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Farming in a changing environment: Increasing biodiversity on farm for the supply of multiple ecosystem services

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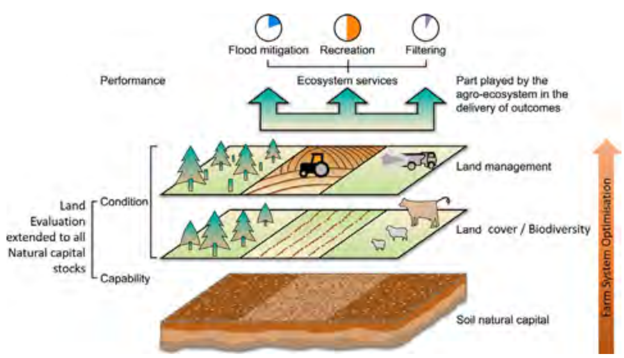
HIGHLIGHTS

- Use of an ecosystem approach to extend land evaluation to include biodiversity
- Ecosystem services supply from all parts of the farm
- Farm system optimisation within ecological boundaries
- Co-benefits of increased profit as well as decreased environmental impacts
- Discussion of strategy to incorporate biodiversity enhancement into farm management

GRAPHICAL ABSTRACT



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ABSTRACT

Among natural resources, soils continue to be poorly represented in ecosystem services frameworks and decision-making processes. Similarly, the supply of multiple ecosystem services from agro-ecosystems and trade-offs between services remains under-researched. As a consequence, it is unclear how and to what extent agriculture can deliver on environmental sustainability, whilst maintaining current levels of profitability. One of the main barriers to implementation of environmental management practices is the perception by the farming industry that environmental gains come at a cost and impact negatively on profitability. Therefore, we need to demonstrate that inclusion of all the natural resources on farm in farm system design and management offers flexibility for the farm system and insures improved sustainability and greater resilience.

In this study, an ecosystem approach was paired with a new generation farm system optimisation model and the inclusion of natural resources beyond land, especially biodiversity, to explore farm system design, and report on ecosystem services beyond food and fibre from different parts of the farm. The approach was tested on a sheep and beef farm in Waikato, New Zealand to explore the added benefits of replanting fragile parts of the farm landscape for soil and biodiversity enhancement on reduced emissions to air and water, and trade-offs between different services and farm profitability. The approach showed that it is possible to define and include ecological boundaries within which resources can be managed to deliver multiple benefits ranging from increased per hectare profitability to decreased environmental footprints. This is a feature analytical farm system frameworks will require in the future. The research also highlighted the importance of developing our understanding of the relationship between the condition and function of indigenous biodiversity fragments and adjacent pastoral

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ecosystems and their contribution to economic, environmental, cultural and social outcomes on and beyond the farm.

1. Introduction

Among natural resources, soils and more generally land continue to be poorly represented in ecosystem service frameworks and decision-making processes (Dominati et al., 2010). Similarly, whilst the degree to which agriculture can provide individual ecosystem services has been well researched (Palm et al., 2014), the supply of multiple ecosystem services from farmland and agro-ecosystems and trade-offs between service remains under-researched. As a consequence, it is unclear how and to what extent agriculture can deliver on environmental sustainability, while maintaining farm profitability (Dominati et al., 2014b; Schulte et al., 2014; van den Belt and Blake, 2014). This is in stark contrast to the research investment in deepening our understanding of the flow of services from natural ecosystems. This is short sighted as agro-ecosystems already provide a wide range of services beyond food and fibre that contribute to environmental, as well as social and cultural outcomes. A large part of community lives in rural settings, in close proximity to agri-businesses. For example, in New Zealand, in 2006, 28% of the population lived in population centres of 30,000 people or less (Statistics NZ, http://archive.stats.govt.nz). There is enormous scope, not available in natural ecosystems, to manipulate the mix and quantity of services supplied by agro-ecosystems: agro-ecosystems cover a large area of land and management practices can be targeted to deliver specific services.

New Zealand, a primary industry based economy, essentially trades on its natural capital, but has been changing in the last 15 years. It has reached a point where land, in addition to water, is becoming a scarce resource. The increasing demand for land ranges from urban growth and lifestyle blocks around the margin of major town and city, and competition between the land-based industries, with forestry competing with sheep and beef systems, dairy competing with sheep and beef and horticulture competing with both dairy and sheep and beef systems (Mackay et al., 2011b). In parallel, emerging policy to protect receiving environments (e.g. water bodies) is placing limits on how and what land can be used for throughout the country. This pressure on land availability adds to the historical natural resource exploitation that includes the poor matching of land use to land type and little attention to the impacts of agriculture on adjacent natural systems and receiving environments. This has created challenges that span from land degradation, biodiversity loss, water pollution, and climate change that are not unique to New Zealand.

Nowadays most primary industry organisations in developed countries promote best management practices in the pursuit of primary production and protection of the environment. While best practices have made some progress in mitigating current environmental impacts, often they do not address the historical issues associated with the poor match between land type and land use or management practices. The implications of changes to the farming system on the provision of ecosystem services beyond food and fibre are still rarely considered by resource management schemes (Dominati et al., 2016; Rana et al., 2018).

According to the World Bank collection of development indicators, Agricultural land (% of land area) in 2015 was reported at 42.2% in New Zealand, 44.3% in the USA and 70.8% in the UK. Because of the extent of agro-ecosystems, there is enormous scope for changing the flow of services from them. Looking forward, a rethink of our expectations of farmland and how they fit in the wider environment is needed.

One of the main barriers to implementation on-farm of environmental management practices is the perception by the farming industry and individual farmers that environmental gains will come at a cost to production and impact negatively on profitability. This thinking is slowly changing with the recognition that historically, land use practice and policy frameworks largely ignored impacts on receiving environments, allowing a single focus on production and profit. Therefore the first step in making progress towards wider implementation of sustainable environmental management is to demonstrate that careful design of farm systems, mindful of the range of natural resources on the farm, including previously considered "non-productive areas", can not only help the farm system perform better but a focus on multi-functionality can ensure improved sustainability and greater resilience in the future.

In the last 100 years in New Zealand, the transformation from indigenous forests to predominantly pastoral landscapes has been beneficial for food and fibre production and the export economy. It has come at a cost to natural capital, with extensive loss of indigenous vegetation, which has been ongoing since human occupation began in 1280 CE (Ewers et al., 2006; Hall and McGlone, 2006). Widespread land degradation, poor water quality in lowland environments and the extinction of a large percentage of indigenous species, as well as a loss of cultural identity are ongoing. The depletion of natural capital compromises the country's long-term productive capacity, threatens food and water security, and reduces the physical, economic, cultural and social resilience of farming landscapes and their communities (Sirami et al., 2010; Fielke et al., 2018). Halting and reversing this decline needs a concerted effort to both protect what biodiversity of significance is left and to reintroduce indigenous biodiversity in places where it has been greatly reduced.

