APPLYING A LANDSCAPE ECOLOGICAL APPROACH AND GEODESIGN FROM A FARMER-CENTRIC POSITION TO INFORM THE CREATION OF FUTURE MULTIFUNCTIONAL, SUSTAINABLE AGRICULTURAL LANDSCAPES

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Declaration

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Abstract

In the wake of environmental challenges, it is important to improve the environmental sustainability of farm systems and landscapes whilst ensuring profitability for the farmers that manage them. This PhD study draws on theories from landscape ecology and geodesign to plan and design multifunctional agricultural landscapes from a farmer-centric position with sustainability in mind. A hill country and steep-land farm in New Zealand is used as a case study. A conceptual framework is proposed to guide landscape planning. The framework applies an ecosystem-based management approach (i.e., ecosystem services approach) coupled with geodesign at the farm scale. A comprehensive spatially explicit assessment of landscape multifunctionality and associated ecosystem services at the farm scale is carried out to understand the spatial variation of ecosystem services provision and how land use and land management goals of the landowners reflect the value and quality of landscape multifunctionality. Afterwards, spatially detailed variations in the relationship between landscape structure and the provision of ecosystem services is quantified to understand how landscape structure can affect the provision of ecosystem services in the farmed landscape. Finally, collaboration with the case farmers and application of different tools and models are carried out to generate future land use and management scenarios for the case study farm, visualise changes, and assess the impacts of future land use on landscape multifunctionality and the provision of associated ecosystem services and economic outcomes. This helps to demonstrate how the proposed approach can be applied to plan and design multifunctional agricultural landscapes that offer improved sustainability in the NZ hill country farmed landscapes. The results from the case study suggest that the proposed approach provides an effective solution for sustainable farm system design and that it can make an important contribution to advancing environmental management in New Zealand, as well as in other countries which face similar issues.

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1. General introduction

1.1. Context of the research

In response to environmental issues associated with land use change and agricultural intensification such as biodiversity loss, land degradation, a reduction in water quality, and greenhouse gas (GHGs) emissions (A. P. Smith et al., 2013; Kiryushin, 2018; Firbank et al., 2008; P. Smith et al., 2013), agricultural production worldwide is increasingly constrained by environmental regulations (Bonnet et al., 2020; Donley, 2019). In addition, consumers are more likely to favour environmentally friendly products and there is a growing concern about the way food is produced and how it impacts ecosystems (Vermeir et al., 2020). While conventional agricultural systems focus mainly on maximising food production, emerging environmental impacts and social expectations shape new roles for agriculture, including food security, environmental protection, climate change mitigation, and the support of human well-being (Byerlee et al., 2009; Divanbeigi & Saliola, 2016). In turn, farming systems are facing complex challenges that have not been seen before, in which farmers must operate under an array of social, environmental, and economic expectations (Pearson et al., 2022). To respond to these challenges, it is suggested that farming systems need a fundamental transformation from productivity-oriented systems to efficient, sustainable, regenerative, and resilient systems (LaCanne & Lundgren, 2018; Schulte et al., 2022).

New Zealand (NZ) is a typical example of an agriculturally based country that is transitioning to a more sustainable farming system (Grelet et al., 2021; Sims et al., 2016). In NZ, agricultural land use occupies 40% of the country's total land area and agricultural products contribute to more than 70% of the country's total exported goods (MFAT, 2021; Stats NZ, 2021). Despite being recognised as an environmentally friendly nation, NZ farming systems are facing a range of challenges, including climate change, GHG emissions, water quality, and consumer preferences (Duff & Saunders, 2019). These challenges are likely to strongly impact NZ hill country farming because environmental issues add to other concerns faced by these farms, associated with contemporary impacts of increasing production costs, market volatility, climate change, highly variable topography and climatic conditions, and more dispersed and isolated families and communities (Scrimgeour, 2016).

Hill country in NZ is defined as "land with slopes above 15° and located below an altitude of 1000 m above sea level" (Jones et al., 2008). Under this definition 37% (~10 million ha) of NZ total land area is classified as hill country, with the majority (6.3 million ha) located in the North Island (Cameron, 2008). In terms of land use capability [1](LUC), hill country is defined as all Class 5, 6, 7 and 8 land from the NZ Land Resource Inventory (NZLRI) (Basher et al., 2008). Hill country is highly vulnerable to soil erosion due to the characteristics of underlying geology, topography, and climatic conditions. For instance, mass movement, particularly soil slip and earthflow erosion, and sheet and gully erosion, are common form of erosion that heavily impacted the hill country and steep-land in Manawatu-Whanganui, East Coast region, inland Taranaki, Coromandel, and Northland. This is because these areas have been developed predominantly on soft rock and crushed soft rock, or deeply weathered sedimentary and igneous rocks. In contrast, surface erosion is the most common form of erosion in the hard rock terrain in some areas in the South Island such as Otago, Canterbury, and Marlborough. Soil slip and gully erosion are also common erosion types occurring on the soft rock terrain in Tasman (Basher et al., 2018). The regulations and environmental legislation in NZ aimed

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[1] LUC is classified on a discrete scale from 1 to 8. Class 1 land is best for sustained agricultural production, while class 8 land has severely limited uses. Classes 1 to 4 are considered suitable for multiple land uses including arable cropping, while classes 5 to 7 are only suitable for pastoral grazing and forestry. Class 8 is not suitable for any productive use. For more details, see Lynn et al. (2009).

at addressing some of the challenges involve "over 750 primary Acts and over 3,000 statutory regulations with the Government creating and amending about 100 Acts and 400 regulations each year" (Valentine, 2015). Among these, the Climate Change Response Act 2002 and following amendment Acts (e.g., Climate Change Response (Zero Carbon) Amendment Act 2019) (MfE, 2002, 2019), and the Resource Management (National Environmental Standards - NES for Freshwater) Regulations 2020 (MfE, 2020) have heavily impacted farming practices and caused frustration amongst farmers. The Freshwater NES sets standard requirements for carrying out farming activities that pose risks to freshwater and freshwater ecosystems. In many cases, farmers will need to apply for a resource consent from their regional council to continue carrying out regulated activities. The government has also introduced mandatory freshwater modules of farm plans in which farmers have to map features such as waterways, critical source areas, and erosion-prone areas and other risks to the health of the freshwater ecosystem, in addition to assessing risk across specific activities including irrigation, application of nutrients and effluent, winter grazing, stock-holding areas, stock exclusion, offal pits, and farm rubbish pits schedule of actions to manage identified features (MfE, 2020). In addition to this, the Climate Change Response (Zero Carbon) Amendment Act targets a reduction in net emissions of GHGs to zero by 2050 and puts in place the agricultural emissions pricing scheme to drive emissions reductions at the farm level (MfE, 2019). Drawing upon recommendations from He Waka Eke Noa – Primary Sector Climate Action Partnership, the NZ government has recently announced a proposal that plans to make farmers pay for agricultural emissions from 2025 (MfE, 2022).

Under an array of new standards and regulations, future farming systems need to improve their profitability and build resilience in order to be able to adapt to environmental problems like a changing climate whilst reducing impacts on the environment. As such, a fundamental change in current farming systems is required to achieve more sustainable agricultural production. Changing land use and land cover (LULC) to create complex landscapes where multiple types of LULC co-exist is suggested as an effective solution to achieve sustainable agricultural landscapes (Powers et al., 2020; Scherr & McNeely, 2008). However, the tools and approaches that appropriately and effectively support the allocation and modification of LULC patterns especially at the farm scale are limited (Hendy et al., 2018; Synge et al., 2013). As such, it is important that farmers, the decision makers who decide on the change to farmed landscapes, are supported with a range of effective tools and information to help with land use change decision-making. Tools that preserve some farmer autonomy around this decision making are particularly valuable so that farmers take ownership of and feel in control of their farm adaptations to reduce environmental impacts.

1.2. The gap in the knowledge

Key to achieving sustainable farming planning is being able to identify appropriate changes to LULC and management practices to obtain the expected outcomes in ecosystem services supply and associated economic and environmental impacts (Dargains & Cabral). Studies conducted at the farm scale in NZ often focus on quantifying the significant impacts of changing LULC and agricultural practices. However, they do not adequately emphasise how and where to make the most effective LULC change to have the greatest environmental impact whilst maintaining agricultural production (Baskaran et al., 2009; Kov et al., 2018; Ledgard et al., 2019; Monaghan et al., 2007; Monaghan et al., 2021). Planning for sustainable future farming in NZ must design farm systems that enable the operation of economic, ecological, and socio-cultural functions of the landscapes so that the multiple objectives demanded by people and nature are met (McFarlane, 2018). Although a number of planning and management tools have been developed to support farmers such as OVERSEER (https://www.overseer.org.nz/overseerfm) and Land and Environment Plan (https://beeflambnz.com/farmplan), there is limited utilisation of advanced spatial analysis tools and models through an integrated approach that can provide comprehensive and spatially-explicit information for farming practice and land management.

Sustainable planning and management of land resources at the farm scale is a complex process because it must consider a wide range of socio-economic and environmental issues and follow an array of regulations and standards (MPI, 2021). In addition, land use planning is spatially heterogeneous and farmers preferences and expectations differ from farm to farm (Birch-Thomsen & Kristensen, 2005). This means that farm planning is associated with both nature and socio-economic systems and therefore, a single approach for single-purpose farm plans is not capable of handling such complexity (Dominati et al., 2018).

Table 1.1 describes a brief history of farm planning approaches applied in NZ (Blaschke and Ngapo, 2003; Maseyk et al., 2019). It can be seen that current farm planning applied in NZ often target a specific land use and environmental management goal or ecosystem service such as soil erosion control, establishing production forestry, improving water quality, or enhancing biodiversity. The most comprehensive approach – "Whole farm plans" tend to integrate environmental, social, and economic goals and capture enterprise development. However, this approach does not assess impact of farm activities (e.g., land use, management practices) on the provision of biodiversity and a wide range of ecosystem services. Certainly, multifunctional farmed landscapes that provided multiple ecosystem services have not been a primary focus of farm plans, although they may be a secondary consideration (Maseyk et al., 2019; Dominati et al., 2019). In addition, applications of spatial analysis tools and models in mapping land resources and a wide range of ecosystem services remain lacking in the development of farm plans in NZ (Synge et al., 2013; Dominati et al., 2021). As such, a multidisciplinary approach that integrates various specializations, tools, methods, and models is needed to take into account the multiple issues and the requirements of a comprehensive land and environmental planning process at the farm scale.

