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Towards a framework for targeting national-scale, native revegetation in Aotearoa New Zealand's agroecosystems

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Abstract: The incorporation of native, woody vegetation into New Zealand's agricultural ecosystems offers a "nature-based solution" approach for mitigating poor environmental outcomes of land use practices, biodiversity loss, and the accelerating effects of climatic change. However, to achieve this at scale requires a systematic framework for scoping, assessing, and targeting native revegetation opportunities in a way that addresses national-scale priorities, supports landscape-scale ecological processes, and recognises that land use decisions are made at farm-scales by landowners. In this forum discussion, we outline the requirements for a spatial decision support system for native revegetation; we provide illustrations of national-, landscape-, and farm-scale components of this framework and outline a range of organisational, societal, and scientific challenges that must be addressed to enable effective and targeted revegetation across the country. Our primary motivation is to provide a focus for discussions among scientists, policy makers, hapū, iwi, landowners, communities, and other interested parties who are invested in restoring biodiverse and resilient agroecosystems.

Keywords: agroecosystems, biodiversity, decision support system, GIS, landscape ecology, multi-criteria, native woody vegetation, prioritisation, restoration, revegetation, spatial analysis

Introduction

Biodiversity and ecological function in agricultural landscapes have been in varying states of decline in many countries globally, exacerbated by ongoing land use and climate change impacts (e.g. Tscharntke et al. 2021). In response to these declining trends, the strategic reintegration and enhancement of 'non-production' vegetation elements, such as forest patches, into production landscapes, has been gaining recognition as key components of contemporary land use mitigation and climate adaptation frameworks such as Natural Climate Solutions (Griscom et al. 2018) and Nature-based Solutions (Cohen-Shacham et al. 2019). Such frameworks have recently gained traction globally (Simelton et al. 2021) and in Aotearoa New Zealand (Ministry for the Environment 2021). In New Zealand, there has been a growing impetus to address significant and ongoing threats to native species, water, and soils, especially across lowland, agricultural areas (e.g. Ministry for the Environment and Stats NZ 2019). There is clearly some urgency for the country to continue evaluating the guiding principles, policies, and regulations related to land management decision-making to ensure a just and equitable transition to a low-emissions response to climate change (Hall 2019). From the perspective of ecosystem function and biodiversity conservation, the benefits of maintaining and reintegrating woody vegetation elements into New Zealand's agroecosystems are clear (Case et al. 2020; Aimers et al. 2021; Easdale et al. 2021). From a services to humanity viewpoint, woody non-production vegetation facilitates erosion control (Stokes et al. 2014), water quality mitigation (McKergow et al. 2016), carbon sequestration (Czerepowicz et al. 2012; Case & Ryan 2020), improved animal welfare (McWilliam et al. 2017), and human wellbeing (Ausseil et al. 2021), among other beneficial outcomes. However, strategic approaches for achieving national-scale, native woody revegetation within New Zealand's agricultural landscapes remain relatively underdeveloped and untested scientifically.

The terms revegetation, regeneration, and restoration are often used interchangeably, warranting some explanation and differentiation. Revegetation is a term formally used to refer to strategic planting interventions in ecosystems where natural regeneration and woody succession are unlikely to occur due to a loss of native seed sources (via dispersal or the seed bank) and/or where the soil conditions have been significantly degraded

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(Standish et al. 2008). Such interventions are designed to use the most appropriate site preparation and maintenance methods, and the woody species having the best chance of establishing in a given set of conditions (Norton et al 2018), leading to soil and ecosystem rehabilitation (e.g. SERA 2018). Regeneration (or 'natural regeneration') refers to the passive ecological process of natural recruitment and establishment of seedlings after a natural disturbance or after the removal of a human-caused barrier to recruitment (e.g. pastoral farming) (Meli et al. 2017; Norton et al 2018). Sometimes, regeneration can be 'assisted' (e.g. Forbes et al. 2020), where targeted planting is used in areas regenerating naturally, along with the management of pest plants and browsing mammals, to effectively speed up the regeneration process and/or to facilitate the establishment of specific species that are not colonising naturally (enrichment planting). In this article, we refer to revegetation as planting interventions along a gradient from complete revegetation on previously farmed soils to assisted regeneration within existing woody vegetation areas; revegetation would be required if the goal was to reforest a considerable portion of New Zealand's rural landscapes, although opportunities exist for natural regeneration in some locations (The Aotearoa Circle 2020). Natural regeneration is more likely to occur in higher rainfall areas and in proximity to native tree seed sources, where the necessary plant-animal interactions are operating (e.g. Kelly et al. 2008), and in locations not dominated by weeds that detrimentally alter successional processes (McAlpine et al. 2018). Specifically, our focus is on the use of New Zealand native tree species as these contribute to the goal of restoring biodiversity and ecosystem integrity and facilitating a return to an indigenous-dominated state (McGlone et al. 2020). Thus, while the terms revegetation and restoration are often considered synonymous, we suggest the latter term implies a restoration of an original suite of native species and functional processes in degraded ecosystems, with the former term referring to a set of planting interventions that promote the general rehabilitation and recovery of soil and ecosystem function.

Targeting the most appropriate areas, species, and methods to use in farm landscapes for revegetation, while also accounting for multiple land use functions and competing priorities (e.g. production, carbon sequestration), is complex and often context dependent. Such decisions require in-depth understanding of agroecological processes within a multi-use landscape, underpinned by landscape ecology theory (e.g. With 2019) and knowledge of the traits and performance of native species as affected by environmental factors (e.g. climate, topography, soils) across multiple spatial scales (Charles et al. 2018). A substantial body of landscape ecology research, both internationally (e.g. Fahrig et al. 2011; Hobbs et al. 2014; Gagné et al. 2015) and locally (e.g. Meurk & Hall 2006), is available to inform revegetation design in fragmented landscapes; guidance from local government bodies (councils) also exists for matching native species to specific locations or conditions. Further, consideration must be given to ecosystem-based approaches for managing privately-owned land that is aligned with landowner values and preferences and thus accounts adequately for the socio-cultural and economic context from region to region in New Zealand (Norton et al. 2020); specifically, a revegetation strategy that is codesigned and codeveloped with Māori must be prioritised (Wehi et al. 2019).

In this forum discussion we argue that, despite some challenges, the adoption of nation-wide revegetation as an effective restoration tool in agroecosystems, to achieve a range of synergistic outcomes, is both applicable and achievable in Aotearoa New Zealand. We discuss revegetation ecology and its context in New Zealand, and consider the benefits of a systematic, multi-scale approach for targeted revegetation planning in New Zealand agroecosystems. Potential methodologies are illustrated for scoping, assessing, and targeting revegetation priorities at the national, landscape, and farm scales; the importance of the landscape scale is given particular consideration as a natural 'scale of integration', where information can most usefully be consolidated for modelling and designing revegetation interventions. Finally, we highlight several organisational, societal, and scientific challenges that must be addressed to support targeted revegetation across the country. We hope that this forum article will offer a focal point for discussions among scientists, policy makers, iwi (Māori tribes), hapū (sub-tribes), landowners, communities, and other interested parties who are invested in actions that could enhance agroecosystems for multiple positive outcomes.