All these pressures raise a number of questions:

1. How best to use our finite land resource and more generally natural capital in the future to address land degradation, protect receiving environments, and ensure the continued flow of ecosystem services for wellbeing?
2. How can farm systems be designed to ensure their natural capital (including soils and biodiversity) are maintained and enhanced to provide the full range of ecosystem services while being profitable?
3. Can the enhancement of biodiversity and farm profitability go hand in hand?
4. Can increasing indigenous biodiversity representation on-farm increase overall farm resilience?

To explore these questions, we pair the ecosystem approach (Dominati et al., 2010; Banwart, 2011) with a next generation farm system model to explore the supply of multiple ecosystem services from different parts of the farm, while giving consideration to the implications and utility of considering all natural capital types of the farm, including soils, landforms and biodiversity across a range of vegetation types, on farm-system design, management and subsequent performance.

2. Material and methods

2.1. Setting the scene – the current state of New Zealand's indigenous biodiversity

New Zealand has a relatively short history of human habitation (from *ca.* 1280 CE) (Wilmshurst et al., 2008) and in this time has experienced a rapid and drastic loss in indigenous biodiversity. At a national scale, this has included the loss of nearly three-quarters of indigenous forest cover (Ewers et al., 2006), more than 90% of wetlands (Ausseil et al., 2011; Myers et al., 2013), and the extinction of more than 70 species (Brown et al., 2015). A further 40% of bird species, 38% of plant species, 85% of lizard species and 74% of freshwater fish species are threatened or at risk of extinction (de Lange et al., 2013; Brown et al., 2015). The patterns of loss reflect patterns of land attributes (most obviously soil fertility, landform and climate) with the areas most suited to settlement and production experiencing the almost complete loss. In the course of transforming our lowlands from forested habitat to a farming landscape, over 90% of indigenous vegetation has been lost (Walker et al., 2006). These lowlands cover 23% of New Zealand's total land area, thus large contiguous areas of the country are almost completely devoid of indigenous vegetation cover and associated indigenous species.

In contrast, an impressive 32% (8.5 million ha) of New Zealand's land mass is protected as public conservation land (DOC, 2014). However, this land is largely concentrated in the 'backcountry' – mountainous areas and hill country less suited to development and farming – with just under half (49%) of land at elevations above 500 m, but only 18% of land below 500 m falling within public conservation land (Norton and Miller, 2000).

Outside of public conservation land, indigenous biodiversity is also proportionally better represented on privately owned hill country farm. For example, 25% (2.8 million ha) of the total indigenous vegetation remaining across New Zealand is found on sheep and beef farms which predominantly occurs in the hill country (Norton and Pannell, 2018). This is the second most important contribution to remaining indigenous vegetation cover in New Zealand after public conservation land. In contrast, dairy farms predominantly in lowland environments contain only 1.4% of the total indigenous vegetation remaining.

Thus, New Zealand's agro-ecosystems represent both opportunities and challenges for biodiversity conservation. Enhancement of biodiversity on-farm is critical for indigenous biodiversity outcomes as well as increasing the long-term sustainability of pastoral farming at a national scale. We need to demonstrate at the farm scale that biodiversity and farm business performance goals can go hand in hand, to not only encourage the sector to shift to a more integrated land management approach, but also to guide government policy and contribution to help farmers deliver outcomes beyond the farm gate.

2.2. Evaluation framework and defining boundaries

For this study, the ecosystem approach to natural resource management (Banwart, 2011) was followed as a conceptual framework. The ecosystem approach brings together the concepts of natural capital stocks and associated flows of ecosystem services. It provides the opportunity to consider all types of natural capital stocks present on farm including soils, water bodies and biodiversity, and to broaden the flows of ecosystem services measured from the farm beyond food and fibre provision (Dominati et al., 2016). This allows the integration of biodiversity into the farm planning process. It also provides the basis for investigating the impacts farm system design and management have on those stocks and the flows of ecosystem services contributing to a quadruple (environmental, cultural, social, and economic) bottom line. The use of an ecosystem approach also provides an opportunity to bring farming and biodiversity conservation into the same decision-making framework.

The challenges currently faced in New Zealand with degrading water quality are largely the result of increased loadings of sediment, nutrients and E.coli, the majority of which can be attributed to losses from farmland (PCE, 2015). This is the result of accelerated soil erosion from land use and practices poorly aligned with land capability (Bouma et al., 2012; McBratney et al., 2014). It also demonstrates that some soils have a finite capacity to retain nutrients (nitrogen (N) and phosphorus (P)) and receiving environments have a finite capacity to assimilate nutrients. In the future, land evaluation frameworks and farm systems analysis and design need to recognise that farms sit in landscapes within catchments and are not isolated and therefore they need to include environmental boundaries within which the farm system should operate.

Operating within boundaries is already an integral part of land evaluation and farm systems planning, as landowners operate daily with a range of financial, social, cultural, and biophysical boundaries. The inclusion of boundaries within which the farm has to operate while appearing to be a new element of the farm system design process, is in fact an extension of current practice (Mackay et al., 2018). Different boundaries will be defined at different scales. The landowner will define some at the farm scale (related to sustaining the quality of natural capital stocks, such as soil quality, through to financial and personal social and cultural values). Some boundaries will be defined at the catchment scale and relate to desired community (thresholds on nutrient losses, sediment) and consumer (practice and produce quality) outcomes. Other boundaries will be defined at the national scale (greenhouse gas emissions to air). Defining these boundaries raises landowners' awareness of how different parts of agro-ecosystems contribute to the flow of ecosystem services, particularly regulating services. Operating within environmental limits is critical for sustaining long-term capacity of natural resources and capacity to respond to global change.

With New Zealand continuing for the near future to trade on its natural capital, farm systems have to fit better their natural environment, limit their environmental impacts and increase their resilience to increasing volatility in weather patterns. This requires the integration of natural resource variability across the farm into farm system design. In this study, the concept of holistic farm planning (Dominati et al., 2018; Mackay et al., 2018; Maseyk et al., 2018b) which is being put forward in New Zealand has been used to demonstrate practically how to reconcile farm business performance and multiple environmental goals. Holistic farm planning is based on the ecosystem approach and translates the finite capability of natural capital stocks such as different soil types (obtained through land evaluation), biodiversity or water bodies into environmental boundaries within which future profitable farms will operate.

2.3. New farm optimisation capability

To deliver multiple outcomes across cultural, environmental, social and economic values, future farm systems will need to be designed to fit within the spatial land capability variability found on the farm, manage often multiple types of land covers and water bodies, and operate within boundaries. Temporal variation to capture the influence of climatic variation and market volatility also needs to be included as it influences environmental outcomes, as well as business investment and decision-making.