Table 1.1: Farm-scale plans planning commonly use in New Zealand

Types of farm plans	**Descriptions**
Traditional farm plans (Soil conservation plans)	Primarily based on an assessment of land use capability (LUC) and farm conservation needs, and mainly focuses on hill country farms with an actual or potential erosion hazard. Soil conservation plans also occurred on flat locations with windbreak schemes developed to reduce wind erosion. Their

	value went beyond erosion management as they also influenced shelter of pasture, crop production and animal welfare.
Soil-based environmental farm plans	This aims to train individual farmers to produce a soil map of their own property, and then to train them to interpret and apply that knowledge for farm business planning. It has now been used in a number of central North Island farming environments and appears to be especially successful in situations where there are strong environmental and soil differences within the property. The method relies on strong farmer participation and ownership and is strongly rooted in ‘traditional’ farm advisory and focus farm approaches.
Forestry-oriented environmental farm plan	This type of plan involves landowners who are mainly interested in establishing open-spaced or plantation forestry. The plan is usually based on a land resource inventory assessment and then a range of alternative forestry options are proposed, and in some cases tested using the Agroforestry Estate Model or other forest evaluation tool. Establishment and management costs and production returns can be modeled for the various scenarios.
Riparian plans	Riparian margin fencing and planting in response to land use induced water quality issues and streambank erosion. Riparian management (e.g., stock exclusion and restrictions for land use activities) is subject to regional regulations and condition of supply for the dairy industry.
Nutrient management plans	Actions needed to optimise use of major plant nutrient such as nitrogen, phosphorus, and potassium inputs to maximise production, while avoiding or minimising adverse effects of these nutrients on receiving environments. Nutrient management plans include a nutrient budget to balance

	nutrient inputs with nutrient losses to ensure nutrient management meets regulatory and industry requirements.
Land environmental plans	Designed primarily for sheep and beef farm systems to optimise resource use. Industry (Beef and Lamb NZ) designed and delivered. Land environment plans identify on-farm environmental risks and management opportunities within regulatory specifications. The focus is on land, water, and soil resources.
Whole farm plans (WFPs)	Increase on-farm capacity to reduce and recover from negative impacts of large storm events and drive land use change to sustain and enhance natural resources. WFPs are relatively narrow in current focus, the primary purpose is the management of erosion and sediment contributions to receiving environments. The development and implementation of a WFP is voluntary and only a few regions across New Zealand have adopted their use.

Source: Adapted from Blaschke and Ngapo (2003) and Maseyk et al. (2019).

Ecosystem services-based management (EBM) is an integrated approach that incorporates biological, socio-cultural, and economic factors into a comprehensive strategy aimed at protecting and enhancing sustainability, diversity, and productivity of natural resources (Delacámara et al., 2020). The United Nations suggests that EBM is considered the most promising paradigm for achieving sustainable development (MEA, 2005). In practice, this involves the planning and management of multifunctional landscapes that enable and promote the supply of multiple ecosystem services. The implementation of EBM is strongly driven by the theories and concepts drawn from landscape ecology (i.e., landscape ecological approach) (Lovell & Johnston, 2009), which is defined as “the study of interactions, across space and time, between the structure and function of physical, biological and cultural components of landscapes” (iale UK, 2010). Even though this approach has been widely applied elsewhere for decision-making associated with agricultural land use planning and management (Atwell et al., 2010; Barral & Oscar, 2012; Cabral et al., 2016; Fürst et al., 2014), to date the relevance of applying such an approach to exploring future land use and sustainable development of agricultural landscapes in NZ has not been fully explored. Although the use of landscape ecology and EBM to help NZ agriculture respond to future challenges has been discussed, their applications in practice to support farmers in future farm system design is limited (Pearson, 2020). In other words, a landscape ecological approach has been discussed conceptually for landscape sustainability, but it has not been widely applied practically in NZ (Mackay et al., 2018). Current land use planning approaches employed in NZ are limited in terms of incorporating the ecosystem services concept into agricultural land use decision-making and often involve inadequate measurements of comprehensive ecosystem services at the farm scale (Dominati et al., 2021). There is also little evidence of the application of a design-driven perspective to land use planning which considers the participation and contribution of farmers as a key factor in the planning process (Eastwood et al., 2022; Romera et al., 2020). Geodesign is a multidisciplinary approach involving participation of stakeholders that combines design principles and geospatial analysis to provide decision-makers a holistic and informed decision-making process that can address complex spatial problems, including land use planning and design of landscapes (Campagna, 2016). The use of EBM within a design framework that incorporates participatory planning could enable the creation of a useful decision support system for sustainable land use planning and environmental management at the farm scale.

1.3. Objectives and research questions

This PhD study aims to develop a spatially explicit landscape design approach that can assist with the creation of sustainable multifunctional landscapes for NZ hill country farms by integrating geodesign and concepts drawn from landscape ecology. The emphasis of the approach applied is farmer-centric focusing on the farmer as the key decision maker for his/her land and giving him/her the autonomy to make informed decisions in the face of regulatory pressures and environmental concerns. The transdisciplinary approach taken will examine the important values and the characteristics that support beneficial ecosystem services to design future land use scenarios. To achieve this goal, the following research questions were derived:

> *RQ 1. Why is it necessary to plan and design sustainable agricultural landscapes in NZ hill country farms?*
>
> *RQ2. How can EBM (and the concept behind multifunctional landscapes) and geodesign be integrated to develop an approach that can assist with sustainable agricultural landscapes planning for hill country farms in NZ?*
>
> *RQ3. How can the proposed approach and framework integrating EBM with geodesign generate useful spatially explicit land use scenarios for sustainable multifunctional landscapes on hill country farms in NZ?*

Specific objectives to answer these research questions are:

1. To define the major challenges facing current and future agriculture in the NZ hill country (RQ1);
2. To develop a framework that integrates the ecosystem services concepts and a geodesign process to assist in the creation of multifunctional landscapes for sustainable agricultural production (RQ2);
3. To implement the framework using a case study farm by:

    a. Quantifying current ecosystem services provision and landscape multifunctionality on the case hill country farm

    b. Determining the relationship between ecosystem services and LULC pattern on the case hill country farm (RQ3);

    c. Designing different adaptive scenarios for a multifunctional agricultural landscape on the case hill country farm following the proposed conceptual framework (RQ3).

