,547,239	$28,810,356
Forestry	$4,771,561	$9,724,743	$20,142,720	$54,997,208
Native	$0	$0	$0	$0
Other Land Use	$63,720	$129,865	$269,017	$723,044
NZ Total	$160,116,110	$204,894,031	$299,086,289	$615,327,965
		Medium Costs		
Dairy	$151,125,796	$210,754,945	$336,186,500	$757,748,072
Sheep & Beef	$577,710,728	$608,260,416	$672,538,535	$888,787,845
Other Pasture	$54,840,449	$60,076,544	$71,094,287	$108,026,275
Arable & Hort	$5,192,987	$10,583,647	$21,922,185	$59,890,298
Forestry	$12,182,957	$24,829,644	$51,431,865	$140,558,122
Native	$0	$0	$0	$0
Other Land Use	$2,189,809	$4,462,974	$9,246,169	$25,323,956
NZ Total	$803,242,726	$918,968,169	$1,162,419,540	$1,980,334,568
		High Costs		
Dairy	$251,576,520	$378,000,760	$643,942,657	$1,537,841,989
Sheep & Beef	$914,004,043	$1,026,232,543	$1,262,376,205	$2,057,163,841
Other Pasture	$89,673,191	$105,108,713	$137,588,194	$246,621,189
Arable & Hort	$10,974,092	$22,365,915	$46,327,630	$126,589,744
Forestry	$32,285,879	$65,800,692	$136,304,935	$372,812,651
Native	$0	$0	$0	$0
Other Land Use	$10,567,084	$21,536,406	$44,618,249	$122,285,650
NZ Total	$1,309,080,809	$1,619,045,028	$2,271,157,871	$4,463,315,064

Table A3
Cost-benefit analysis of NZ national riparian planting initiative (mil. NZ$/yr).

		Costs				Benefits				Net benefits	
		Fencing	Planting	Alt water	Opp costs	Net GHG	N leach	P loss	Sediment	Net benefits	Benefit-cost ratio
Low cost	5 m	79.7	0	37.3	43.1	33.3	2274	475	523	3146	20.6
	10 m	79.7	0	37.3	87.9	56.0	3275	686	579	4390	22.4
	20 m	79.7	0	37.3	182.1	115.7	3901	822	587	5128	18.1
	50 m	79.7	0	37.3	498.3	313.6	4010	868	596	5172	9.4
Medium cost	5 m	318.7	7.6	373.1	86.3	56.4	2274	475	523	2544	4.2
	10 m	318.7	15.4	373.1	175.8	114.9	3275	686	579	3771	5.3
	20 m	318.7	32.0	373.1	364.2	238.1	3901	822	587	4461	5.1
	50 m	318.7	87.7	373.1	996.7	653.1	4010	868	596	4351	3.4
High cost	5 m	637.4	126.1	373.1	172.5	56.4	2274	475	523	2020	2.5
	10 m	637.4	256.9	373.1	351.7	114.9	3275	686	579	3035	2.9
	20 m	637.4	532.3	373.1	728.4	238.1	3901	822	587	3278	2.4
	50 m	637.4	1459.4	373.1	1993.4	653.1	4010	868	596	1664	1.4

Table A4
Annual net benefits of national riparian buffer initiative (NZ$).

Scenario	Sensitivity analysis assumption					
Benefit unit values:	Medium	Medium	Low	High	Low	High
Effectiveness:	High	Low	High	High	Low	Low
5 m - low cost	$3.146	$1.493	$1.493	$6.452	$0.666	$3.146
10 m - low cost	$4.390	$2.093	$2.093	$8.986	$0.944	$4.390
20 m - low cost	$5.128	$2.414	$2.414	$10.554	$1.058	$5.128
50 m - low cost	$5.172	$2.278	$2.278	$10.960	$0.832	$5.172
5 m - med cost	$2.526	$0.861	$0.861	$5.855	$0.029	$2.526
10 m - med cost	$3.735	$1.408	$1.408	$8.389	$0.245	$3.735
20 m - med cost	$4.387	$1.612	$1.612	$9.936	$0.225	$4.387
50 m - med cost	$4.147	$1.083	$1.083	$10.274	−$0.449	$4.147
5 m - high cost	$2.020	$0.356	$0.356	$5.350	−$0.477	$2.020
10 m - high cost	$3.035	$0.708	$0.708	$7.689	−$0.456	$3.035
20 m - high cost	$3.278	$0.503	$0.503	$8.827	−$0.884	$3.278
50 m - high cost	$1.664	-$1.400	−$1.400	$7.791	−$2.932	$1.664

Table A5
Benefit-cost ratio of national riparian buffer initiative sensitivity analysis.

Scenario	Assumption					
Benefit unit values:	Medium	Medium	Low	High	Low	High
Margin effectiveness:	High	Low	High	High	Low	Low
5 m - low cost	20.6	10.3	10.3	41.3	5.2	20.6
10 m - low cost	22.4	11.2	11.2	44.9	5.6	22.4
20 m - low cost	18.1	9.1	9.1	36.3	4.5	18.1
50 m - low cost	9.4	4.7	4.7	18.8	2.4	9.4
5 m - med cost	4.2	2.1	2.1	8.3	1.0	4.2
10 m - med cost	5.3	2.5	2.5	10.1	1.3	5.3
20 m - med cost	5.1	2.4	2.4	9.5	1.2	5.1
50 m - med cost	3.4	1.5	1.5	6.2	0.8	3.4
5 m - high cost	2.5	1.3	1.3	5.1	0.6	2.5
10 m - high cost	2.9	1.4	1.4	5.7	0.7	2.9
20 m - high cost	2.4	1.2	1.2	4.9	0.6	2.4
50 m - high cost	1.4	0.7	0.7	2.7	0.3	1.4

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