Quantitative information on the variability of land capability, current condition and trends (see graphical abstract) are key to the farm system design process to ensure closer alignment. Accounting for them will require new analytical capability in farm systems analysis and design. AgInform® (Integrated Farm Optimisation and Resource Allocation Model) is a new farm system optimisation model (Rendel et al., 2015; Rendel et al., 2018) that has the ability to integrate specific information from different areas of the farm, called land management units, which have similar natural resources, produce similar amounts of forage in a similar annual pattern, meaning they can be managed in the same way. Most farm scale tools use average pasture growth data for the whole farm and are not able to differentiate the contribution made by different areas of the farm to the whole the farm system.

AgInform® was built in collaboration with Beef +Lamb NZ and Deer Industry NZ and has the ability to isolate and analyse the contribution of each land unit of a farm to the business. AgInform® also has the capacity to place operational boundaries on the use or emissions from each land unit based on land capability, while simultaneously optimise resource use to maximise profit. For example, operational boundaries can include grazing restrictions on fragile soils over winter to protect soil structure from pugging and broaching (pugging occurs when wet pasture is trampled by cows, resulting in soil and pasture damage), higher pasture covers on steep land units to limit phosphorus (P) and sediments loss, or a cap on the deposition of urine on free draining units to limit nitrogen (N) leaching to ground water.

The linear optimisation used by the model incorporates information from each land management unit to identify the mix of production enterprises and management regimes that maximise profit (EBITDA – earnings before interest, taxes, depreciation and amortization) for the business with defined boundaries. Pasture production over the year as well as animal performance (growth and reproduction) along with costs of production (animal and land) and income from sales of livestock are key drivers in determining the optimal mix of enterprises, including animal sale dates, to maximise profit. Essentially the optimal mix of capital stock and animal sales dates are identified that maximises profit while making sure forage (usually permanent pasture but can include forage crops) is maintained in a productive state. This represents a step change over a standard approach that typically explores production and economic outcomes first and then mitigates back for specific losses (e.g. nitrates (N), phosphorus (P), and greenhouse gases (GHGs)).

AgInform® produces information about the farms financials, and physical measures over the years, which include pasture cover for each land management unit and detailed animal movement across the farm for each animal class. It also reports animal purchases and sales for each animal class and uses of crops and N fertilisers. AgInform® does not report the environmental footprints of the optimised farm system. The output from the optimal farm system described by AgInform® was entered in the OVERSEER® nutrient budget (AgResearch, 2005) to model N, P and GHGs losses from each land management unit.

The OVERSEER® nutrient budget model (https://www.overseer.org.nz/) was designed as decision support software to aid with maintenance nutrients and lime recommendations, nutrient use efficiency and reporting to emissions to water and air. It helps users develop nutrient budgets (including nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, and sodium) at the block and farm scales. It also provides a greenhouse gas emission and energy inventories for each farm.

2.4. Case study site

A sheep and beef farm situated near Tirau in the Waikato Region, New Zealand was used to demonstrate the use of the ecosystem approach for designing the farm system to optimise the flow of ecosystem services and limit the impact of the farming business on receiving environments. The farm covers 480 ha of undulating to rolling down lands (26%), moderately steep to steep hill country (15–26°) (56%) and flat to undulating terraces (5–15°) (18%). Some river flats are present in the west of the property. The geology is mainly rhyolitic ignimbrite overlain with Tirau ash soils developed on the ash are Tirau sandy loams (Typic Orthic Allophanic Soil in New Zealand Soil Classification, or Typic Udivitrand in U.S. soil taxonomy) (Hewitt, 1993). The average annual temperature is 13.8 °C and rainfall is 1374 mm (New Zealand's National Climate Database, https://cliflo.niwa.co.nz/). The farm at 1st July (mid-winter) has 6240 stock units[1] with a sheep to beef ratio of 55:45 on 450 ha effective (i.e. 55% of the wintered stock units are sheep, the remainder are cattle). The sheep flock produces lambs for sale (finishing or slaughter) with replacement ewes purchased each year. The cattle herd is primarily a Hereford breeding herd with progeny sold at weaning. This farm purchases and sells steers and sometimes grazes dairy cattle depending on the market and the season.

The farm is divided into a number of land management units (LMUs) (Table 1 and Fig. 1). These LMUs were set up using the resource information found in the property's whole farm plan produced by the Waikato Regional Council, the local government agency with responsibilities for resource management. The whole farm plan includes information on: (1) the soils and land use capability (LUC) (Lynn et al., 2009); (2) strengths and weaknesses of each land unit on different parts of the farm (for example, susceptibility to erosion, sensitivity to treading damage, drainage characteristics); (3) reflection on current and future potential uses of each land unit, (4) risks of soil erosion or compaction based on LUC; (5) connectivity between different parts of the farm; and (6) the need to protect receiving environments. The information detailed in the farm plan was combined with a broader evaluation of the farms natural capital including waterways, indigenous biodiversity remnants and plantation forests. This enabled identification of areas prone to erosion, as well as low-lying areas sensitive to pugging, which might offer more to the business replanted using indigenous species (LMU6 in Fig. 1 and Table 1).

The biodiversity restoration programme on the study farm included the creation of new habitat by planting a range of indigenous plant species. A planting plan was developed by a restoration ecologist working in consultation with the farmer. Thus, the species chosen are both ecologically suited to the geography, topography, and local soils, and have the potential to be used commercially. The restoration plan included initially planting mānuka (*Leptospermum scoparium* var. *linifolium*), an early successional, pioneer species, for honey and potentially oil production; followed by supplementary planting with indigenous tree species suited for timber production once the conditions became suitable as the regenerating mānuka matures (between 3 and 5 years old, and 2 and 3 m in height). Indigenous tree species in the family Podocarpaceae (a large family of mainly Southern Hemisphere conifers) will be interplanted (5 m apart) to provide for a potential future timber crop. Tree species will be ecologically sited, with totara (*Podocarpus totara* var. *totara*) planted on the more free-draining soils on hillslopes and terraces, kahikatea (*Dacrycarpus dacrydioides*) and rimu (*Dacrydium cupressinum*) which can tolerate imperfectly drained soils would be sited within gully floors. Given the proximity to seed sources from other areas of indigenous forest in the catchment, the restoration plan anticipates that other indigenous species will establish and the natural successional processes occur. The ultimate goal is to maintain the area as restored habitat long-term, and extraction of resources (honey or timber) will ultimately cease.

For the purposes of the farm modelling, only the impacts of planting mānuka over 42 ha was modelled, and it can be assumed that additional services and benefits will accrue from the area once the site has transitioned to a more diverse vegetation community and the canopy timber trees have established.