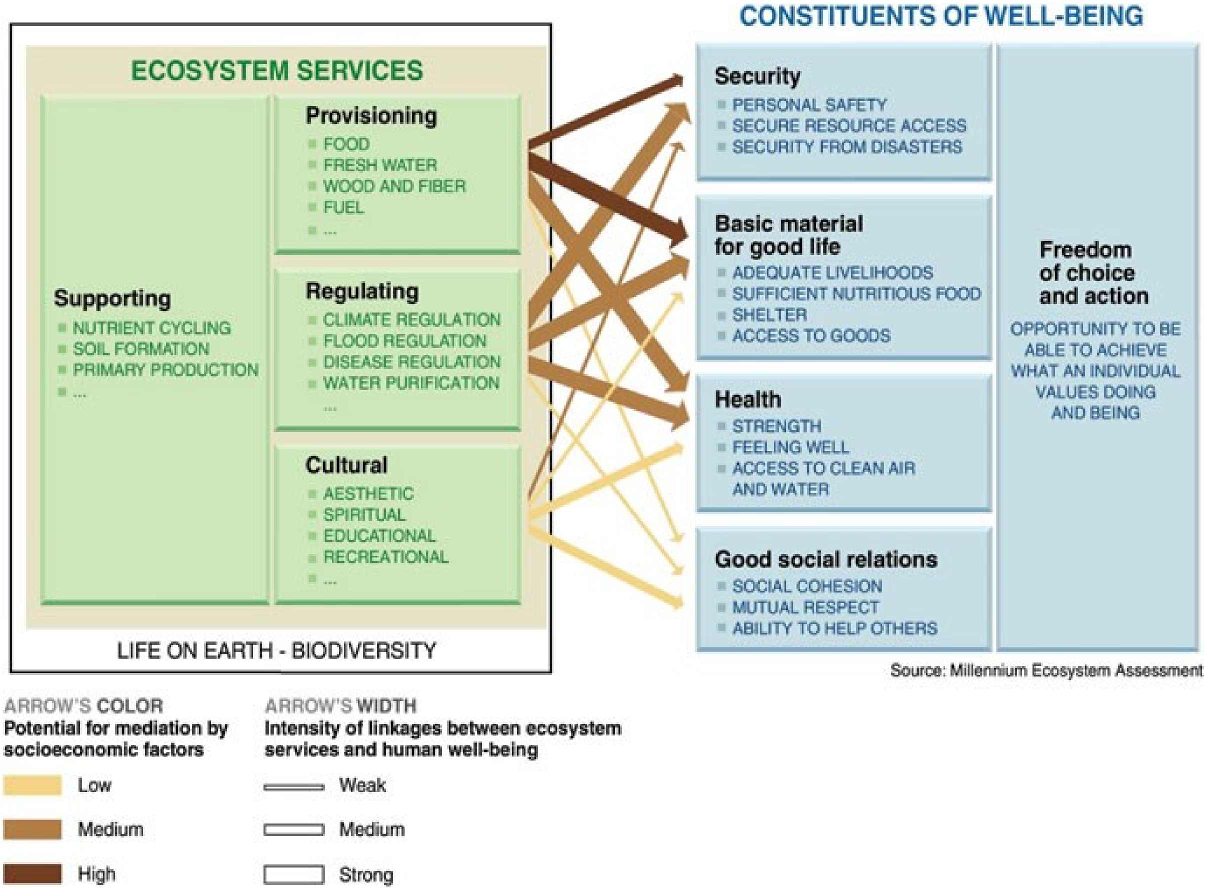
1.4. Proposed methodology

To achieve multiple objectives of future farming systems, the necessary course of action is to create multifunctional agricultural landscapes that enable future farming to support livelihoods and increase agricultural production whilst maintaining the valuable ecosystem services required for environmental sustainability (Bretagnolle et al., 2018; Iverson et al., 2019; Rallings et al., 2019). *The methodology applied in this study to help with planning for sustainable farmed landscapes integrates an ecosystem services-based management approach supported by landscape ecology principles within a geodesign framework.* The ecosystem services concept gained recognition among policy makers and scientists when the UN published the “Millennium Ecosystem Assessment” (MEA) in 2005 (Figure 1.1). The UN ecosystems approach is an integrated strategy for managing land, water and living resources that recognises the strong linkage between ecosystem services and human well-being. The idea is that these important services should be included in farmed landscape planning and that by actively maintaining or restoring important ecosystem services, this will help to maintain agricultural production, improve landscape health, reduce environmental impacts, and promote landscape resilience in the face of climate change. In this study, I adopt the terms "ecosystem functions" and "ecosystem services" instead of "landscape functions" and "landscape services" to ensure consistency with the existing literature and ecological sciences, especially the MEA framework and the Natural Capital Project ecosystem modeling concepts (i.e., the Integrated Valuation of Ecosystem Services and Tradeoffs - InVEST). Although these concepts are often used interchangeably, the use of the "ecosystem functions" and "ecosystem services" in this PhD study enables these terms to be aligned with established terminology in the field (Costanza et al., 1997; Mauerhofer, 2018; MEA, 2005). Landscape ecology has played a vital role and made an enormous contribution to the implementation of ecosystem services-based management (Iverson et al., 2014). Landscape ecology is an interdisciplinary scientific discipline that focuses on spatial patterns and heterogeneity, and specifically their characterisation and description over time, their causes, and consequences and how humans manage those (Turner et al. 2001).

The conceptual and theoretical core of landscape ecology links natural and social sciences to understand landscapes as arenas where structural features and social construction converge (Pinto-Correia & Kristensen, 2013). Utilising theoretical and applied principles from the fields of landscape ecology is suggested to achieve the creation of multifunctional landscapes (Lovell & Johnston, 2009). Tools developed or adapted for landscape ecology are being increasingly used to assist with the quantification, modelling, mapping, and valuing of ecosystem services. In this PhD dissertation, the application of landscape ecology or a landscape ecological approach is translated to as the method to implement EBM in farmed landscape planning and management.

Geodesign brings together multiple disciplines such as geographic information science (GISci), environmental science, landscape planning, and spatial data analytic tools to address environmental challenges and questions in multidisciplinary ways (Steinitz, 2012). This type of approach allows the utilisation of spatial data, tools, and models to help to identify significant areas that require active environmental management, design alternative land use options, and evaluate various impacts of these land use scenarios (Gottwald et al., 2021). This approach can suggest appropriate land use practices and recommend areas where agricultural production will have minimal environmental impact and therefore could be sustainably managed intensively to increase economic output (Karrasch et al., 2017). The analysis carried out using the proposed approach also enables locating targeted areas that need to be preserved as hot spots for providing important ecosystem services. The geodesign framework incorporates the different views, values, and preferences of land users and considers collaboration and participation as an important part of the landscape design and decision-making process. This will allow the development of sustainable landscape scenarios and encourage the implementation of selected scenarios in practice.

Although there is abundant evidence illustrating the benefits of applying an EBM approach, the ability to effectively apply this to farm planning so as to be widely adopted by farmers remains challenging (Maseyk et al., 2021). A common reason for this is that without careful consideration of the farmers perspective land use planning scenarios may not be aligned with the farmers needs and may not suit the farm perspective. For instance, a land use scenario that increases a significant amount of natural forest and wetland (e.g., 30-40%) might be preferred by the wider public community, but not the farmer. The implementation of such a plan may not be realistic for a number of reasons. These reasons might include (1) the high cost in time and human resources making it not affordable to a farmer and (2) the scenario could actually conflict with landowners' desires and expectations for their farm. If an increase of only 5% of these natural land cover could enable the farmers to meet both environmental constraints and regulations, the proposed plan might be more practical from the farmers perspective. The fact is, in farm planning farmers/landowners are central to the decision-making process on their land and they fiercely protect their autonomy in making these decisions (Rose et al., 2018). This makes farmer land management different to that of public land/conservation land management which often involves the wider public communities and authorities in decision-making (Brown & Brabyn, 2012; Drazkiewicz et al., 2015; Engen et al., 2018; Klein & Arts, 2022). Bottom-up approaches where farmers take control of land use decision-making so they meet their own land management aspirations as well as comply with environmental regulations and consumer preferences are gaining moment in NZ (Eastwood et al., 2016; McCole, 2022; McFetridge, 2022; Stokes et al., 2021). This is because farmer-controlled decision making in favour of environmental outcomes is deemed to have a more significant and long-lasting impact (Stokes et al., 2021). Catchment management groups supported by MPI (MPI, 2021) are a good example of farmers leading the way for environmental outcomes. Therefore, in this PhD I proposed taking a farmer-centric approach to land use planning that could demonstrate the implementation of an EBM approach in a practical and beneficial way. To do this I applied a design-driven perspective to land use planning which considers the participation and contribution of farmers as the key element in the planning process. This is consistent with the recommendation of a number of recent studies (Eastwood et al., 2022; McCole, 2022; Romera et al., 2020). Implementing an approach that integrates EBM into a geodesign framework and customises this in a land use planning context at the farm scale can therefore be seen as providing a significant contribution to land and management planning studies and practices at the farm scale. The contribution this PhD makes is to be one of the first attempts to integrate an EBM approach with a geodesign framework from a farmer's perspective to address farm scale land and environmental planning in NZ.



Source: Millennium Ecosystem Assessment

Figure 1.1. Ecosystem services (ES) classification and linkages between ES and human well-being defined by the Millennium Ecosystem Assessment (MEA, 2005).

1.5. Geographic focus/case study

The hill country farmed landscape is the geographic focus of this study (i.e., farm-scale). Farm scale analysis means that the underlying land and environmental data and associated analysis for land use planning and management need to be able to reflect variations across the farm. In terms of map scale, common scales used in farm analysis in NZ vary between 1:500 and 1:15,000 with a minimum mapping unit of 0.1 to 1 ha (Landcare Research, 2023). This is a larger map scale which provides finer spatial detail than the catchment/regional scale (for example, 1:20,000 to 1:100,000) and strategic/broad planning maps (1:100,000 to 1:250,000) (Manderson & Palmer, 2006).

The hill country of NZ is used as a case study to demonstrate how the proposed approach can be applied to plan and design multifunctional agricultural landscapes that offer improved sustainability. Hill country farming faces considerable challenges relating to environmental degradation. Land use and land cover (LULC) changes that have occurred largely because of the European settlement of NZ have resulted in deforestation and loss of native vegetation and soil degradation (McGlone, 1983). Agricultural intensification and inappropriate agricultural practices in the hill country have significantly modified the landscape structure and pattern and resulted in the loss and degradation of landscape functions and ecosystem services (Blaschke et al., 1992). Consequently, several environmental issues have emerged such as an increase in soil erosion on steep lands where native bush and shrubs were cleared for pasture, a reduction in biodiversity, water quality, and future carbon stocks (Betterige et al., 2017; McIvor et al., 2011; Moller et al., 2008; Parfitt et al., 2009; Parliamentary Commissioner for the Environment, 2016). This is impacting on the long-term sustainability of hill country landscapes, and it is likely that the possible effects of climate change will exacerbate these problems (Kenny, 2001; Macinnis-Ng et al., 2021). One solution to address these environmental challenges is to redesign hill country landscapes to promote agricultural production whilst adapting and mitigating climate change and environmental issues.

The proposed approach is implemented using a sheep and beef farm that is in the Pakihikura catchment, in Waituna West, Manawatu-Wanganui region (Figure 1.2). This farm was selected as a case study because it is a typical hill country farm characterised by complex topographical pattern (various slope classes and landforms), geology, and soil types, and the landscape has been deforested and significantly modified for pasture production. A farm with complex landscape pattern will require various land use and management practices applied to different parts of the farm in order to better utilise available land resources whilst minimising the environmental impacts. The conversion of natural forest to pasture has led to a decrease in quality and provision of regulating/supporting and cultural ecosystem services. This requires an increase in landscape multifunctionality that enhances and promotes the provision of multiple ecosystem services. As such, using this farm as a case study provides a good example for demonstrative purposes, illustrating the application of the proposed approach which integrates ecosystem services with geodesign to plan more sustainable farmed landscapes. Moreover, the farm owner is interested in the environmental issues that the property faces and developing approaches for sustainable land management. The willingness of the landowner to be involved in the research was important to the study as stakeholder engagement (or collaboration) is one of the key features of landscape design. This makes the use of the farm as a case study more feasible and successful.