Revegetation and landscape ecology

Over the past decade, the ongoing land sharing vs land sparing debate has provided a useful lens for scientific discussion about how nature, via revegetation or other interventions (e.g. maintaining crop borders, weed and pest animal removal), might be best re-integrated into contemporary agricultural landscapes to improve biodiversity conservation outcomes (Green et al. 2005; Grass et al. 2019). Land sharing involves the revegetation of localised patches of non-production vegetation for biodiversity within the farming matrix, while land sparing advocates for setting aside larger, reserve areas within the agricultural landscape for conservation purposes, along with concomitant actions to increase yields on the remaining farmland (Phalan 2018). Parallel to this debate, other research has assessed the relative benefits of "single large or several small" vegetation patches in the landscape for supporting biodiversity (the so-called SLOSS debate; Fahrig et al. 2022). Evidence globally suggests that the integration of both land-sparing and land-sharing approaches are key to restoring biodiversity and ecosystem function (Kremen 2015), as each contributes to different functional aspects of agroecosystems (e.g. connectivity, core habitat, resource provision, seed sources; Grass et al. 2019). Further, recent studies have revealed that the total amount of woody cover in many agroecosystems matters more for supporting biodiversity than the sizes of the patches per se (Arroyo-Rodríguez et al. 2020; Watling et al. 2020), and many small patches often convey larger biodiversity benefits than fewer large patches (Fahrig 2019). Such lines of inquiry have increased our overall understanding of the functional roles of non-production vegetation in fragmented landscapes. Thus, while there remain many knowledge gaps regarding the extent to which fragmented agroecological landscapes support ecosystem function (Case et al. 2020), there exists a baseline of ecological understanding against which revegetation approaches for New Zealand's agroecosystems could be considered and evaluated.

New Zealand's present-day pastoral agricultural sector, comprising over 50% of the nation's total land area, has developed out of more than a century of increasingly intensive land management, with a focus in recent decades on increasing yields (MacLeod & Moller 2006). During this time, conservation action has most consistently occurred within the conservation estate, which comprises about 33% of New Zealand's land area. This situation represents a classic 'land-sparing' (sensu Green et al. 2005 and Grass et al. 2019) scenario, with large contiguous conservation areas, mainly in higher-elevation ecosystems, that are spatially segregated from intensively-managed production land located predominately in lowland areas. As recognised elsewhere globally (Balmford et al. 2019), the biodiversity costs of this large-scale land-sparing context has been the degradation and loss of many components of native biodiversity across New Zealand's lowland ecosystems (Ewers et al. 2006). Pannell et al. (2021) showed that, while sheep and beef farmland accounts for 17% of remaining native forest in New Zealand and contributes to the conservation of biodiversity of underrepresented lowland ecosystems, much of it is fragmented and in varying states of poor condition due to lack of fencing and pest management.

Landowner- and community-led native revegetation has a long history in New Zealand (Peters et al. 2015) and continues to be an important contributor to enhancing native woody vegetation and associated biodiversity in agroecosystems. However, despite extensive, small-scale native restoration efforts across the country, minimal research has been undertaken to understand the impacts of spatial landscape design on New Zealand's native flora and fauna or how to use such information to target revegetation interventions in agricultural landscapes specifically to provide synergistic outcomes for ecosystems that are also acceptable to, and easily adopted by, landowners (MacLeod et al. 2008). To begin to address these knowledge gaps, we first consider how national-scale prioritisation could provide a useful starting point for spatially informed revegetation planning.

National scoping for potential revegetation impact

Native revegetation can generate synergistic outcomes, such as enhancing biodiversity and increasing the amount of carbon-sequestering vegetation. Additionally, depending on where native revegetation is targeted, there are potentially additional benefits that relate to restoring degraded environmental conditions associated with erosion, poor water quality, and lack of habitat and resources for native fauna. Thus, one approach to targeting areas for revegetation at a country scale is to spatially delineate areas where poor environmental outcomes are co-occurring across multiple indicators and to consider targeting revegetation interventions at these locations.

Spatial multi-criteria analysis (MCA) is a commonly used method to achieve this type of prioritisation and spatial targeting. The method involves the evaluation and priority ranking of spatial data for multiple indicators with respect to a given objective (e.g. Nguyen et al. 2015; Langemeyer et al. 2016). In brief, the MCA method involves: (1) identifying relevant spatial indicators that are hypothesised to contribute substantively to, and reflect variability in, an objective or state (e.g. environmental condition), (2) categorising the data for each spatial indicator into ranked impact scores that describe, in a standardised way, how an indicator influences the objective, (3) assigning weights to the spatial factors that describe their overall relative contribution to the final prioritisation, and (4) overlaying and combining the factors spatially, usually using a weighted average or sum approach. The result is a map that identifies overall spatial priorities with respect to the objective of interest.

To illustrate this process, we applied MCA to target where native revegetation activities could be prioritised across agricultural lands in New Zealand to contribute towards the mitigation of poor environmental conditions. We identified seven spatial indicators, grouped in terms of biodiversity restoration, habitat provision, water quality enhancement, and soil protection (Table 1); we ranked data for each indicator on a standardised good-to-poor (1–5) environmental condition priority scale. This list of spatial factors is not exhaustive, but nonetheless reflects multiple facets of current environmental conditions that we propose would benefit from priority-driven native remediation via revegetation. The seven ranked layers were summed to create a combined spatial layer, reclassed as ordinal scores from 1 to 4 (labelled as Low, Moderate, High, and Very High, respectively) representing the relative priority of any given area to be considered for revegetation intervention. In this case, for an area to be included in the Very High category for example, at least five of the seven

Table 1. Summary of datasets used to illustrate the national-scale spatial prioritisation approach.

Priority	Dataset name	Derivation of dataset	Source
Biodiversity	Threatened Environments Classification	Combination of national-scale datasets to quantify distribution of environments relative to their level of protection	Cieraad et al. 2015
Soil protection	NZ Empirical Erosion Model dataset	Modelled extrapolations from sediment loads in rivers	Dymond et al. 2010
	Erosion Susceptibility Classification	Risk of erosion and landslides from plantation forestry activities	Bloomberg et al. 2011
Water protection	River Water Quality for Swimming	Modelled and actual data regarding E coli levels	Snelder et al. 2016
	Freshwater Ecosystems of NZ – catchment rankings	Multiple spatial datasets for ranking freshwater environments for NZ streams	Leathwick et al. 2010
Ecological resilience	Habitat provision	Area (ha) of woody veg within 1-km moving window around 1ha cells	Custom GIS-derived
	Habitat connectivity	Mean connectedness of patches > 4ha in size	Custom GIS-derived

indicators needed to be ranked as High or Very High on the intervention priority scale.