2.5. Farm system analysis

The ecosystem services framework was used in this study to explore the impacts of shifting from the current farm system and practices where there were no limits on emissions to receiving environments to a farm system optimised to operate within environmental boundaries and respectful of the farm's inherent variation in natural capital. A number of authors have determined and quantified the ecosystem services beyond food and fibre provided by agro-ecosystems (Bockstaller et al., 1997; Swinton et al., 2007; Zhang et al., 2007; Sandhu, 2008; Dominati et al., 2014a; Dominati et al., 2016; Bommarco et al., 2018; Hatt et al., 2018) including for example flood mitigation, filtering of nutrients and contaminants and carbon storage. In this study a range of ecosystem services were considered (Table 2) to look at the trade-offs of optimising a farm system following the ecosystem approach.

For the farm system analysis, modelling was used to explore the impacts of changing practices on the eroding and wet low-lying land units from a pastoral use to areas planted with indigenous species. Three scenarios were used to explore the trade-offs in the supply of ecosystem services from the farm including profitability. Scenario 1 represents the status quo: the current farm system. Land management unit, animal numbers and financial information were obtained directly from the

[1] One stock unit is equivalent to the pasture dry matter consumed by a 55 kg ewe over the year and her single lamb up to weaning, which is approximately 550 kg DM at 10.5 MJME/kg DM.

Table 1
Description of land management units (LMU) use and area.

	Identifier	Use and boundaries	Area (ha)		
			Scenario 1: current situation	Scenario 2: optimised base	Scenario 3: optimised with plantings
Pastoral units					
Front Hill Country	LMU1	Lambing country: no heavy cattle between June and October	100	89	89
Back Hill Country	LMU2	No heavy cattle between June and October	172	145	145
Hay and Silage	LMU3	Sheep, cattle and cropping	73	71	71
Cattle Country	LMU4	Sheep, cattle (calving), hay and silage and cropping	95	93	93
Holding paddocks	LMU5	For sheep and sires	10	10	10
Area identified for planting	LMU6	Areas grazed in scenarios 1 and 2 and replanted in scenario 3 No heavy cattle between June and October	0	42	0
Total pastoral area			450	450	408
Non-pastoral units					
Races and tracks		House, yards	7	7	7
Forestry		Eucalyptus	4	4	4
Indigenous biodiversity		QEII[a] covenants + biodiversity restoration	16	16	58
Buildings, yards		Non effective	3	3	3
Total non-pastoral			30	72	72
Total			480	480	480

[a] QEII- Queen Elizabeth II covenants in native bush

farmer. AgInfom® was not used for scenario 1; only the OVERSEER® nutrient budget was run to determine the environmental impacts of the current farm system. In scenario 2, the area of the farm grazed was kept the same as scenario 1, but LMU6 was defined (Table 1). Land management unit 6 consists of 42 ha taken out of LMU 1, 2, 3 and 4 based on information from the whole farm plan of the farm. The land identified as LMU 6 was either steep and prone to erosion and difficult to graze with poor pasture quality, low lying and wet in winter and therefore prone to pugging damage by animals, or unfenced gullies where indigenous vegetation had already started to regenerate, providing good connectivity for already protected remnants of indigenous forests. For this scenario, the farm system was optimised with AgInform®, taking into account the lower pasture growth and quality on LMU6 and the management restrictions associated with it such as restricted grazing in winter due to wetness (Table 1). The optimised farm system was modelled in OVERSEER® to determine environmental impacts. In Scenario 3 (Table 1), the 42 ha identified as LMU6 were planted in indigenous vegetation for soil conservation, improved sediment management and biodiversity restoration. Livestock was removed from LMU6 and the farm system re-optimised with LMUs 1 to 5 in pasture (408 ha) and LMU6 planted in mānuka (Table 1). The resulting farm system was again modelled with OVERSEER®. The costs associated with fencing and planting of LMU6 during the transition phase from pasture to indigenous vegetation were not included in the scenario 3. The potential impact the changes in vegetation and practices on LMU6 in Scenario3 had on the supply of a number of ecosystem services was quantified using a range of proxies (Table 2).

3. Results

Several models had to be used to explore if farm business performance and biodiversity enhancement goals can be reconciled at the farm scale within ecological boundaries. Currently, no single farm scale model is able to optimise the use of the range of natural resources found within a farm, as well as supply a range of outputs for different parts of the farm.

3.1. Changes to the farm system

The current farm system (Scenario 1) cannot be compared directly with Scenario 2 and 3, due to likely differences in inputs. The optimised systems are based on an estimate of a single year of predicted pasture growth, while the current system is based on actual pasture performance data over many years. The current system has been developed over time by the farmer who will also have personal drivers influencing the livestock policy, in addition to inter-annual variation.

The optimisation of the farm system within environmental boundaries using AgInform® resulted in a livestock policy with a sheep to beef ratio close to 50:50 for both Scenarios 2 and 3 and stock unit per effective hectare of 15.1 and 15.7 SU ha^{-1} for scenario 2 and 3, respectively. The current business had a sheep to beef ratio of 55:45 and stocking rate of 13.9 SU ha^{-1} (scenario 1). The optimised systems also had more breeding cows, with some finishing of young cattle, and some sold at weaning (Fig. 2). Ewe numbers remained stable, but the optimised systems had lower numbers of lambs sold, as no lambs were purchased to finish in the two optimised systems (Fig. 2). In scenarios 2 and 3, the AgInform® model chose not to put in a forage crop, a practice currently employed by the farmer (Scenario 1).

3.2. Provisioning services

When comparing the two modelled scenarios (2 and 3), planting 42 ha (LMU6), that is 9.3% of the total land area, decreased overall profit (earnings before interest, tax, depreciation and amortization (EBITDA) in NZD) by 5.1% (Fig. 1). Profit per hectare for the land still in pasture increased by 5% between the two modelled scenarios (Fig. 1).

3.3. Regulating services

3.3.1. Filtering of nitrates

The change in filtering of N was quantified using the reduction in nitrates leaching losses (kg N ha^{-1} yr^{-1}) as a proxy, estimated using the OVERSEER® model. In the two optimised systems (scenarios 2 and 3), N losses were higher on LMU3 and LMU4, with cattle carried year round. Average N loss for the whole farm decreased by 6% from Scenario 2 to 3 with the planting and removal of livestock off LMU6 demonstrating that environmental impacts can be mitigated somewhat when aligning the farm system closer to the farm's natural resources.