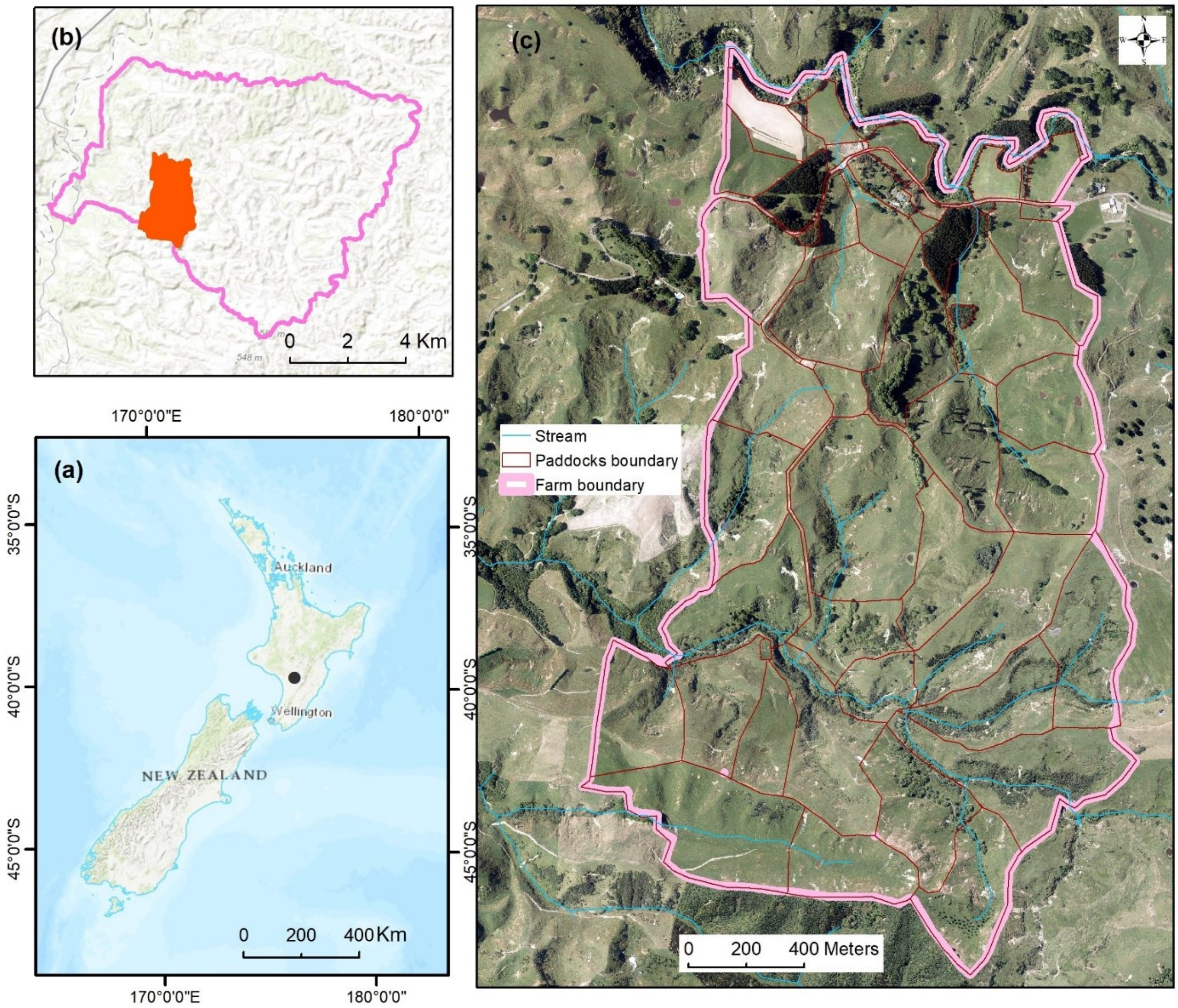


Figure 1.2. Location of Pakihikura catchment in New Zealand (a); study site in Pakihikura (b); and farm and paddock boundary (c).

The case study farm covers 380 ha of various LULC types such as grassland (74%), indigenous Manuka and indigenous forest (8%), short rotation cropland for forage (8%), exotic forest (6%), and other LULCs (e.g., water bodies, space planting, residential area) (4%). The farmed landscape is complex with heterogeneous topographical features (e.g., slope groups, aspect, elevation) soil types, and land use capability. More than 60% of the farm landscape is classified as hill country (16–25°) (39.8%), and steep-land (>25o) (27.1%), whereas flat and rolling land (0 – 15o) occupies 33.1% the total land area (Table 1.1). The farm lies 330m above sea level with elevation ranges between 201 and 420m. Rock types include two main groups: very loose to compact sedimentary rocks (loess, alluvial gravels, and unconsolidated sands and gravels) and very compact to weak sedimentary rocks (massive mudstone and massive sandstones). The average annual temperature in the Waituna West region where this farm located is 12 °C and rainfall is 1140 mm (Climate data, 2022).

Table 1.2: Land area and proportion by slope group in selected study site

Slope group	Slope group (degrees)	Area (ha)	Percentage
A	0 - 3	10.3	2.7
B	4 - 7	29.5	7.8
C	8 - 15	85.7	22.6
D	16 - 20	82.7	21.8
E	21 - 25	68.4	18.0
F	26 - 35	87.9	23.1
G	> 35	15.4	4.0

Source: Calculated from Digital Elevation Model (DEM) data obtained from Land Information New Zealand (LINZ)

1.6. Scope

The study focuses specifically on developing a land use planning approach to develop land use options that can address environmental issues experienced by hill country farms. Ideally, it would be best to use several case studies to evaluate the efficiency and replicability of the proposed approach. However, this requires a large amount of time for data collection and processing, and it would substantially increase the cost associated with the project because of the need to conduct multiple field surveys and soil sample assessments. Given the detailed level of analysis at the farm scale, utilising more than one farm in order to provide numerous case studies is not feasible for a 3-year PhD with a limited research budget. Moreover, the purpose of this study is to develop a framework for land use planning (i.e., proof of concept) rather than building a commercial land use planning tool. Apart from this, it is important that in farm planning practices, a farm plan is developed based on individual farm condition. This means that farm plans vary between farms because farmed landscapes and farming practices are highly variable (i.e., ten farms may have ten different farm plans). As such, the focus of this PhD is to propose an approach for farm landscape planning that incorporates a wide range of tools, methods/models, and data into a standardised process (i.e., framework). This means that the case study is used to demonstrate how the proposed approach applying relevant tools and analysis can be used to support a farmer designing a farmed landscape. Thus, illustrating that a similar procedure can be applied and followed by other hill country sheep and beef farms. Therefore, only one hill country farm was deemed necessary and has been selected to test the proposed proof of concept.

It is not the purpose of this research to create new tools and models to quantify specific ecosystem services at the farm-scale as well as develop a new land use planning model. It is not feasible that a PhD project can develop a range of new models for ecosystem services and environmental impact assessment at the farm-scale. Given that there are many relevant tools and models available, this study will focus on how to utilise and integrate existing models and indicators into the new framework to address the problem in a useful and novel way. As such, priority will be given to the tools and models that are readily available. The evaluation of the performance of the proposed approach will concentrate on whether this can support the landowners to design sustainable land use scenarios for their farm.

The proposed approach applied in this study considers the involvement of farmers and collaboration between farmers and relevant stakeholders as central to the farmed landscape design framework. It is acknowledged that it would be better practice when attempting to design a future landscape for the case study farm to involve a variety of participants (e.g., local people and iwi, farm consultant, regional council, and the Department of Conservation). Having a wide variety of relevant participants would help to demonstrate the collaboration process. By collecting and considering a wide range of perspectives on land management, more land use scenarios could be developed for the study site. However, the study was carried out during the COVID-19 pandemic which meant that NZ went through a couple of periods of lock down, and public meetings and gatherings were severely restricted during this time on health and safety grounds. This meant that original plans to involve the wider Catchment Group and local community had to be amended. Therefore, the collaboration demonstrated in this study is just between the farmers (i.e., farm owners) on the case study farm, a spatial scientist (i.e., PhD candidate), and a soil scientist (field expert who has expertise in land resources evaluation and land use planning at the farm-scale and familiar with hill country landscapes) to minimise the risk and to ensure the study could be completed within given time frame.

In taking an integrated EBM approach it is important to note that in the proof of concept the PhD focuses more on environmental and economic values than other ecosystem services as these are considered to be the ones that are major focus for developing farm plans, especially in the case of average and marginal hill country farms. For the socio-cultural values, the research uses landscape aesthetics in the analysis as an example. Other socio-cultural indicators, for example, educational service, eco-tourism, or those associated to public preferences will be included in the conceptual framework but excluded in the ecosystem services modelling for the selected case study farm. This is because modelling social-cultural ecosystem services is challenging and covering them in full would increase the complexity of the research. The financial and human resources required to extend the scope of this study to include broader socio-cultural consideration, while acknowledged, was not feasible within the confines of a three-year PhD study.

1.7. Structure of the thesis

This PhD follows the format of a "PhD with publication" so the thesis is a combination of four submitted or published journal articles (Chapters 2-6) instead of producing one large monograph. It meets the guidelines and requirements as outlined by Massey University. As such, the thesis is organised differently to the traditional dissertation. For instance, this thesis does not present the literature review, research methods, results, and discussion as separate chapters. Instead, all relevant information is included in each chapter (paper). A brief description of the structure of the thesis is shown in Figure 1.3.

This thesis contains four research chapters i.e., chapters 2 to 5 (Figure 1.3) which have been written as individual journal articles. All these articles (chapters 2 - 5) have been published. A statement of contribution for each journal article can be found at the end of each chapter and in Appendix 1. The thesis also has an Introduction and a Conclusion/Synthesis chapter. Chapter 1 provides an overall introduction to the PhD, including the context of the study, the gap in knowledge and the proposed approach taken. The objectives and research questions, and structure of the thesis are also presented in this chapter. The conclusion chapter (Chapter 6) synthesises the main findings and the contribution of the study to the literature and farm planning and management practices. It also demonstrates how the research questions are answered and incorporates a broader discussion of the relevance of the research for sustainable farm management in NZ and an evaluation of the approach used. It discusses the limitations of the research and presents some recommendations for future research.