The map outputs from this exercise provide a spatial perspective on the distribution of potential hot spots of environmental concern, based on multiple impacts, some of which might not be obvious using only one or two indicators alone. For instance, of the c. 108 000 km^2 of privately-owned farmland assessed, over 40% of that area is classed as either High (27%) or Very High (14%) priority for mitigation interventions. Breaking this down by region, most highly degraded areas (red and yellow colours in Fig. 1) are concentrated in the Southland, Otago, and Canterbury regions in the South Island, and Hawke's Bay, Manawatu-Wanganui, and Waikato regions in the North Island (Figs 1, 2a). High and Very High priority areas occur mainly on sheep and beef and dairy farmland, in comparison to other land uses (Fig. 2b). The highest priority areas make up about 11% of sheep and beef farmland and about 23% of dairy farmland. Approximately 250 000 ha of High and Very High priority area occurs on land that is classed as having extreme to severe land use capability (LUC) limitations (LUC 7 and 8) for pastoral farming (Fig. 2c). By comparison, Māori owned land comprises only about 2.5% of the total production land area (c. 2675 km^2); 524 km^2 (one fifth) of this land is ranked as high to very high priority for environmental mitigation, most of it occurring on sheep and beef farmland (Fig. 2c) with moderate to severe land use capability (Fig. 2e) limitations (LUC 6 and 7).

This priority mapping exercise provides a basis for strategic discussions around the suitability of revegetation interventions in key highly degraded locations and, in concept, could be used to mobilise and prioritise funding and advisory mechanisms. In the context of recent calls for increasing the large-scale reintroduction of native trees into our rural landscapes (Parliamentary Commissioner for the Environment 2002) and country-scale programmes for achieving this (e.g. the One Billion Trees programme; Te Uru Rākau 2018, Climate Change Commission 2021), spatial information and relevant maps are critical (Case 2020; also see Schmidt-Traub 2021). For example, assuming 500 million trees outside production forests will need to be located somewhere in the agricultural landscape to meet the goals of the One Billion Trees initiative, up to 170 000 hectares of land will be required to achieve this goal at an average stocking density of 3000 trees per hectare. Our national-scale assessment above indicates that this level of tree integration into the landscape could be fully encompassed within the most vulnerable land use capability zones alone

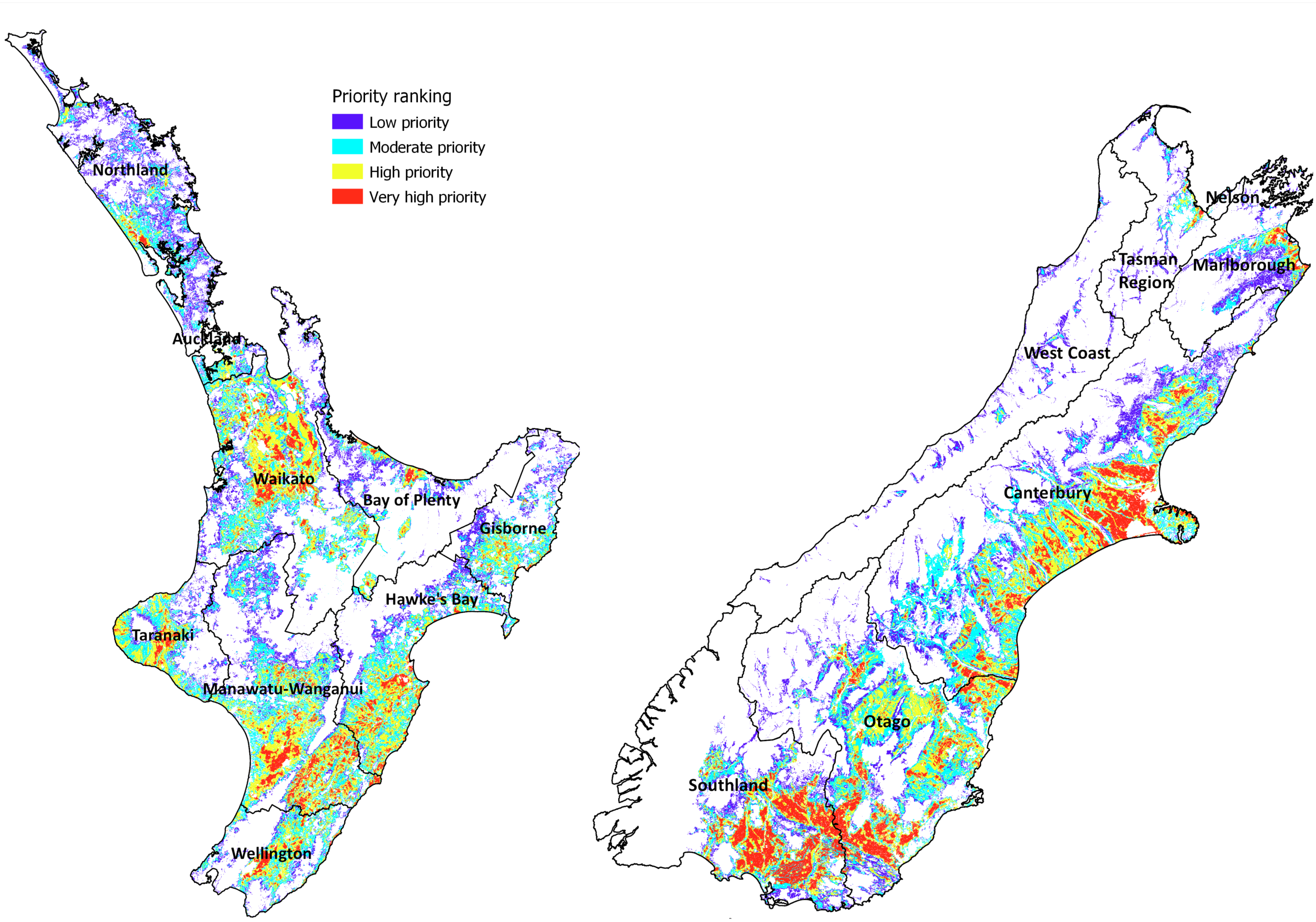


Figure 1. The result of an illustrative national-scale spatial prioritisation analysis for targeting native re-vegetation activities across New Zealand agricultural lands. The analysis was based on a multi-criteria assessment (MCA) of seven spatial datasets describing the state of water quality, habitat provision, biodiversity, and soil protection across the country (see Table 1). In the map, areas classed as Very High priority are locations where there is a co-occurrence of relatively high impact rankings across many of the seven factors. The black-outlined oval in North Canterbury delimits the general vicinity of the case-study area where the landscape-scale scoping analysis, and farm-scale biodiversity enhancement planning, were carried out (see Fig. 3).