3.3.2. Filtering of phosphorus

The filtering of P was quantified using the change in P losses (kg P ha^{-1} yr^{-1}) as a proxy, estimated by the OVERSEER® model. In setting up AgInform® for exploring scenarios 2 and 3, environmental boundaries were set to limit soil erosion and P loss. Cattle did not graze land management units 1 and 2, the steeper and more fragile parts of the farm, in the winter months to limit soil damage and

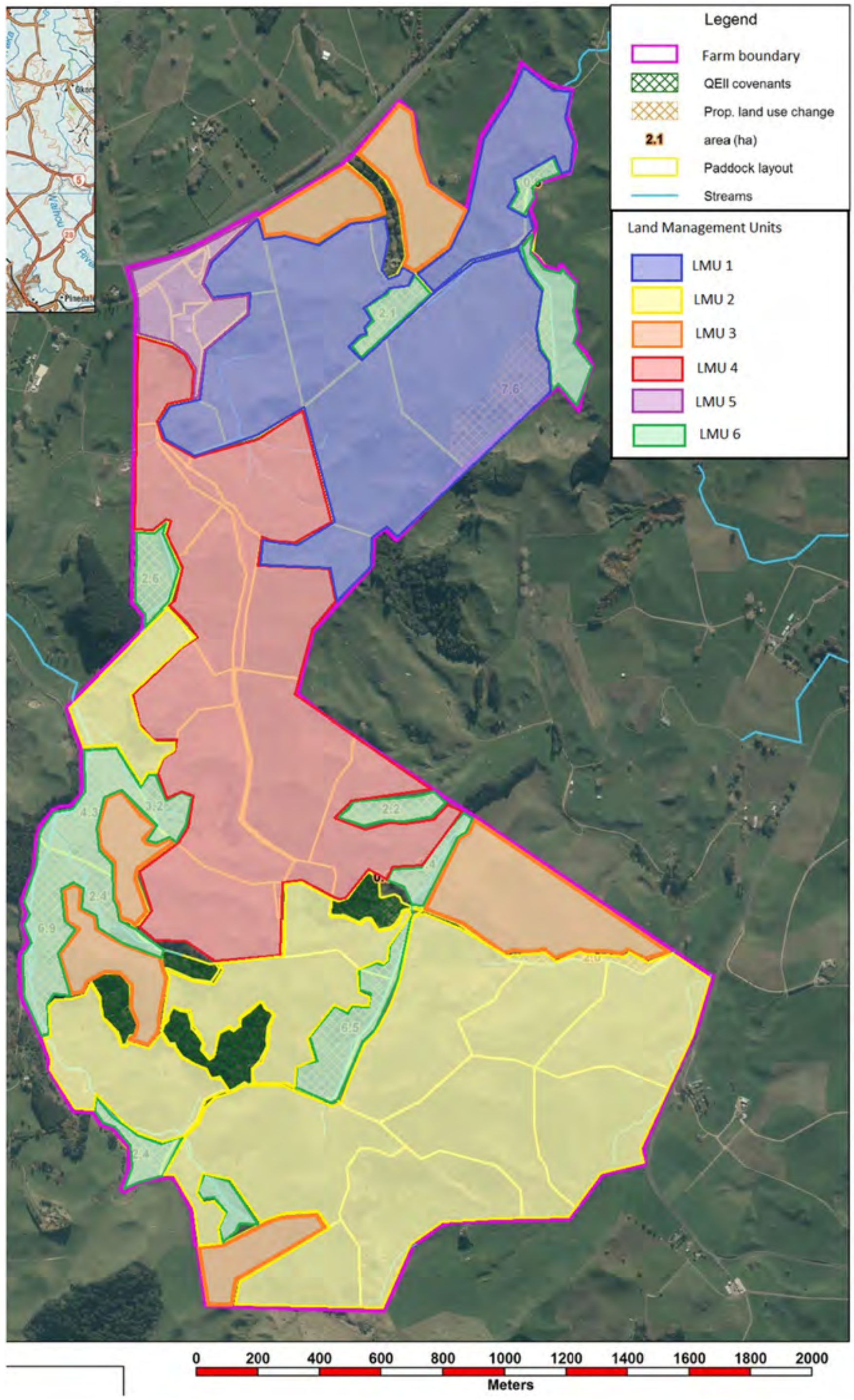

Fig. 1. Land Management Units split for the farm. Areas in light green include eroding land and wet low-lying areas were identified for biodiversity enhancement (LMU6).

sediment loss. In Scenario 3, LMU6 has been planted in mānuka and retired from grazing. These changes in management practices reduced P losses from the farm by 14% in Scenario 3 (Fig. 3).

3.3.3. Flood mitigation

Flood mitigation was modelled using runoff in mm ha^{-1} yr^{-1} as a proxy. The planting of LMU6 decreased average runoff across the whole farm by 21% between scenarios 2 and 3 (Fig. 3). Not grazing and planting the steeper part of the farm means more rainfall is intercepted and has time to penetrate the soil, thereby enhancing the flood mitigation service.

3.3.4. Greenhouse gases mitigation

The OVERSEER® model outputs the GHGs emissions from the farm, including carbon dioxide, methane and nitrous oxide, all converted to CO_2eq ha^{-1} yr^{-1}. With the increase in cow numbers for Scenario2 and Scenario 3, GHGs emissions of the farm increased compared to the current system. However, with the planting of 42 ha in Scenario 3, emissions dropped by 4.8% between Scenarios 2 and 3 (Fig. 3).

3.3.5. Carbon sequestration

The farm already has 16 ha of regenerating native bush protected under a Queen Elizabeth II (QEII) Trust Open Space Conservation

Table 2
Ecosystem services considered and proxies used if quantified.

	Ecosystem services	What to measure	Indicators used to quantify the service
Provisioning services	Food and fibre (wool)	Pasture yield from natural capital stocks converted to marketable products	Profit (EBITDA) NZD ha^{-1} yr^{-1}
	Provision of fibre (wood)	Timber yield	Not quantified here but potential for future harvest from the studied farm from LMU6
	Provision of honey from Manuka	Honey yield	Not quantified here but potential for future harvest from the studied farm from LMU6
Regulating services	Flood mitigation	Rainfall absorbed by the soil	Modelled runoff in mm ha^{-1} yr^{-1}
	Filtering of nitrogen	Part of N retained by the soil	modelled N leaching in kg N ha^{-1} yr^{-1}
	Filtering of phosphorus	Part of P inputs retained by the soil	Modelled P runoff in kg P ha^{-1} yr^{-1}
	Filtering of contaminants	Part of contaminants retained by the soil	Not quantified here
	Detoxification and recycling of wastes	Amount of wastes decomposed fully in situ	Not quantified here
	Carbon sequestration	Net C flows	Net C sequestration in new plantings in CO_2eq ha^{-1} yr^{-1}
	Green House gases mitigation	Amount of CO_2, N_2O and CH_4 regulated	Modelled GHGs emissions in CO_2eq ha^{-1} yr^{-1}
	Pollination	Availability of floral resources	Not quantified here
	Regulation of pest and disease populations	Part of the pest population regulated by biological control	Not quantified here
Cultural services	Amenity value	Landscape diversity	Not quantified here
	Cultural values	Socio-ecological values associated with biodiversity	Not quantified here

Covenant. QEII Trust is an independent charitable trust that collaborates with private landowners to protect natural and cultural heritage sites on their land. The farm also had a small plantation (4 ha) of exotic eucalyptus trees (Table 1). It was assumed here that the potential of the farm's existing indigenous and exotic vegetation to sequester C was negligible (<0.1 t CO_2eq ha^{-1} yr^{-1}) because of the advanced age of the canopy trees within the bush block, and ongoing likelihood of loss of condition due to climatic conditions (e.g. drought, wind), or pests. The new mānuka plantings on LMU6 (42 ha) have the potential to sequester 7.6 t CO_2e ha^{-1} yr^{-1} (Trotter et al., 2005). Under Scenario 3, the sequestered carbon represents 11% of the total emission from the farm (Fig. 3). This is far from off-setting the farms annual emissions, but it does make a quantifiable contribution to the mitigation of emissions.