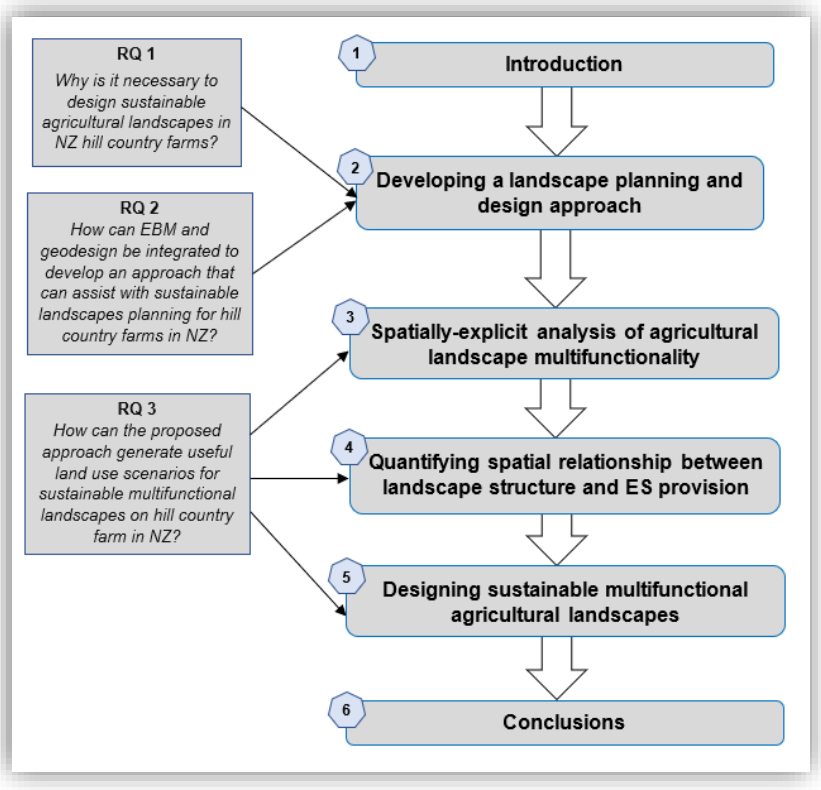


Figure 1.3. Overview of the thesis structure

Chapter 2: Developing a planning and design approach for sustainable management of hill country farms in New Zealand

This chapter first provides an overview of the key literature that is relevant to this PhD study which relates to (1) the environmental challenges facing the sustainable development of NZ hill country farms, (2) tools and approaches for supporting sustainable land use planning in NZ, and (3) multifunctional landscapes and geodesign concepts. Based upon key literature, a conceptual framework using geodesign and ecosystem services concepts (drawn from landscape ecology) is proposed to plan and design multifunctional landscapes that offer improved sustainability for NZ hill country farm systems and landscapes. The conceptual framework and associated landscape design stages and methods presented in this paper provides the basis to carry out empirical analysis for a case study farm (demonstrated in Chapters 3, 4, and 5). This chapter has been published in the journal Land.

Publication citation: Tran, D. X., Pearson, D., Palmer, A., & Gray, D. (2020). Developing a landscape design approach for the sustainable land management of hill country farms in New Zealand. *Land, 9*(6), 185. https://doi.org/10.3390/land9060185

Chapter 3: A comprehensive spatially-explicit analysis of agricultural landscape multifunctionality using a New Zealand hill country farm case study

This chapter quantifies the spatial pattern of the provision of multiple ecosystem services and landscape multifunctionality utilising a wide range of spatial models, tools, and methods. A hill country farm in NZ is chosen as a case study. This study enables the researcher to answer important questions related to the spatial variation of ecosystem services provision across the farmed landscapes and how land use and land management goals (of the farmers) relate to the value and quality of landscape multifunctionality. This chapter provides key information to design future multifunctional landscapes and inform decision making in relation to sustainable land use management. This chapter has been published in the journal Agricultural Systems.

Publication citation: Tran, D. X., Pearson, D., Palmer A., Gray, D., Lowry, J., & Dominati, E. J. (2022). A comprehensive spatially-explicit analysis of agricultural landscape multifunctionality using a New Zealand hill country farm case study. *Agricultural Systems, 203*, 103494. https://doi.org/10.1016/j.agsy.2022.103494.

Chapter 4: Quantifying spatial non-stationarity in the relationship between landscape structure and the provision of pasture productivity, sediment retention, and water yield: an example in the New Zealand hill country.

This chapter examines the relationship between landscape structure and the provision of some ecosystem services using a hill country and steep-land case study in NZ. Spatially and quantitatively detailed variations of the relationship between landscape structure and the provision of ecosystem services provide a scientific basis to inform the design of sustainable multifunctional landscapes. Information derived from this analysis can be used for spatial planning of farmed landscapes to promote multiple ecosystem services which meet multiple sustainable development objectives. This chapter has been published in the journal Science of the Total Environment.

Publication citation: Tran, D. X., Pearson, D., Palmer, A., Lowry, J., Gray, D., & Dominati, E. J. (2022). Quantifying spatial non-stationarity in the relationship between landscape structure and the provision of ecosystem services: An example in the New Zealand hill country. *Science of The Total Environment, 808*, 152126. https://doi.org/10.1016/j.scitotenv.2021.152126.

Chapter 5: Integrating ecosystem services with geodesign to inform the design of sustainable multifunctional agricultural landscapes: a case study of a New Zealand hill country farm.

This chapter demonstrates how the conceptual framework developed in Chapter 2 and methods and results obtained from Chapters 3 and 4 are utilised to design sustainable multifunctional landscapes at the farm scale, using a NZ hill country farm as a case study. A geodesign framework is employed to generate future land use and management scenarios for the study area, visualise changes, and assess the impacts of future land use on landscape multifunctionality and the provision of associated ecosystem services and economic outcomes. This chapter demonstrates the effectiveness of the approach and associated conceptual framework proposed in Chapter 2. This chapter has been published in the journal Ecological Indicators.

Publication citation: Tran, D. X., Pearson, D., Palmer, A., Dominati, E. J., Gray, D., & Lowry, J. (2023). Integrating ecosystem services with geodesign to create multifunctional agricultural landscapes: A case study of a New Zealand hill country farm. *Ecological Indicators, 146,* 109762. https://doi.org/10.1016/j.ecolind.2022.109762.

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2. Developing a landscape design approach for the sustainable land management of hill country farms in New Zealand

Abstract

Landscape modification associated with agricultural intensification has brought considerable challenges for the sustainable development of New Zealand (NZ) hill country farms. Addressing these challenges requires an appropriate approach to support farmers and design a better landscape that can have beneficial environmental outcomes whilst ensuring continued profitability. In this paper we suggest using geodesign and theories drawn from landscape ecology to plan and design multifunctional landscapes that offer improved sustainability for hill country farm systems and landscapes in NZ. This approach suggests that better decisions can be made by considering the major ecosystem services that are, and could be, provided by the landscapes in which these farm systems are situated. These important services should be included in future landscape design of hill country by creating a patterning and configuration of landscape features that actively maintains or restores important landscape functioning. This will help to improve landscape health and promote landscape resilience in the face of climate change. Through illustrating the potential of this type of approach for wider adoption we believe that the proposed conceptual framework offers a valuable reference for sustainable farm system design that can make an important contribution to advancing environmental management globally as well as in NZ.

***Keywords*:** Multifunctional landscapes; Ecosystem services; Geodesign; Landscape ecology; Agricultural landscape planning.

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2.1. Introduction

The green revolution in agriculture that occurred during the second half of the 20th century has greatly contributed to increased global food and fiber production, which has enabled a rapidly growing world population to be fed (Welch & Graham, 1999). In order to increase productivity, agricultural intensification has taken the form of an increase in single crop cultivation and chemical and mechanical inputs (Kenmore et al., 2004). This has led to negative impacts on the environment, evident through a loss of biodiversity and a decline in soil and water quality (Kanianska, 2016). In response to the resultant environmental issues and the need to feed a growing population, agriculture needs to evolve from a production paradigm that has focused primarily on productivity and profitability to a more sustainable paradigm that focuses on how to ensure productivity can support human needs whilst also preserving important land resources and environmental integrity (FAO, 2018). Recently, society and the market have initiated a shift from a focus on agricultural productivity and intensification to a focus on sustainable farming (with an emphasis towards efficiency, sustainability, and resilience) (Proudfoot, 2010). New Zealand (NZ) is a good example of an agriculturally-focused nation that faces sustainable production challenges. It has achieved great improvements in agricultural productivity and product quality over recent decades (Robertson, 2010) but progress has come with significant environmental costs (Baskaran et al., 2009).

Although NZ is accredited as one of the more sustainable countries in the world and was ranked 11th globally in 2019 for sustainable development (Sachs et al., 2019), its agricultural sector is facing a number of significant issues, such as soil degradation (MfE & Stats NZ, 2019), water pollution (Duncan, 2017), greenhouse gas (GHGs) emissions (Kelliher et al., 2014; Safa et al., 2016) and soil erosion (Fernandez, 2017). Moreover, the possible impact of climate change (e.g., increased flood risk, storm damage and drought severity) is also a crucial threat to agricultural production (Reisinger et al., 2010). To respond to these environmental issues farmers are now faced with a situation of having to operate farm systems that are productive and profitable as well as being sustainable with limited impacts on the environment (Dewes, 2014). This is a major challenge facing NZ farmers, as agricultural production could potentially become increasingly constrained by environmental regulations (MfE, 2019b) as governments also respond to growing environmental concerns.

The environmental challenges facing future farming systems are likely to strongly impact upon NZ hill country farming. This is because environmental issues compound already high concerns for these farms, which are associated with the contemporary impacts of increasing production costs, market volatility, climate change, highly variable topography and climatic conditions, and more dispersed and isolated families and communities (Scrimgeour, 2016). This means that future hill country farming systems will need to improve its profitability and build resilience in order to be able to adapt to a changing climate whilst reducing its impacts on the environment. To do this, farmers will need good support systems to help with land use decision-making. However, current land use planning and management approaches that support farm and landscape decision-making in NZ reveal several limitations, such as lack of data and model transparency, insufficient collaboration capability among researchers, policy-makers and other end users, and are limited in terms of the communication of modelling results to end-users (Hendy et al., 2018). Additionally, some land and environmental planning tools are not simple to implement, as farmers are overwhelmed with information and the process required to develop the land and environmental plans (Synge et al., 2013). Consequently, these limitations will reduce the effectiveness of land and environmental planning strategies. Therefore, the development of an effective landscape design approach will be central to helping farmers develop profitable and sustainable farming systems in the future.

The multiple objectives of sustainable agriculture require a multifunctional agricultural landscape that promotes agricultural production whilst ensuring environmental standards are met (McGranahan, 2014), and landscape ecology can have an important role to play in this (Pearson, 2020). Developing a multi-functional agriculture landscape that provides multiple ecosystem services for society in addition to the service of food and fiber production (Lankoski, 2000) has become a key focus for sustainable agricultural research and policy-making, and this has been widely discussed internationally (Atwell et al., 2010; Dalgaard et al., 2007; Estrada-Carmona et al., 2014; J. Huang et al., 2015). However, there is a gap between theory and practice (Bürgi et al., 2017), and transferring the concept of creating multifunctional landscapes into the practice of landscape planning and management has proved to be challenging (Di Lucia et al., 2018). The reason for this is that agricultural landscape planning needs to be implemented for a specific geographical region that is strongly associated with local knowledge (Zasada et al., 2017). This needs the planning process to involve the considerations of local people and therefore requires participation and collaboration of the main stakeholders (Natarajan, 2017). Often this does not happen and as a result, local people (or "people of the place") may not agree or may not be able to afford the future landscape scenarios proposed by landscape planners (Steinitz, 2012), so it is critical that the relevant different stakeholder groups can actively contribute to designing the future landscape by bringing their knowledge and aspirations to the table (Karrasch et al., 2017). It is important that effective landscape planning and scenario development involves an iterative collaborative process and that a design-driven perspective is taken (Opdam et al., 2013).