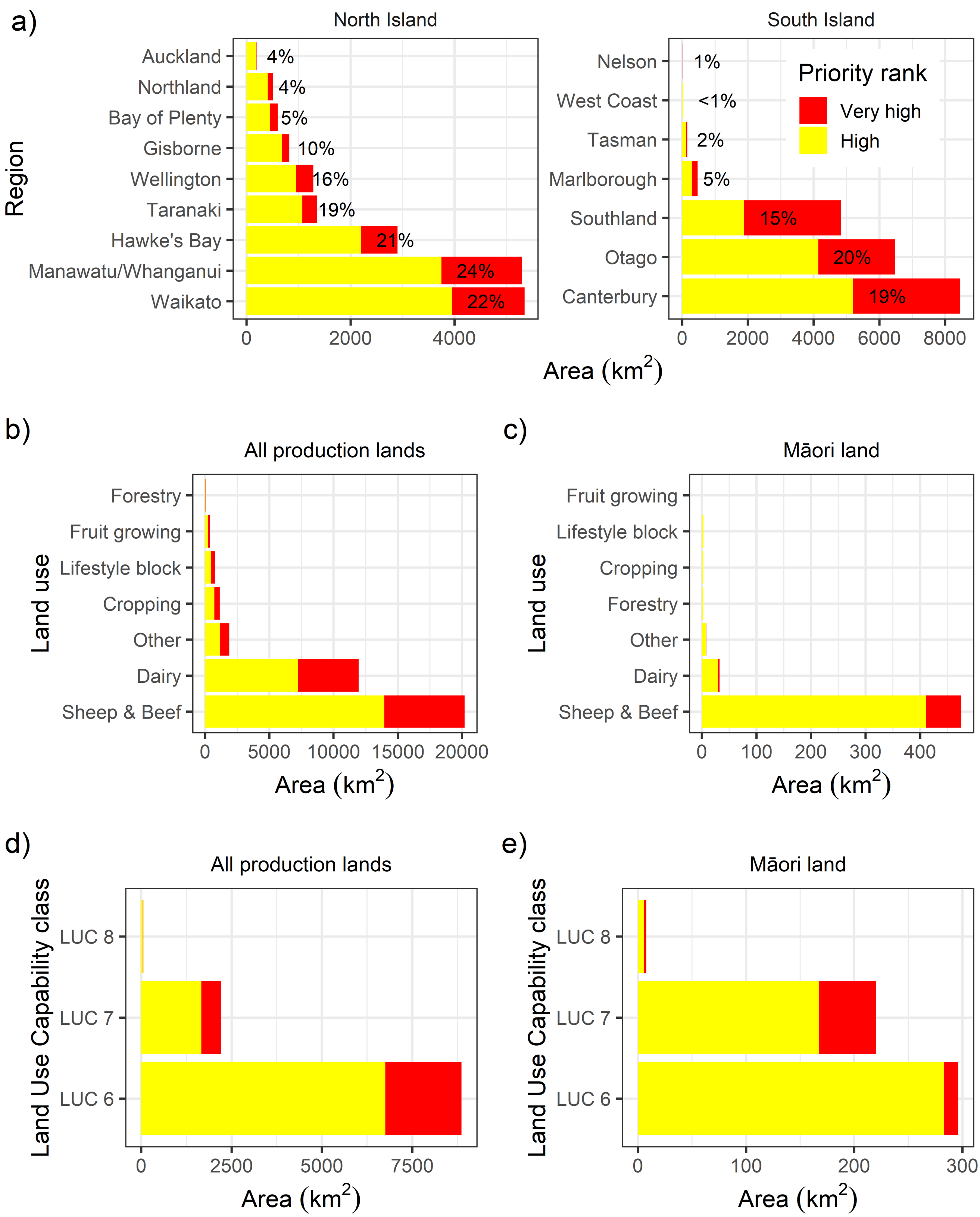


Figure 2. The amount of area (ha) categorised as High (yellow) priority and Very High (red) priority for ecosystem mitigation activities on primary production lands, based on a national-scale GIS-based scoping analysis, and summarised by: (a) administrative regions in the North and South Islands; numbers in parentheses are areal proportions of each region comprising high and very high priority zones, (b) major land use types; the 'other' land use type consists of farm areas used for secondary purposes such as pig farming, deer farming, plant nurseries, etc., (d) land use capability (LUC) classes for all NZ production lands; LUC categories 6, 7, and 8 comprise areas of moderate, severe, and severe-to-extreme limitations for pastoral or forestry activities, respectively, and (c and e) land use types and LUC classes for Māori-owned land only. Datasets used for this analysis: Land use – 2017 Agribase TM data purchased from AsureQuality; LUC – New Zealand Land Resource Inventory (Lynn et al. 2009); Māori land – 2017 Māori Land Court spatial dataset (https://www.maorilandonline.govt.nz/).

(e.g. Fig 2c), although it is critical that all landscape areas and ecosystems be represented by revegetation efforts. The prioritisation approach described above could then be combined with other information, such as where natural regeneration is most likely to occur (e.g. The Aotearoa Circle 2020) and thus, where a combination of natural successional and targeted intervention approaches might be most useful.

Designing revegetation interventions at the landscape scale

A desired outcome of native revegetation is to enhance agroecosystem function by restoring and enhancing ecosystem processes and biodiversity (e.g. Manning et al. 2018). Achieving improved ecological function and biodiversity requires a spatial design (sensu Landis 2017, Lawton et al. 2019) and implementation methodology that is specific to a given landscape. Different sets of stressors, both abiotic and biotic, are responsible for the degradation of agroecosystem processes in different parts of New Zealand; a recognition of this context dependency is fundamental to targeting appropriate landscape revegetation interventions (Norton et al. 2018). The landscape design approach therefore recognises both the historical context and the contemporary natural capital of a landscape, focussing on improving heterogeneity in both landscape composition and configuration (e.g. Fahrig et al. 2011) and increasing the overall quantum of indigenous habitat (e.g. Fahrig 2013).

In production landscapes, a further critical consideration involves identifying where indigenous revegetation could be targeted without significantly impacting farm production (Welsch et al. 2014; Norton et al. 2020). Such landscape zones might include farm and field margins, riparian strips, erosion-prone areas, connectivity or enhancement zones between or around existing vegetation patches, existing exotic vegetation scheduled for replacement, or stream gully areas (e.g. Norton & Reid 2013). For example, in hilly pastoral farmland in New Zealand, stream gullies and their associated catchments are common features that are often identified by farmers as "marginal" in terms of productivity and challenges related to stock access and recovery (Welsch et al. 2014); in some areas of New Zealand, gullies have also become highly eroded and continue to lose soil annually (Basher 2013). Further, these upland riparian areas have obvious linkages to downstream water quality (Harding et al 2006; Death & Collier 2010).