4. Discussion

We found that the planting of mānuka on LMU6 (42 ha of eroding land, wetlands and gullies) enhanced existing natural capital stocks and increased the provision of a range of ecosystem services.

The steady state single year version of AgInform® used here to model the farm system over-estimates livestock numbers and profitability compared to a multiple year version of the model in development (Rendel et al., 2016). This is the reason for the inclusion of Scenario 2, which allows for an objective evaluation of the influence of a change in management of LMU6 on the provision of services and environmental impacts. The current system (Scenario 1) was included as a reference to provide an indication of the current flow of services and environmental footprint. The comparison of scenarios 2 and 3 is a more rigorous approach that removes the complexities inherent to the current system that reflect for example personal objectives and bespoke management practices, which are missing from the modelled systems.

The steady state single-year version of AgInform®, like the Overseer® model which calculates a long-term average effect of the system on emissions, are not designed to explore the behaviour of systems in transition, for example during biodiversity restoration, such as fencing and planting over multiple years. In the present study, the costs of fencing and planting of LMU6 were not included in scenario 3, but it was assumed that the establishment phase was complete and the farm system and performance were at equilibrium.

A multi-year version of the AgInfom® model is being developed to capture the costs and impacts on overall farm profit of variability in weather as it influences pasture growth and animal performance and market prices, in addition to changes in the annual cost structure and farm performance during transition. These factors often determine the

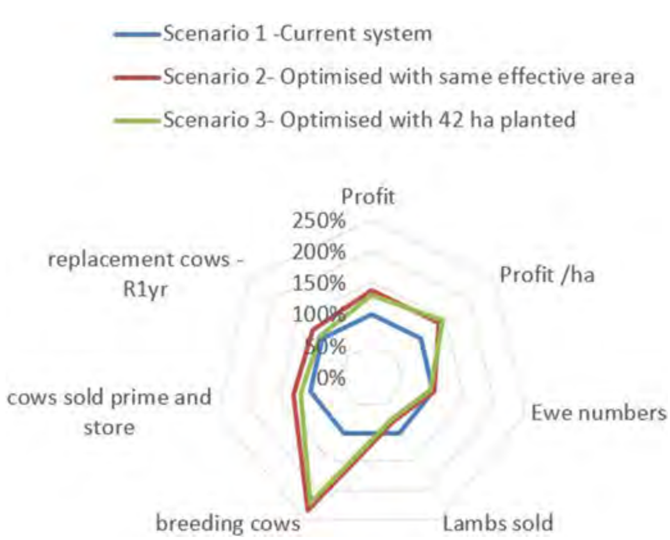

Fig. 2. Farm system information for the three scenarios modelled with AgInform®. All indicators in % difference from current situation (Scenario 1).

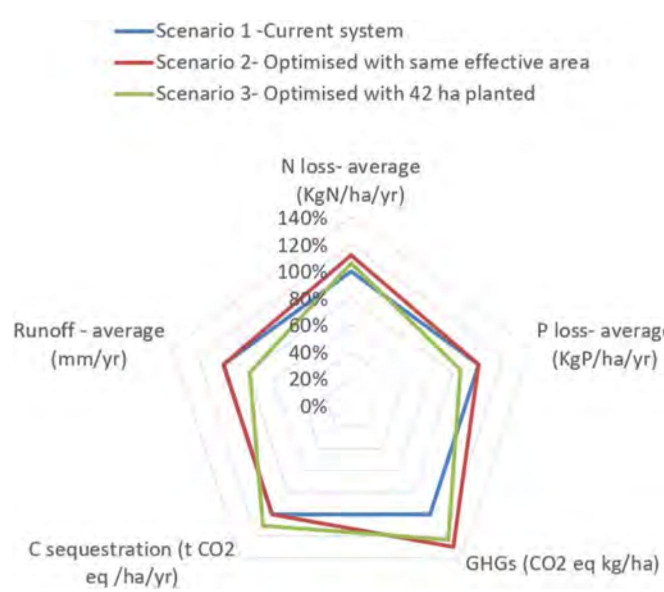

Fig. 3. Environmental footprint for the three scenarios modelled with OVERSEER®. All indicators in % difference from current situation (Scenario 1).

feasibility of the change. The multi-year version of the model also enables an exploration of the sensitivity of a system to change. This is why a sensitivity analysis was not undertaken in the present study, with the primary focus of the study on the differences in the performance of scenarios 2 and 3, rather than on the transition between the two scenarios.

4.1. Ecosystem services provision

Most farm scale models, including the ones used in the present study, can calculate a range of indicators relative to the areas of the farm in production, here pasture. These indicators are usually related to the performance of the production system or emissions to the environment, but do not quantify directly the supply of other ecosystem services from the farm. Moreover, most models have very limited capacity to measure the supply of ecosystem services from the non-pastoral parts of the farm, such as wetlands or indigenous vegetation (Turner et al., 2015). As a consequence, data for example on nutrients filtration or C sequestration from those parts of the farm are often limited. In this study, the attempted was made to quantify, using proxies, the flow of ecosystem services for the whole farm and not just the part in livestock production.

The provision of food and fibre refers to the amount of pasture produced and therefore the amounts and type of products produced. This is captured in farm revenue and profitability. Modelled using AgInform®, the proxies used to measure this service are earnings before interest, tax, depreciation and amortization (EBITDA) in NZD and profit/ha (NZD ha^{-1}). For the farm case study, profit per hectare for the land still in pasture increased by 5%. However, overall profit for the farm decreased by 7% (Fig. 1), with the shift in the use of the eroding land, wet low-lying land and gullies to native vegetation and specifically mānuka. This is a very important result to demonstrate to farmers that replanting sensitive land, for soil conservation or biodiversity restoration reasons, while impacting on profit, does create the opportunity to improve returns from the better parts of the farm, and explore other revenue streams for the underperforming parts of the farm. For example, the income from honey production from the areas planted in mānuka (LMU6) would have to be more than NZD 320 ha^{-1} for overall farm profitability to be maintained over scenario 2. Currently returns from honey production are in the order of NZD 500 to NZD 1200 ha^{-1}, once the trees are mature after 7 years. Landowners generally only receive a share of this based on current ownership structures. Net profit from mānuka honey has the potential to cover most of the profit lost as a result of the shift in enterprise.