Recently, geodesign has emerged as an efficient instrument for the implementation of sustainable landscape planning (Slotterback et al., 2016). Geodesign integrates geospatial technologies and scientific methods (e.g., geospatial science, environmental science) to inform spatial decision-making based on the knowledge and information obtained from spatial data (Campagna, 2016). By integrating multiple layers of geographic information and spatial analysis models, geodesign enables the identification and development of a future landscape that has an appropriate spatial pattern or configuration of landscape features (Lee et al., 2014). This also enables the rapid generation of future landscape scenarios for a study area, the ability to visualise change scenarios, and the assessment of the impacts of future landscape designs on multiple landscape functions and services

(Flaxman, 2010). In addition, visualization tools and iterative quantitative modeling used in geodesign can promote collaboration between participants, as they enable stakeholders to enter into the discussion and express their opinions and aspirations as part of the design procedure (Albert & Vargas-Moreno, 2012). Among the geodesign frameworks that have been published, the operation framework developed by Steinitz (2012) has been disseminated to a wide range of landscape and environmental design situations (Hollstein, 2019). This framework considers landscape design as an iterative process in which the collaboration among the group of people involved in the design process (which includes design professionals, the people of the place, information technologists and geographic scientists) is an integral part of the design procedure, and the relevant stakeholders play a central role in all of the design stages (Campagna, 2016).

The adaptation of the framework outlined by Steinitz offers a potential solution to guide farm system decision-making for the creation of multifunctional landscapes. This paper develops these ideas by proposing a landscape design approach for the sustainable land use planning and management of hill country farms in NZ. The approach developed utilises geodesign and the concepts of landscape function and services as informed by landscape ecology. The specific objectives of this paper are to: (i) define the major challenges facing current and future agriculture in the NZ hill country that need to be considered in future farm landscape planning; and (ii) design a framework that can assist in the creation of multifunctional landscapes for sustainable agricultural production. In doing this, the paper highlights the benefits of integrating geodesign into multifunctional landscape planning for the creation of multifunctional farm landscapes in NZ. This research offers a valuable reference for sustainable farm system design that can make an important contribution to advancing environmental management globally as well as in NZ.

2.2. Multifunctional landscape and geodesign

2.2.1. Multifunctional landscapes and its application in agricultural landscape planning

A multifunctional landscape is seen as being one capable of providing a wide range of ecosystem services covering three main areas relevant to landscape management, i.e., ecological, cultural and production functions (Wiggering et al., 2003). Natural and semi-natural landscapes are considered as multifunctional landscapes because they provide a variety of goods and services to people, such as food and fiber, climate regulation and water purification (Millennium ecosystem assessment, 2005). However, multifunctional landscapes of the past have been transformed into more simple landscapes (e.g., single-function landscapes), which have a dominant land use type (e.g., croplands). This is because land managers and decision-makers have focused on increasing agricultural productivity rather than considering the benefits that can be provided by a multifunctional landscape (De Groot & Hein, 2007). The transformation of a natural landscape into an agricultural landscape, especially one that is farmed intensively, leads to landscape simplification. This occurs as diverse stands of native vegetation are cleared and replaced with a monoculture, resulting in a loss of biodiversity and a reduction in the provision of multiple ecosystem services (Emmerson et al., 2016). Many studies have demonstrated the negative effects of landscape simplification, such as an increase of insecticide use (Meehan et al., 2011), loss of habitats (Poveda et al., 2012) and a reduction in biological control (Grab et al., 2018). As such, developing a multifunctional landscape is increasingly being recognised as offering an appropriate solution for solving the issues and challenges that have arisen from agricultural intensification (i.e., landscape simplification) (McGranahan, 2014).

A landscape ecological approach based on the concept of the multifunctional landscape has been widely applied in sustainable agricultural landscape planning (Fagerholm et al., 2019; Groot et al., 2010; Otte et al., 2007; Rallings et al., 2019). In the European Union (EU), multifunctional agriculture is significantly encouraged, as it is a key concept of the Common Agricultural Policy for the EU countries (van Zanten et al., 2014). This concept is also applied in many developed countries, like the United States of America, Canada and Australia (Otte et al., 2007). The overall goal of agricultural landscape planning that is based on the concept of the multifunctional landscape is to develop future or alternative landscapes that can enhance and increase the multifunctionality of the current landscape, in order to achieve a better balance between agricultural production and other ecosystem services (Chopin et al., 2017).

An ecosystem services approach has been applied in order to examine a wide range of issues in NZ, such as biological control (Fiedler et al., 2008), biodiversity (Gillespie & Wratten, 2012) and land use planning and management (Dominati et al., 2014; Dominati et al., 2016; van den Belt et al., 2013). However, some limitations have been identified, such as the obstacles associated with incorporating the ecosystem services concept into agricultural land use decision-making and the lack of participation and contribution of farmers in the creation of a future multifunctional landscape (van den Belt & Blake, 2014). Another important limitation is the inadequacy of the link between ecosystem services supply and demand. For instance, there is a lack of research that assesses the imbalance between ecosystem services supply and non-market demand in a spatially explicit manner (e.g., where and to what extent in the landscape are certain services generated by agro-ecosystems needed to maintain desirable environmental conditions) (van den Belt & Blake, 2014). In addition, current research involves limited measurements of ecosystem services (e.g., biodiversity) other than production services (e.g., food and fiber) across small areas (e.g., farm scale) (Dominati et al., 2019). Therefore, the ability to fully integrate multiple ecosystem services into land use planning and the implementation of a collaborative planning process will provide a greater opportunity to address these gaps.

2.2.2. Geodesign

Geodesign is defined as “a design and planning method which tightly couples the creation of design proposals with impact simulations informed by geographic contexts, systems thinking, and digital technology" (Flaxman, 2010) (p. 29). Geodesign often involves collaboration among essential groups (e.g., the design experts, geographical information system (GIS) scientists, information technologists and the stakeholders) to develop and decide sustainable scenarios for the future landscape of their area (Steinitz, 2012). These groups comprise a geodesign team, and collaborate based on a set of questions and methods, typically within a framework that consists of six key questions (Nyerges et al., 2016):

1. How should the landscape be described in content, space and time?
2. How does the landscape operate?
3. Is the current landscape working well?
4. How might the landscape be altered? By what policies and actions, where and when?
5. What differences might the changes cause?
6. How should the landscape be changed?

Six models are employed to answer the six questions, ranging from the description of the study area to the decision on a desired future landscape. The process presented in the framework is an integrated and continuous procedure, because the outcome of each phase serves as an input for the subsequent phase, and all the stages of the design (understand study area, specify methods and perform study) are incorporated into one unified system.

Recently, geodesign has emerged as an innovative design approach, developed to provide alternative scenarios for future landscapes, based on a rich knowledge base about the environment (Campagna, 2016). Geodesign has been extensively applied to different landscape planning and management case studies, such as urban development (Gu & Deal, 2018; Newman et al., 2020; Pettit et al., 2019), environmental management (Sophronides et al., 2016; Zandvoort & van der Vlist, 2014), and sustainable agricultural land use (Jordan et al., 2018; Raumer et al., 2016; Xie et al., 2017). This approach is also flexible in terms of the scale of application (e.g., a street, a farm, small town, catchment and regional scales) (Esri GeoDesign Team, 2020; McElvaney & Rouse, 2015).

Various examples of geodesign applications were discussed at the Geodesign Summit in 2019 (ESRI, 2019). In the case of agricultural landscape planning, a typical example of the application of geodesign is illustrated through the use of the approach to increase food production and biofuel commodities and improve water quality and habitat performance in the Seven Mile Creek watershed, Minnesota, United States (Slotterback et al., 2016). At the farm scale, another example is a geodesign project that utilises 3D modeling and geospatial analysis to design strategies for climate change mitigation on a farm in Iowa, United States. This project applies geodesign for real-time scenario development and interactively evaluating alternative farm design (Iowa State University, 2019).

In NZ, GIS tools and techniques have been widely applied to solve environmental problems (Borrelle et al., 2015; Claessens et al., 2007; Longdill et al., 2008; MacMillan et al., 2016; Singh et al., 2019), but the tools and approaches that link design and GIS have not been readily available (Eagle Technology, 2019) and there is a limited number of applications that follow the geodesign framework to solve problems in landscape planning, especially at the farm scale. For instance, only one previous paper was identified that applied geodesign to plan a route for visitor access across a farm in NZ (Moore et al., 2018). Meanwhile, there is an absence of geodesign applications that focus on developing a multifunctional agricultural landscape. Hence, research that utilises geodesign procedures in an agricultural landscape, especially at the farm scale, has the potential to contribute to environmental management studies in NZ but has not yet been fully explored.

2.2.3. The benefits of integrating geodesign into multifunctional landscape planning

Geodesign offers an efficient solution to implement the adaptive design of multifunctional landscape planning. It is an effective approach because it can (1) promote collaborative and adaptive landscape design among different stakeholders, (2) advance landscape multifunctionality in agricultural landscape planning and (3) enable the implementation of the landscape design problem on a large scale. One key advantage of geodesign compared to traditional landscape planning approaches is that it allows for collaboration among researchers, policy-makers, and other end users, because it divides the landscape planning into different processes (with six distinct phases) and allows the participants involved to provide feedback and suggestions at any step in the process (Eikelboom & Janssen, 2017). With the latest geospatial technologies (e.g., WebGIS application, human–computer interaction tools), participants can directly interact with both the data and the analysis procedure. This is considered an efficient way to initiate discussion among different stakeholders about alternative futures or visions for the new landscape (Hansen & Pauleit, 2014). In addition, a geodesign framework includes a decision model (Nyerges et al., 2016) so this can make the application of landscape planning more adaptive and practical. It supposes that decision-makers may agree with or oppose the proposed change, so the decision model that includes a negotiation process (e.g., discussion) and method (e.g., Delphi method) will be able to effectively build consensus among decision-makers and other stakeholders, as well as able to suggest necessary modifications to the proposed changes or the development of new adapted plans (Campagna, 2016). Additionally, alternative landscape plans are not always going to provide a first and ultimate fix, so decision-makers can iteratively discover the trade-offs and synergies inherent in different design scenarios until a final decision is achieved (Burgin, 2003). In the case of NZ, where agricultural land is under private ownership and farmers are the final decision-makers, the inclusion of a decision model in landscape planning is critical because it increases the role of farmers in the landscape design process. This can potentially facilitate the approval by private landowners of proposed landscape change and therefore make the implementation of future landscape change more feasible (von Haaren et al., 2014).