Here, we provide an example that considers upland stream gullies as a focal unit for targeted revegetation in a North Canterbury mixed-used pastoral landscape. We used a Geographic Information System (GIS) procedure to identify gully areas that were: (1) associated with 1st to 4th order, upland watersheds, and (2) had gully hillslope angles greater than 20 degrees, thus representing only those areas that were most likely to be prone to erosion and/or be difficult for animals to graze and be recovered by farmers. We then spatially overlaid potential gully areas meeting the above criteria with a GIS layer depicting existing woody vegetation types and their relative canopy cover, created via an image classification of freely available 30 cm resolution colour aerial imagery. We quantified in the GIS the relative proportions of gullies that were vegetated or un-vegetated, and the relative area and proportion of main woody vegetation types comprising vegetated gullies. For the Canterbury landscape example, Figs 3a to c and Table 2 show the types of spatially explicit information that can be usefully extracted and integrated from such an analytical approach.

By characterising both the existing vegetation and potential locations for revegetation in a landscape area, informed decisions can then be made regarding the best way to deploy a range of re-forestation, vegetation enhancement, or natural regeneration methods that can be tailored to best suit the context of the given site (Table 3). Additional ecological understanding of landscape features also informs this process. For example, gorse (Sullivan et al. 2007) or other woody weed species (Wotton & McAlpine 2013) present in the landscape can serve as effective facilitators for the natural regeneration of native tree and shrub species. Similarly, light wells created in mature kānuka canopies (Tulod et al. 2019), and underplanting in exotic *Pinus* plantations (Forbes et al. 2015), can enable the establishment of podocarp species. Further, spatial data generated for landscape features can be used as part of modelling exercises to investigate possible spatial landscape designs aimed at achieving desired ecological outcomes. For example, Zhang et al. (2021) explored how simple revegetation scenarios affect landscape patch distribution and potential native bird habitat connectivity in this north Canterbury landscape. Ultimately, landscape-scale revegetation options require input from farm scale assessments and discussions with landowners or landowner collectives (e.g. catchment groups) to ensure that scenarios are practically achievable (Norton et al. 2020).

Farm-scale assessment of revegetation opportunities

Most operational decisions regarding revegetation are made by landowners at the farm scale, guided or constrained by factors such as time, money, and an understanding of the interventions most appropriate for a given farm. Mechanisms that enable landowners to carry out farm-scale ecological assessments to identify revegetation and biodiversity enhancement opportunities are currently limited (Norton et al. 2020). For instance, the lack of on-the-ground advisory support is a recognised barrier to farmers' willingness to invest in ecological enhancement activities despite a credible understanding of biodiversity and its importance (Maseyk et al. 2021). In recent years, farm management planning has emerged as a tool for strategically integrating revegetation activities at the farm scale while accounting for such constraints (e.g. Dominati et al. 2021). Although farm management planning requirements in New Zealand have been traditionally focused on improved nutrient management and decreased soil loss, there is growing recognition for the need to include biodiversity as a component of whole-farm management planning (Maseyk et al. 2019) and that revegetation is one useful mechanism for enhancing biodiversity while increasing amenity and carbon sequestration benefits for farms (Suryaningrum et al. 2021).

What would a farm-scale assessment of biodiversity enhancement and revegetation options look like? For illustration, we created a biodiversity enhancement plan (via site visits by DN and subsequent mapping) for one farm within the Canterbury case study landscape that could be incorporated as part of a whole-farm management plan. This process involved first assessing the condition, composition, and arrangement of existing non-production vegetation patches that were mapped for the farm (Dominati et al. 2021); this assessment included an inventory of plant species present within these elements