Flood mitigation, which refers to how much annual rainfall is intercepted by vegetation and absorbed by the soil before running off, is generally not an output in farm scale models. In this study, runoff was estimated for each LMU based on soil, slope and vegetation in mm ha^{-1} yr^{-1} and then summed for the farm. The change in the management of the eroding land, wet low-lying landscape and gullies (LMU6) resulted in a 21% reduction in run-off for the whole farm. While planting LMU6 reduces the risk of the farm contributing sediment and P to receiving environments, it also reduces the yield of water from the farm to the wider watershed.

When quantifying the filtering of nutrients and contaminants, proxies should measure the amount of nutrients and contaminants retained by the soil and not leached (Dominati et al., 2010). However, because most mechanistic models do not measure this, the proxies used here are the changes in the N and P losses representing changes in filtering capacity.

The detoxification and recycling of wastes refers primarily to the amount of plant litter, dung and urine decomposed by soil-plant systems. This service is critically important for agro-ecosystem and depends heavily on soil functionality and biodiversity (Schon et al., 2010; Pascual et al., 2015; Schon et al., 2015). It was not quantified here, as the models used did not assess than service directly. However, it is reflected partly in nutrients losses from the farm. Management practices, which build soil natural capital and biodiversity (Marichal et al., 2017; Schon et al., 2017) impact greatly on the provision of this service. In scenario 3, by replanting the most vulnerable parts and the farm and putting in place grazing restriction to protect soils, the provision of this service is likely to have increased.

Ecosystems regulate the global climate by storing and sequestering carbon. The GHGs emissions from the farm as well as extra amount of C that could be stored by the newly planted mānuka stands were estimated and used to complete a carbon budget for the farm. Greenhouse gas emissions (methane, nitrous oxide, carbon dioxide) from this farming operation (5.2 t CO_2eq ha^{-1} yr^{-1} for Scenario 1) are at the upper range of emissions for sheep and beef operations (Mackay et al., 2011a; Smeaton et al., 2011). It is important to note that biomass C stocks (e.g. standing forest, peat mires, soil C) do not create any offset benefit, only change (increase) in those stocks such as the new plantings on LMU6 with mānuka offer C sequestration additional to the existing operation. It is important to note that the contribution of the mānuka plantings will ultimately plateau as the plantings reach maturity. In the future, the C footprint of livestock operations will be guided by the value chain as the agricultural industry strives to capture value by linking the producer directly with the customer.

Insects, animals and wind pollinate plants and trees are all essential for the development of seeds, fruits and vegetables. Many authors have examined the pollination potential of different types of indigenous vegetation in New Zealand (Newstrom-Lloyd, 2013; Ausseil et al., 2018) and when comparing land cover types, Ausseil et al. (2018) found that mānuka had the highest nectar production. Mānuka was chosen for replanting in this study because of its qualities as a fast growing nursery plant to facilitate the reintroduction of other indigenous species as well as potential harvesting and commercialisation of mānuka honey and oils.

Ecosystems are important for regulating pests and vector borne diseases that attack plants, animals and people. This is an important service in agro-ecosystems as pests and disease can affect greatly a production system (Sandhu, 2008; Porter et al., 2009). This is also important for biodiversity restoration where pests' population can be a real threat to endangered indigenous species.

Maseyk et al. (2017) found that dairy farmers who reintroduced biodiversity in riparian margin plantings along waterways identified a range of benefits from doing so, including improvements in social values and cultural services. Benefits included improvements in the farm's appearance, lower staff turnover, the ability to attract better staff, and increased property values (Maseyk et al., 2017). An increase of indigenous biodiversity on-farm was also estimated to increase amenity values across a lowland pastoral landscape (under dairy land use) in the North Island of New Zealand when multi-tier planted riparian margins were compared to fenced-only or grazed margins (Maseyk et al., 2018a). We anticipate that similar improvements in amenity values and cultural services can be expected by reintroducing indigenous species on sheep and beef farms, particularly when this is achieved by the planting or enhancement of sizable areas of land, which contributes more proportionally to the landscape matrix than riparian margins, which are typically long, narrow and restricted to valley floors.

Māori, the indigenous people of New Zealand, have like many indigenous culture alternate perspectives centred on the quality of the relationship between humans and the environment. They also bring holistic approaches to the sustainable use of natural resources based on complex social-ecological interactions (Harmsworth and Awatere, 2013). Therefore, biodiversity restoration in New Zealand needs to be in partnership with local Māori entities to ensure cultural values are an integral part of the process.

4.2. Future land evaluation

Changes to the farm natural capital stocks are rarely considered. Historically, land development is based on compensating for a lack of natural capital of primarily soils by using built capital. For example, draining poorly drained soils, irrigation of soils with low water holding capacity, standoff pads for soils that are damaged when wet, and pesticides on soils with low biology. The renewed interest in soil quality in the last 10 years (Bouma, 2018) demonstrates that the agricultural sector, under immense pressure from the general public about environmental sustainability, is starting to reconnect with the concepts of land use capability and environmental boundaries.

In answer to the question of how best to use our finite natural resources, we suggest the focus of land evaluation should be shifted from soils only to one that includes the whole range of natural resources including biodiversity on the farm. A broader evaluation of the farm system would shift the focus towards the contributions all the farm resources can make to a more diverse, resilient, multi-use landscape. Rather than a singular emphasis on the farm's economic performance, greater emphasis should be placed on equal consideration of environmental, cultural, social, and economic outcomes – quadruple bottom lines.

Adding an ecosystem services element to land evaluation would enable the supply of all the benefits obtainable from land to be linked to the performance of a combination of land type, enterprise (use) and practices (management). This provides a more complete assessment of the use of natural resources, assists in defining natural ecosystem boundaries and provides better information on progress towards not only economic, but also the environmental, social and cultural outcomes desired by land owners and community of interests (Dominati et al., 2016). The concept of adding ecological or operational boundaries, within which land use must operate, moves the analysis from managing a farm as an island to managing the farm within a landscape from which the community seeks multiple outcomes.

4.3. Increasing farm resilience by enhancing biodiversity

The enhancement of biodiversity on-farm creates an opportunity to change the farm's environmental footprint, improve farm resilience to major climatic events, and provide the basis for communicating provenance and on-farm practice with the consumer. This is because biodiversity natural capital contributes to the provision of ecosystem services (MEA, 2005; TEEB, 2010) which is reflected in changes in the provision of regulating services, reducing the impacts of the farm on receiving environments. For example, establishing multi-tier plantings within riparian margins contributes to the retention of sediments and sediment-bound P, thus reducing P losses to water; reintroduction woody vegetation onto soils vulnerable to erosion increases the resilience of the farm by increasing the magnitude of rainfall events that the farm can withstand before incurring erosion (Dominati et al., 2014a); maintaining or enhancing wetlands and seepages on farm improves filtration and retention of nutrients on-farm, and increases the ability of the farm to absorb rainfall by slowing overland flows. When indigenous species are the focus of these reintroductions, then indigenous biodiversity is also increased across the landscape with the potential for greater biodiversity outcomes as new habitat for additional species becomes established.