Compared to other landscape design methods and techniques, geodesign has a great potential to break new grounds in the design industry, as it is based on advanced geospatial technologies (Huang et al., 2019). State-of-the-art remote sensing, image processing, and GPS tools and techniques enable the collection and processing of large amounts of biophysical data in high spatial and temporal resolution. This means that geodesign can be implemented at various scales (Li & Milburn, 2016). This is an asset in the case of NZ hill country, where geospatial data, and especially data for farm scale application, is poor. For instance, it is common that there is a lack of detailed land use land cover (LULC) data at the farm scale, so in this case high-resolution remotely sensed data can be used to produce necessary LULC information. In addition, a wide range of tools, techniques, and models that have arisen from GIS, geospatial information, spatial statistics and computer programming can be incorporated into one spatially informed planning platform so as to allow comprehensive landscape design issues to be resolved (as it is a multidisciplinary or transdisciplinary problem) and to provide a more efficient communication mechanism for the modeling processes and results (Kastuari et al., 2016). Geodesign can also integrate different kinds of environmental and socio-economic models to quantitatively and spatially measure the cost and benefit of implementing alternative land use scenarios (ESRI, 2013). The outcome from each geodesign question, such as landscape structure and pattern, environmental sensitivity and risk, and future landscape scenarios, are presented in a meaningful and intuitive visualization (e.g., dynamic map, table and graph) so as to provide better assistance for decision-makers. Once the farmers can see the environmental issues on their farms and measure how much they must invest and can benefit from the future landscape, they will be more confident to make a decision.

In order to effectively co-design future multifunctional landscapes, non-technical people (i.e., farmers) may require an understanding of the basic landscape concepts, such as different socio-economic and ecological landscape functions and services (Slotterback et al., 2016). Through collaboration with other participants, farmers can receive support from technical people (e.g., scientists) to acquire the necessary knowledge. More importantly, geodesign employs GIS models, tools and applications to incorporate numerous layers of geospatial information and transfer the key multifunctional landscape concepts into realistic visualization forms (e.g., map, graph) (Soini, 2001), as well as to develop future landscape scenarios, visualise them and analyse the impacts of the different proposed landscapes on multiple ecosystem services (Flaxman, 2010). This may encourage farmers to pay attention to not only commerce and food production but also the role of the non-trade functions of agricultural landscapes. In addition, the adaptive design capability of geodesign enables farmers' priorities to be considered, as their preferences or requirements can be set in the land change model, and this can subsequently increase the ability to reach a consensus between farmers and other stakeholders on future multifunctional landscape scenarios.

2.3. The case study

2.3.1. Introduction to New Zealand hill country and its environmental challenges

NZ hill country is defined as land with slopes above 15° and located below an altitude of 1000 m above sea level (Blaschke et al., 1992). This landscape type covers a variety of land class types, climatic conditions, geology, and topography properties (Molloy, 1988). The hill country landscape is a mixture of steep-land, rolling land, and flat land (Lynn et al., 2009)(Figure 2.1).

Most of the hill country is classified as land use capability classes (LUC[2]) 5–7, which are suitable for pastoral grazing, tree crops or production forestry (Jones et al., 2008). Other LUC (e.g., classes 3, 4 and 8) often occupy a small proportion of hill country land. Overall, approximately 10 million hectares of NZ's total land area is classified as hill country (approximately 37.5% of the NZ land surface), with the majority located in the North Island (6.3 million hectares or 23.5% of NZ's total area) (Hedley et al., 2015). Approximately half of the hill country land (5 million hectares or 18% of NZ's total area)

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[2] LUC class 1 is flat highly productive land and LUC class 8 is very steep unproductive land.

is allocated to pastoral farmland used for sheep and cattle farming (Kerr, 2016). It has been reported that sheep and cattle farms, the bulk of which are located on hill country, also own some 25% of the total native vegetation remaining in NZ (Beef and Lamb,2018). This significant proportion of native vegetation plays an important role in carbon sequestration and biodiversity conservation (Norton & Pannell, 2018).

Figure 2.1. Hill country landscapes: (a) earth flow; (b) slump/earth flow; (c) steep slopes > 25°; (d) flat topped ridges; (e) hilly slopes 15-25. Photographed by Duy X. Tran in 2019.

In recent years, hill country farms have become increasingly concerned about environmental issues (Beef and Lamb, 2019c). For instance, Beef and Lamb NZ, an industry organization representing NZ's sheep and beef farmers, has defined four pillars for an environment strategy (created in 2018) for sheep and cattle farms. These include working towards cleaner freshwater, healthy and productive soils, thriving biodiversity and reduced emissions in order to achieve the goal of being carbon neutral by 2050 (Beef and Lamb, 2018). However, several environmental problems and the negative effects of climate change are challenging the sustainable development of this type of farming (Rutledge et al., 2016; Scrimgeour, 2016).

Understanding the major environmental challenges facing hill country farming is vital to ensure that good planning for future landscape and farm systems is made for the future. In the following section, the five major issues that need to be considered prior to landscape planning in order to make progress towards a more sustainable future for hill country farming are examined in the discussion below. These are land use change and deforestation, soil erosion, climate change, agricultural intensification and change in consumers preferences.

Large areas of native forests and shrubland on the steep erodible terrain of NZ hill country were cleared for pastoral farming by the European settlers (Phillips et al., 2018). Although limited deforestation has occurred since the 1980s, the response to historic deforestation and land clearing is still affecting the current landscape and environment (Harding, 2003). The negative impact of deforestation has been reflected in a significant increase in soil erosion (Basher, 2013). Over the last three decades, reforestation and regenerating of native vegetation has been increasingly implemented on hill country (MPI, 2019) to reduce sediment loss from steep slopes into river channels (Marden et al., 2014) and to increase the capacity for climate change mitigation and adaptation (Evison, 2018). Plantation forestry has a number of positive effects on the environment, such as a reduction in soil erosion and flooding, an increase in carbon sequestration and a reduction in the GHGs emissions, and it has also reduced pressure on native forests for timber (Yao et al., 2013). For instance, a report on erosion-prone hill country (for the period of 1997 to 2002) reported that the area prone to soil erosion had been reduced by 36,000 hectares (3% of the total erosion-prone area) due to the planting of exotic forest or through reversion to native shrublands (Basher, 2013). However, removal of forest cover at harvest on steep-land can result in significant environmental impacts, such as landslides, debris flows and significant impacts on water quality due to sediment loss into waterways (Phillips et al., 2018).

Over the period of 1990–2015, the total area of hill country sheep and beef farms decreased by approximately 1.3 million ha (Beef and Lamb, 2019c). This is because the more productive land was converted to dairy farming or higher-value horticultural crops (Kerr, 2016) whilst the steeper, less productive land, which is more vulnerable to erosion and generates lower financial returns (Lang, 2019), was converted to an alternative land use, such as forestry, manuka[3] for honey production or retirement and a return to native vegetation (Scrimgeour, 2016). Recently, carbon farming, which is a conversion from pasture to forest, is emerging as an alternative to sheep and beef farming in hill country due to the dramatic increase in the price of carbon credits, and this conversion can bring high economic profit if this occurs in eligible areas (the land areas where there has been a net land use conversion to new forests since January 1, 1990) (Funk et al., 2014). Therefore, it is important that relevant scientific information (e.g., mapping of suitable areas for alternative land use options) is available so as to allow landowners to make appropriate decisions (Funk & Kerr, 2007).

In the NZ hill country, soil erosion is a critical issue that contributes to land degradation (MfE & Stats NZ, 2018). The hill country has a high level of both natural and human-induced erosion (Mclvor et al., 2011) due to the amalgamation of coarse-textured soils, high slope terrain, high precipitation and agricultural intensification (Rodda et al., 2001). Soil erosion presents a significant problem to the practices of current pastoral land, and it is especially severe on hill country, which has substantial areas of steep slopes and erodible rocks (e.g., soft rock) (Marden, 2012), especially in combination with high rainfall and high-intensity rainstorms (Basher, 2013). It is estimated that 192 million tons of soil are lost every year because of erosion and 44% of this takes place on grassland (MfE, 2019a). Soil erosion does not only represent a reduction in NZ's natural resources, but it also results in a decline in soil productivity and a reduction in water quality (Mclvor et al., 2011). In relation to the economic cost, the effects of soil erosion on hill country can be on-site (e.g., a reduction in productivity) and off-site (e.g., an

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[3] Manuka honey is a monofloral honey produced from the nectar of the manuka, a native tree (Leptospermum scoparium) that grows in New Zealand and parts of Australia.

increase in flood damage in downstream regions) (Jones et al., 2008). The cost of erosion control and mitigation has often surpassed the value of the production that can be obtained from that land (National Water and Soil Conservation Organisation, 1970), and an increase in vegetation cover (e.g., regenerating native trees, tree planting and reforestation) has been described as being the most efficient solution for this problem (Piégay et al., 2004). For instance, it is argued that the reforestation of unstable and degraded land can not only effectively control current erosion problems, but also preclude the formation of new forms of erosion (Marden et al., 2014). For these reasons, soil erosion control is important in land use planning and management in hill country. Characterising the detailed spatiotemporal pattern of soil erosion and the capability of landscape options to reduce this environmental problem are central to managing this issue.