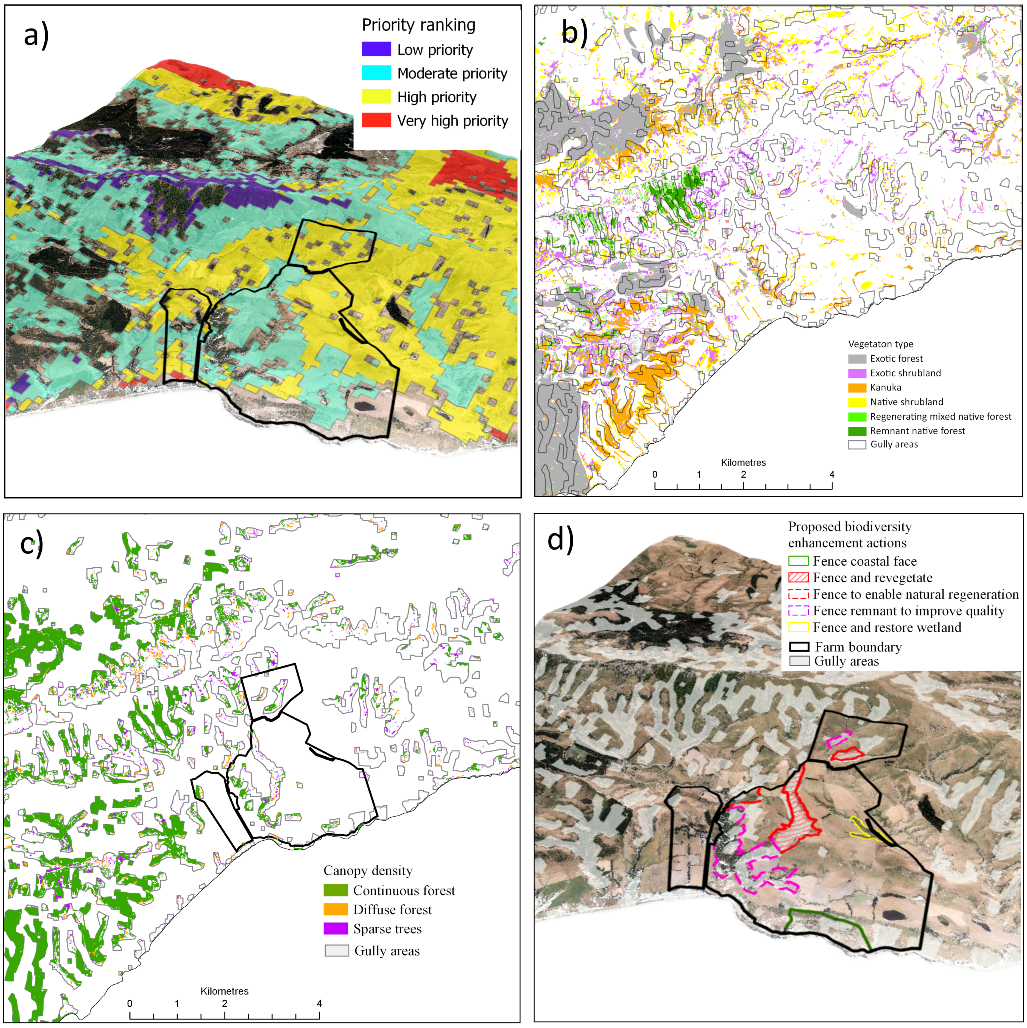


Figure 3. Generating spatially explicit scoping information at multiple scales to inform the evaluation of potential revegetation options within agroecosystems. (a) Top-down, national-scale priority rankings could be used to provide initial information regarding the overall urgency for landscape revegetation activities. Landscape-scale vegetation classifications from aerial imagery provide information regarding (b) the spatial distribution of dominant woody vegetation types and gully areas (c) the relative canopy cover for these vegetation components within gullies. Such information is critical for spatially targeting appropriate restoration locations for erosion and water quality mitigation, and for biodiversity enhancement via enrichment plantings or natural regeneration via local native seed sources (see Table 3). (d) Bottom-up, farm-specific biodiversity enhancement actions, including revegetation, can be proposed and developed in conjunction with landowners.

Table 2. An example of the information provided by a spatial overlay of GIS-delineated gully areas with image-classified vegetation types and canopy closure information, in this case for a c. 90 km^2 case-study landscape in Canterbury. The results show the relative areas (ha) of six different exotic and native vegetation classes within gullies, broken down by three canopy density categories (continuous = > 70% cover, diffuse = 15–70% cover, sparse trees = < 15% cover) for each delimited vegetation patch. This information, in conjunction with relevant spatially mapped data (e.g. Fig. 3) and consideration of ecological drivers and barriers to native revegetation (Table 3), forms a starting point for informed decision making regarding targeted revegetation at a landscape scale.

Vegetation class	Continuous forest	Diffuse forest	Sparse trees	Total area (ha)	% of total gully area
Exotic forest	360	6	10	376	15
Exotic shrubland	144	21	27	192	8
Kānuka	203	7	26	236	9
Native shrubland	84	24	20	129	5
Regenerating mixed native forest	71	5	11	88	4
Remnant native forest	48	< 1	3	51	2
Total area (ha)	910	63	97	1072	

Table 3. Revegetation options for the re-establishment of forested areas in New Zealand agroecosystems.

Revegetation methods	Outline of method	Typical locations/targets	Benefits	Specific risks*
Management of natural regeneration	Altering management to enable native tree regeneration. Retiring land from pastoral production and managing natural regeneration Feasible where native seed sources are present and where climate is favourable	Hill-country areas where repeated scrub-cutting (e.g. clearing kānuka regeneration) has been necessary to maintain pastoral cover Steep terrain where stock losses occur, and pastoral productivity is low Retirement areas between existing forest remnants (and seed sources), gorse patches, pine plantations in some circumstances	Low establishment costs Suitable for large or small areas Passive, so fewer resources required Species are suitable for the site Propagules are sourced from local genetic stocks	Requires expert assessment to determine management inputs Desirable species may be missing due to constraints on dispersal or establishment Uncertain successional trajectory, especially towards old-growth condition (may benefit from enrichment planting) Requires control of feral animals
Enrichment planting	Planting seedlings of desirable species (normally long-lived canopy species) to accelerate and direct successional development Can involve grid planting or planting seed islands on the most practical/ favourable sites	Secondary scrub or forest distant from natural seed sources (or restoration plantings that lack these species) Novel treatments of light-demanding weeds to attain native dominance Planted exotic stands to achieve native-exotic mixed forest	Lower establishment costs Can restore lost forest components Opportunities to direct succession to meet objectives (e.g. high biomass or biodiversity)	Requires eco-sourcing to maintain genetic integrity Requires expert input for species choice Requires post-planting monitoring and maintenance, and consideration of the need for exclusion of feral animals
Forest restoration planting (‘broad acre planting’)	High-density planting (e.g. typically 2500–4444 stems ha^{-1}) of early-successional tree and shrub species to establish a closed native canopy. Needed where a natural canopy will not form, natural regeneration is unlikely, or specific species are missing.	Retired grassland where natural regeneration is limited Using specific compositions to deliver economic outputs (e.g. mānuka for honey or timber) Planting to deliver ecosystem services (e.g. water quality and erosion mitigation)	High level of certainty over future forest composition and structure Accelerated rate of forest establishment.	Requires high levels of active interventions; suited to smaller areas Higher financial cost: seedlings, site preparation and maintenance Requires expert input for species choice Requires active ecosourcing Feral animal control

Notes: *in addition to these treatment-specific risks, all native forest revegetation methods inherently are at risk from degradation of the treatment from extreme climatic events, or from excessive herbivory or wildfire.

(including rare or threatened species), the need for fencing to exclude stock, whether pest mammal control was being undertaken, the extent to which non-production vegetation elements were currently connected within the farm and to patches on adjacent farms, and whether there were particularly important or rare ecosystems present that could be prioritised.

This assessment informed the development of a biodiversity enhancement plan in conjunction with the landowner, resulting in specific recommendations for on-farm ecosystem enhancements (Fig. 3d). For this farm, recommendations included fencing gully, wetland, and coastal scrub areas combined with revegetation methods ranging from full restoration planting, enrichment planting (planting native tree seedlings within existing vegetation) and allowing passive natural regeneration from local seed sources along with restrictions on grazing by stock and ongoing control of invasive pest plants and mammals. It is clear how such farm-scale information is critical to ensuring meaningful, practical, and affordable interventions; what is more complicated is how to compile and integrate farm-level information at landscape scales.

Integrating information across scales: decision support for revegetation

The complex task of strategic revegetation at a national scale warrants thinking about how multi-scale spatial information might be integrated for practical decision making. The natural scale of integration is the landscape scale, where the focus is on how the composition, structure, condition, and spatial arrangement of non-production vegetation can be varied to generate multiple ecosystem benefits. While scenario models that investigate the effects of varying landscape-scale elements and designs on ecosystem services and functional outcomes (e.g. Powers et al. 2020) contribute to understanding of agroecosystem function, care must be taken that such models are grounded in real, context-specific information and rules for decision making (e.g. Chopin et al. 2019). Thus, we propose a decision support framework with spatial, landscape-scale scenario modelling at its core, guided by expert stakeholder input and information regarding top-down national-scale priorities and bottom-up farm-scale realities (Fig. 4). We contend that this approach would enable realistic and comprehensive revegetation designs to be considered, implemented, and tested. To make such a framework operational, the following gaps need to be addressed:

(1) Explore, demarcate, and evaluate decision rules for revegetation across scales (Fig 4a)

At each scale, priorities, motivating/guiding principles, and ecological and socio-cultural realities must be considered to generate the rules governing revegetation planning and implementation. Decisions regarding, for example, the landscape zones in which to focus revegetation and the types of woody species and revegetation methods to use, must be guided by, and incorporate, national-level priorities, the interventions most relevant and achievable for each farm within a landscape area, while also considering possible future conditions under regional climate change trajectories. The datasets generated by the MCA approach and the farm-plan level biodiversity assessments (via whole-farm plans) outlined above would provide a basis for this. Relevant government regulations and policies, and catchment/regional scale priorities and plans, would further contribute towards aligning revegetation within landscape areas where landowner actions are already required by law (under, for example, the National Environment Standards for Plantation Forestry). Informed by these top-down and bottom-up decision rules, landscape scale scenarios could then be generated within a more restricted domain, thus better reflecting priorities and on-the-ground realities for a particular catchment or landscape area. Clearly, the development of such decision rules needs to be based on expert input (and buy-in) from multiple stakeholders.