In New Zealand, less intensively farmed hill country farms in particular are already well placed to shift farm practice to integrate indigenous species and habitats in their daily decision-making. For lowland and more intensively farmed landscapes where indigenous vegetation is limited to a few small-dispersed fragments, simply protecting and managing what is left will not be enough to build resilience at the farm-scale. The reintroduction of indigenous vegetation will be required. This would represent a paradigm shift from current practice, but we suggest that demonstrating the utility to the farm system of doing so will make the required management actions have greater relevance to individual farmers. Further quantification of the relationship between specific management actions, response in biodiversity to these actions, and the provision of ecosystem services (including cultural) is required, and represents a priority for next-steps in this research.

An increased understanding of the private and public benefits from enhancing indigenous biodiversity on-farm can also serve to inform policy for biodiversity management on private land, including the use of incentives and provision of outreach and resources. Central and local government coordination of interventions, in combination with industry, will likely be required. For example developing restoration plans that capture key principals that result in ecologically functioning ecosystems that enhance species diversity as well as structural diversity, management of species threatened species and habitats, and landscape-scale management of invasive animal pests and weeds that compromise the ecological integrity of biodiversity areas (Mackay et al., 2018).

4.4. Farm system design for multiple ecosystem services provision

Even while using two different farm scale tools, we were only able to quantify using proxies some of the ecosystem services supplied by some parts of the farm. Historically, farm scale tools only concentrate on the "productive" parts of the farm, while other parts are often not reported on and hence not valued. This stems in part from the general lack of scientific data quantifying the provision of ecosystem services from "non-productive" parts of the farm (meaning not producing food or fibre) such as shelterbelts, riparian margins, wetlands, native bush remnants, forestry blocks and so forth, as well as a lack of appreciation of the contribution these parts of the farm are likely to play in the farm business in the future. Some services from those non-productive areas such as biological control or pollination are well researched and documented (Losey and Vaughan, 2006; Newstrom-Lloyd, 2013) but what is lacking is a consistent approach looking at all services supplied by all land units that make up the whole farm, as well as flows of services between productive and non-productive parts of the farm. Until farm scale tools are able to model ecosystem services supply from both pastoral and non-pastoral parts of the farm, we will have limited ability to demonstrate the real impacts of environmental practices such as a change in cattle policy through to biodiversity restoration. In the future, such analyses demonstrating gaps in the quantification of ecosystem services supplied by different parts of the farm should be used for the design and development of new analytical tools for farm system design. A range of ecosystem services models exist using spatial data sets at multiple scales, such as ARIES (aries.integratedmodelling.org/) or InVEST (www.naturalcapitalproject.org/invest/). Although these models can be very useful at the landscape scale, they are often too coarse to deal with the farm scale, and cannot be translated to provide meaningful insights to land managers for decision-making.

Given farm plans will for the near future be an important vehicle in on-farm decision making, it is important that the limitations in the evaluation process continue to be tackled (Dominati et al., 2016). If the goal is to design farm systems in a way that ensures their natural capital (including soils and biodiversity) are maintained and enhanced and they provide a range of ecosystem services while being profitable, the way land evaluation and farm planning are currently carried out need to change. Implementing this will require moving from a mainly pedocentric approach, which is currently the norm in land evaluation and farm planning processes in New Zealand, to a more holistic approach where the capacity and condition of all the farm's natural capitals stocks (soils but also water bodies and biodiversity) are informing long-term goals and day-to-day management decisions.

Farm plans already collect a large amount of information on the areal extent of native bush fragments, riparian margins and wetlands, along with hectares in pasture and crops, plantation forestry, woodlots, length of shelterbelts, and the number and age of spaced planted conservation poplar and willow trees (Manderson et al., 2007). Compared with the data we collected on pasture growth, growth of the forestry woodlots and effectiveness for example of the shelterbelts and spaced planted poplar, little is often collected on the condition and function of the bush fragments, wetlands or riparian margins. This makes it difficult to assess the condition and function and hence contribution to the supply of ecosystem services on-farm. The influence of farm-scale actions on ecological function and connectivity at landscape scale beyond the farm is rarely considered, although it is an important aspect of achieving regional and national biodiversity objectives.

For example, a stocktake of biodiversity will require evaluation of indigenous biodiversity assets and ecological processes on-and beyond the farm against appropriate reference values to determine both relative condition and ecological or conservation importance. The later will require an assessment of on-farm indigenous biodiversity assets against regional and national objectives, priorities, and regulations.

Suggestions that farming landscapes are not the place for indigenous biodiversity take a short-sited view that overlooks the role farms play in the wider landscape. It is crucial that we blur the boundaries between areas of the farm producing traditional commodities (food and fibre) and those non-pastoral areas of the farm, which produce other benefits. An example of the urgency to make such approaches reality is Beef + Lamb New Zealand recently launched their Environment Strategy (https://beeflambnz.com/environment-strategy), which lays out a progressive long-term vision for the sector based on four priority areas, one of which is 'thriving biodiversity'. The other three are healthy productive soils, clean water and reducing carbon (C) emissions, which are interrelated with biodiversity priorities.

5. Conclusion

In this study, the ecosystem approach, based on extending land evaluation to multiple natural capital stocks and the consideration of supply of all ecosystem services from different part of the farm, was paired and used with a new generation farm optimisation model. It showed that it is possible to explore and integrate multiple benefits ranging from increased profit to decreased environmental footprints, into the farm system to design systems which not only fit better in their wider environment, but also take into consideration the environmental, social and cultural outcomes desired by both land owners and the wider community.

Although, the data used in this study to quantify the supply of ecosystem services is limited, some co-benefits are apparent. The tools currently used for farm system design, including land evaluation and farm planning, need to include an ecosystem approach in order to advance beyond reporting on environmental impacts and profitability, towards the provision of multiple ecosystem services.

Most current farm scale models are limited in their ability to quantify ecosystem services delivery from different parts of the farm, especially areas not producing food and fibre. This needs to be addressed urgently. The novel capabilities showcased by the AgInform® model including system optimisation and the inclusion of ecological boundaries within which resources should be managed are features that analytical farm system frameworks will require in the future. It also creates the capacity to assess if the farm system is sustaining natural capital stocks (soils, vegetation, waterways) on which the future business opportunities are based.

It was suggested that indigenous biodiversity has a pivotal role in building resilient farms and communities as it is a fundamental component of many existing farm assets. Integrating biodiversity in daily decision-making on-farm will be no easy task, and will require new knowledge and understanding of the interactions that occur between adjacent ecosystems. The increasing urgency to sustain our natural capital is such that we cannot afford to be daunted.

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