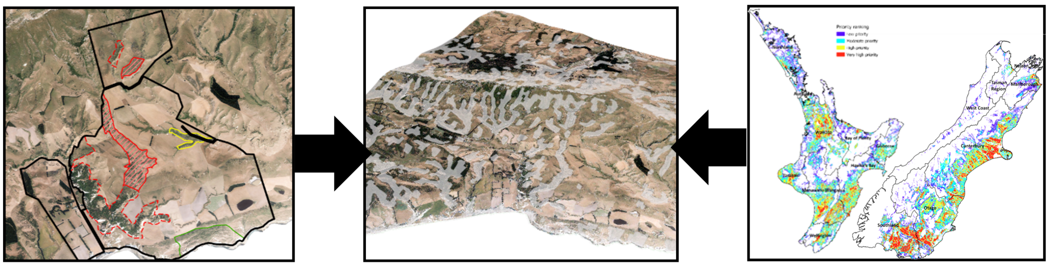
(2) Establish, and enhance existing, connector and advisory services (Fig. 4b)

Recent modelling of social network influences in rural New Zealand on environmental outcomes suggests that desirable outcomes are mediated by the interactions between landowner peer influence and spatial knowledge transfer through the network; the latter factor enables spatial clusters of pro-environmental behaviour to act as seeds that trigger uptake of those behaviours locally via peer pressure (Yletyinen et al. 2021). Indeed, land managers consistently state that a lack of knowledge is a barrier to biodiversity conservation efforts and emphasise the need for additional practical assistance, resources, and advice that is not necessarily affiliated with councils (Maseyk et al. 2021). An example of this would be regional independent advisors, funded by government, whose roles are to provide expert ecological assessments and knowledge, connections to funding sources and resources, and advice to landowners that could feed directly into farm management plans (Norton & Reid 2013). In 2019/20, Te Uru Rākau, through the One Billion Trees fund, trialled a new position – a restoration ambassador – to specifically provide advice on native reforestation on farmland while the MPI Sustainable Food and Fibre Futures Fund is now supporting a new project to set up a biodiversity extension resource (2021–2023); we suggest such advisory input is essential for achieving widespread native revegetation and biodiversity enhancement.

(3) Consider roles, responsibilities, and governance (Fig. 4c)

Success of the revegetation planning framework outlined here depends as much on the social as the ecological context (Wade et al. 2008; Case et al. 2020). Involvement of all relevant parties in a collective and coordinated planning and decision-making process is necessary (Chapin et al. 2012), supported by relevant advice, policy, regulatory bodies, and funding mechanisms (Brown & Penelope 2016). An important part of this is the development of genuine partnerships among farmers, community groups, hapū, scientists, and both private and public sector interests (Norton et al. 2016). At the landscape scale, collective planning programmes that have been successfully implemented in multi-use rural landscapes in New Zealand can be used as model examples, such as integrated catchment management approaches (e.g. Tyson et al. 2017; Scott et al. 2019) and landscape-scale, rural predator control programmes (Glen et al. 2019). Ultimately, a combination of both top-down, centralised oversight and bottom-up, broad-actor network of stakeholders will likely be optimal (e.g. Leventon et al. 2019).

Fundamentally, New Zealand land use decision making remains driven by a colonial, dispersed, private ownership model of responsibility, where the costs of environmental outcomes are externalised (e.g. Joy & Canning 2021). The focus



	Farm scale information and realities	**Landscape/catchment scale design and planning**	**Regional/national scale priorities**
a) Decision rules	• Farmer goals (e.g., for biodiversity) • Existing natural capital and possible sites for revegetation • Suitable and economical revegetation methods • Schedule of intervention activities that fit within a whole-farm plan	• Revegetation goals for a given landscape (informed by national priorities) • Existing landscape structure, context, and species information • Availability of target areas/zones (informed by farm plans)	• National and regional goals and priorities for revegetation (e.g., species vs ecosystem perspectives and aims) • Choice and weighting of priority indicators (environmental, social, cultural, spatial) • Socially-accepted intervention options
b) Support	• Local advisory, regulatory, and financial support to landowners	• Evidence for effective landscape designs • Knowledge transfer • Collective planning	• Coordinated government support programmes
c) Roles, responsibilities, & governance	• Landowners driving decision making • Whole farm plan development	• Collective actions to spread knowledge and motivate revegetation • Co-design with iwi/hapū, co-integration of conventional science and mātauranga	• Coordinated government strategies and policies • Broad stakeholder and expert input, alignment with Te Tiriti/co-governance aspirations
d) Revegetation finance options	• Subsidy/grant accessibility • ETS potential • Covenanting	• ETS collectivisation • Carbon & biodiversity co-planning	• Development of biodiversity payment scheme • Green bonds
e) Research needs	• Measuring and monitoring biodiversity, function, condition • Quantifying social, cultural, economic impacts of revegetation	• Modelling approaches to 'optimise' for multiple benefits under constraints • Empirical testing of landscape ecology hypotheses with existing data	• Development of long-term monitoring network in agroecosystems • National gap analysis for environmental and biodiversity needs

Figure 4. Challenges and considerations at multiple scales that inform the development and implementation of a national-scale revegetation framework for Aotearoa New Zealand.

of this model has been, and largely remains, on investment in capital assets that enable shorter-term profit-making, hampering the ability to adapt smoothly to changing land use requirements into the future (Mackay et al. 2011). Thus, we need to consider the critical role that Māori should play in helping generate a fit-for-purpose and agile revegetation framework for Aotearoa New Zealand's agroecosystems. Although only c. 2.5% of the country's production lands are under direct management by Māori (freehold, general, and customary land types), tikanga Māori (e.g. katiakitanga), and the right to express self-determination with respect to land use (tino rangatiratanga), should form a basis for agroecosystem revegetation (Smith et al. 2020); both mana whenua and private landowners can benefit from shared knowledge, governance, and decision-making at the most appropriate social and ecological scales (Lyver et al. 2019).

(4) Design and implement revegetation finance options (Fig. 4d)

Addressing financial barriers to native revegetation and ongoing maintenance is critical. Rural decision makers are not solely driven by financial motives when it comes to tree planting: they give priority to intrinsic values such as landscape and amenity value, personal and spiritual wellbeing, kaitiakitanga and guardianship duties, and instrumental values such as livestock health, water quality, and erosion control. However, the major reasons for not planting are overwhelmingly economic, in particular, the opportunity costs for the highest and best land use, in addition to cost of planting trees (Stahlmann-Brown 2019). Potentially, finance enables decision makers to achieve the outcomes they value.

Yet the biodiversity financing and policy landscape is inadequate. Central and local government provide various subsidies and grants to support native tree planting, such as direct landowner grants through the One Billion Trees Programme and revegetation funding for covenanted land in the QEII National Trust; however, this funding is fiscally constrained and uncertain across successive governments. Philanthropic and corporate funding contributes to community restoration efforts, but it is often time-limited and accompanied by prohibitive transaction costs (Brown 2018). Finally, the Emissions Trading Scheme (ETS) has both upsides and downsides for native biodiversity. On the upside, native afforestation that meets the forest definition can register in the ETS to generate carbon credits and thereby generate cashflow by sales to emitters. On the downside, the ETS generates far greater financial incentives for fast-growing exotic species like pine and eucalyptus, because higher rates of carbon sequestration result in higher volumes of credits to sell. Although the presence of native biodiversity is greater in exotic forests than exotic grasslands (Brockerhoff et al. 2008), mass exotic afforestation carries a significant opportunity cost compared to restoring native habitats which optimise biodiversity value. Moreover, the restrictiveness of the forest definition, which excludes small forest patches as well as non-forest ecosystem types, means that carbon revenue through compliance or voluntary carbon markets is inaccessible or challenging for many habitat types that nevertheless create significant biodiversity value.

There are growing calls to adjust ETS settings to mitigate its perverse impacts for native biodiversity, landscape resilience, and regional economic wellbeing (Collins & McFetridge 2021; Rau 2021;). The ETS exemplifies a singular outcome mechanism (carbon offsetting in this case) that often leads to detrimental outcomes for other equally important co-benefits (Easdale et al. 2021) like biodiversity; this siloed approach has often been the rule rather than the exception in Aotearoa New Zealand. Thus, there has been recently renewed interest in creating meaningful and dependable payments for other ecosystem services, in particular a direct payment for biodiversity value (e.g. Aotearoa Circle 2020). An effective economic instrument would enable multiple outcomes to be encompassed holistically, and further facilitate financial innovation, such as the issuance of green bonds, to diversify sources of funding and financing (Hall & Lindsay 2021). However, a precondition for policy and financial innovation is a robust and credible framework for monitoring, reporting and verification of biodiversity improvements (UNEP FI and UNEP-WCMC 2021).

(5) Fund research and data collection to fill knowledge gaps and test ideas (Fig. 4e)

While there is foundational understanding that can be drawn on to guide agroecosystem revegetation, there remain many gaps in scientific knowledge regarding: (a) how key native plant and animal species function in fragmented landscapes and their interactions with non-native flora and fauna, (b) the distribution and status through time of many indigenous species, (c) the ecological thresholds that may determine critical losses or gains of biodiversity or ecosystem function under differing environmental contexts or future climate or land use change scenarios, (d) the most optimal landscape designs providing synergistic outcomes, and (e) which components of the agroecosystem should be monitored to best-indicate when benefits are achieved in terms of, for instance, soil health (e.g. Hermans et al. 2020), functional biodiversity (Case et al. 2020), and water quality (Gadd et al. 2020). Further, available spatial datasets (such as the Land Cover Database used in our national analysis example) are typically not of sufficient resolution to represent important existing, small vegetation features such as small riparian zones, hedgerows, shelterbelts, and wetland elements. Increased investment is needed to develop detailed vegetation datasets at the country scale that would facilitate ecological analyses. Thus, directed research and investment is required to fill these knowledge and data gaps and to monitor the state and change of agroecosystems into the future.

Simulation and/or optimisation modelling work is required to help explore how to best-arrange and schedule revegetation actions in the landscape according to ecological, socio-cultural, and economic objectives (Thomson et al. 2009; Jellinek 2017; Powers et al. 2020). Revegetation concept designs need to also be carefully validated against the most responsive ecosystem process indicators (Fahrig 2013) using natural experiments that represent situations along the land sparing-sharing gradient and which provide useful examples of landscape variability (Pasher et al. 2013). Finally, research is urgently required to determine which native tree and shrub species are most effective, as alternatives to exotic species, for mitigating erosion and water quality degradation, and for carbon sequestration (but see Kimberley et al. 2021), in different environmental contexts and in response to climate change effects, including increased droughts and intense rainfall events.

There is a handful of examples emerging from New Zealand agroecosystem research that illustrates the types of positive gains in ecosystem parameters achieved via planned revegetation and restoration actions (Dodd et al. 2008), by enhancing existing native woody vegetation through fencing patches on farms and/or controlling for pest mammals (Burns et al. 2011; Dodd et al. 2011), through protecting native patches under covenanting schemes (Norton et al. 2018), and achieving water quality benefits via large-scale riparian planting (Daigneault et al. 2017). The challenge, therefore, will be to ensure adequate investment into future research that results in science-based revegetation scenarios and methodologies that are also grounded in reality.

Conclusions

Progress towards achieving extensive and impactful revegetation must start with a multi-scale spatial assessment and planning approach to enable discussion around possible priorities and revegetation opportunities. Ideally, the aim of these discussions would be to make progress towards collectively designed management plans for restoring and enhancing both native biodiversity and ecosystem functioning to achieve multiple beneficial social-ecological outcomes. Native revegetation, when done in a targeted manner, underpinned by ecosystem restoration principles, and accounting for landowner, iwi, and community requirements and motivations, could be a highly effective intervention to enhance native biodiversity and ecosystem function in New Zealand's agroecosystems. If decisions can be made collectively, supported by relevant spatial datasets, within a multi-criterion, landscape ecology design context, interventions are more likely to optimise connectivity and animal resource requirements, and lead to concomitant improvements for erosion and soil loss, water quality, and biodiversity.

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Author Contributions

BSC carried out the spatial analyses and mapping and led the development and writing of the manuscript. All other authors contributed to discussion of the ideas in the manuscript and to its conception, development, and writing.

Data Availability

The derived datasets created in this manuscript are available from the corresponding author upon request. The raw datasets used to create these derived datasets are all freely available via online data repositories.

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Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. Maps of the seven spatial factors used in the national scoping analysis.

The New Zealand Journal of Ecology provides supporting information supplied by the authors where this may assist readers. Such materials are peer-reviewed and copy-edited but any issues relating to this information (other than missing files) should be addressed to the authors.