Climate change is recognised as one of the significant challenges facing agricultural development in NZ hill country (Lang, 2019), as the country's land-based economy is profoundly reliant on climatic conditions for the growth of pasture and crops (Clark et al., 2012). Increased frequency of intense rainfall events is a threat to soil erosion, predominantly on hill country steep-land (Mclvor et al., 2011). The expected increase in drought frequency and intensity in some drier regions may severely affect the water supply, agricultural production and magnitude of wildfire risk (Hendy & Halliday, 2018; Moot et al., 2010; Mullan et al., 2005; Pearce & Clifford, 2008). Climate change may also directly affect pastoral production, because the seasonal variation of pasture growth is influenced by rising temperatures, CO_2 fertilization and changes in rainfall patterns (Clark et al., 2012). Thus, climate change may result in greater variation in sheep and cattle growth and productivity (Grafton & Manning, 2017). Adaptation solutions have been developed to reduce risks and build resilience to climate change impacts in NZ. Some of the major adaptation strategies put emphasis on a long-term perspective and suggest an integration of climate change adaptation into the decision-making process (Climate Change Adaptation Technical Working Group, 2017).

The impacts of climate change on hill country farming may also be off-site and long-term (NZAGRC, 2019). For example, climate-concerned international consumers or markets might result in an increased demand for the outputs from production that has low GHGs emissions (McDonald & Kerr, 2012), which will mean that NZ agricultural production will have to change accordingly to maintain their market share. Considerable effort has been made by both the public and private sector to determine climate change mitigation solutions in NZ, and central to this is to reduce the GHGs emissions caused by agricultural production (MfE, 2016). For instance, in the agricultural sector it is suggested that changes to land use and pasture management will be key solutions for reducing GHGs emissions along with other strategies (e.g., innovation in animal genetics and breeding) (Cortés Acosta et al., 2019). It is therefore suggested that multiple land use options (e.g., pasture, forestry, horticulture) need to be considered in relevant areas of the hill country and the integration of climate change scenarios needs to be made into future land use plans for more comprehensive land use planning and management models capable of addressing issues related to climate change.

Intensive pastoral farming in hill country increased rapidly from the late 1940s to early 1980s. This was due to the increasing demand and rising prices for meat and wool products on the world market (Haggerty et al., 2009). It was also supported by government subsidies for land development, as well as the emergence of new technological developments (e.g., aerial topdressing—application of aircraft for fertilizers spreading and pasture seeding) (Dodd et al., 2008). Intensive farming during this period was reflected in a re-clearance of a substantial area of native vegetation that was planted in pasture grass for meat and wool production, an extensive application of fertilizers and agrichemicals, and a high stocking rate (Peden, 2020). Agricultural intensification and inappropriate agricultural practices in the hill country have resulted in negative impacts on the environment. This includes an increase in soil erosion on steep-land where native bush and shrubs were cleared for pasture, a decrease in biodiversity (Moller et al., 2008), an increase of nutrient leaching (Parfitt et al., 2009), a reduction in water quality (Betteridge et al., 2017) and a reduction of future carbon stocks (Parliamentary Commissioner for the Environment, 2016).

Since 1984, hill country farming has undergone a dramatic reduction in sheep numbers, as more productive pastoral land was converted to other land use types, and farmers also reduced the stocking rate (Haggerty et al., 2009). Recently, sustainable practices such as organic farming have also been increasingly implemented on some NZ hill country farms (Swaffield, 2014). These sorts of changes have resulted in both productivity improvement and better environmental outcomes (Ford & Ford, 2016; Tayler et al., 2016). However, despite these successes, some hill country farms have been managed intensively to improve economic profitability and unsuitable agricultural practices are still happening (Fraser & Vesely, 2011; Hoogendoorn et al., 2017). For example, farmers tend to eliminate the reinvading bush, shrubs and exotic weeds in some high-altitude farms, or marginal land is not fenced off, and this limits the restoration of native forest, which can cause problems associated with soil erosion as well as reducing future carbon stocks (Parliamentary Commissioner for the Environment, 2016).

With increasing concerns about the environmental impacts of agricultural intensification and the need to mitigate the impacts of climate change, it is necessary to promote a wider uptake of more sustainable agricultural practices in the hill country (Dodd et al., 2008; White et al., 2010). Several studies have shown that applying appropriate farming practices, such as developing shelterbelts and hedges, using native plants, or riparian plantings can significantly enhance the provision of ecosystem services (e.g., increase biodiversity, pest control, water purification) (Hahner et al., 2014; Sandhu et al., 2008, 2010; Todd et al., 2016). Moreover, by applying appropriate land management decisions it is possible to increase farm productivity whist reducing the impacts on the environment (Struik & Kuyper, 2017). For instance, using soil data, topographic maps and spatial analysis can help to determine optimum fertilizer application to the appropriate areas and assist in the reduction of nitrate runoff (Gillingham et al., 2003). Making informed decisions requires good land use planning and management tools, which can provide detailed land use and environmental information at the farm scale.

Meat and fiber from NZ hill country farms are well recognised on the world market because they are safe, nutritious and grass-fed (Lang, 2019). However, international consumers are increasingly becoming aware of environmental issues that arise from intensive agricultural production and are requesting more eco-friendly agricultural products or products that respect environmental standards (Ghvanidze et al., 2016; Yadav & Pathak, 2016). Therefore, the way food is produced (i.e., considering factors such as environmental impact, animal welfare and carbon footprint) is becoming an important focus of consumer preference that now needs to be considered alongside the more traditional values associated with high quality (Lang, 2019). Subsequently, environmental and sustainability standards are being added to the traditional quality and health standard requirements for produce. As a result of changes in consumers' preferences, NZ hill country farmers are required to adopt more sustainable farming systems that take into account the impact of their practices on the environment (Fennessy et al., 2016; Mcdermott & Scrimgeour, 2016). Adopting more sustainable farming practices will not only improve the environmental health of NZ hill country; it also presents an opportunity for farmers to capitalise on the growing market for environmentally friendly products. The utilization of effective tools for land use planning and appropriate resource allocation will contribute to solving many of the issues faced by NZ's hill country.

2.3.2. Tools and approaches for supporting sustainable land use planning used in New Zealand

Government organizations, research institutions and the private sector have developed a wide range of land use models and tools to help to address some of the impacts associated with land use issues and environmental concerns in NZ (Samarasinghe, 2011) as well as supporting farm and landscape decision-making in hill country (Beef and Lamb, 2019d). Various types of models have enabled the user to deal with specific environmental concerns, such as carbon sequestration (McNally et al., 2017), greenhouse gas emissions (Safa et al., 2016), soil erosion (Dymond & Vale, 2018), nutrient loss (Burkitt et al., 2016) or water use (Higham et al., 2017). There are also various applications to help farmers deal with the issues of farm production: AgInform (Rendel et al., 2017), BiomeBGC (Keller et al., 2011), MitAgator (Risk et al., 2011) and Farmax

(Bryant et al., 2010). There are more complex land use models (e.g., Agent-Based Rural Land Use New Zealand (ARLUNZ) (Morgan & Daigneault, 2015), New Zealand Forest and Agriculture Regional Model (NZ-FARM) (Landcare Research, 2013), Waikato Integrated Scenario Explorer (WISE) (Rutledge et al., 2016), which can take into account different factors, such as land use information, socio-economic conditions and environmental parameters (climate, water quality and biodiversity) to provide projected outcomes for land use and environmental, economic and demographic indicators. There are also Whole Farm Plans (WFP), which are a long-established land management tool that is being widely used across NZ to deal with both economic considerations and environmental constraints on farming systems (AgResearch, 2016). Recently, the Land and Environment Plan (LEP) was developed by Beef and Lamb NZ to support sheep and beef farmers to have a better understanding about the land and environmental issues that exist on their farms so that they can develop a land use and environment plan to manage these issues (Beef and Lamb, 2019d).

Land use and environmental planning tools and models have contributed significantly to agricultural development as well as supporting farmers in decision-making to address sustainability issues in NZ (Hendy et al., 2018). However, several improvements are required to increase the effectiveness of the model outcomes. A review conducted by Motu Economic and Public Policy Research in 2018 (Hendy et al., 2018) pointed out some gaps that NZ land use modeling needs to take into account in order to improve its usability. These include increasing the reliability of the data and increasing model transparency, improving collaboration capability among researchers, policy-makers and other end-users, enhancing the communication associated with the model results to stakeholders and enabling a climate change mitigation framework in the land use planning process (Hendy et al., 2018).

Of upmost importance for improving model reliability is the use of data with a better spatial and temporal resolution. It was conceded that NZ lacks good GIS data when compared to many other developed countries (Hendy et al., 2018). Using data that are too generalised means that it is not possible to achieve accurate analysis, especially at the finer scales (e.g., farm and paddock) (Cameron, 2016), as it will fail to capture the variability present at the a farm scale in relation to factors such as variations in slope, soil types, soil fertility and effective rainfall (Kerr, 2016) (see section 2.3.4 for more details). Therefore, it is important to consider acquiring better data at a high resolution so that land use optimization models can adequately represent the environmental and ecosystem services variability within small farm-scale areas (van den Belt & Blake, 2014). It is also important to have an appropriate amount of time-series data to enable trends in environmental issues to be examined over time (Tran et al., 2019). This is critical for predicting change to the future environment and is an important basis on which to develop long-term land use and environmental planning.

It is also important that land use planning takes into account the collaboration between different stakeholders so that they can be involved in the planning process (Hendy et al., 2018). Farm system research has evolved to recognise that there needs to be a shift towards more trans-disciplinary approaches to farm system management, which require collaboration and integration of knowledge and ideas between different people, disciplines and methods (Stevens et al., 2016). A framework that allows the collaboration among researchers, policymakers and users will enable them to easily and actively be involved in the planning process and develop a comprehensive land use plan that satisfies multiple objectives (i.e., socio-cultural, economic and environment issues).

A land use planning framework needs to enable the integration of different models and tools to better solve different aspects of land use planning. Various tools and applications have been developed to deal with a wide range of the land use and environmental issues in NZ, and these continue to receive support and investment from the government, research institutions and the private sector (van den Belt et al., 2010). However, the integration of different models into a single framework to solve interdisciplinary questions has been limited in NZ (Belt et al., 2010). Hence, future land use models need to consider the synergies between different models and techniques so that they can be utilised to solve real world problems.

It is necessary to improve the communication of both the modeling processes and the outcomes from this process. In NZ, some land use and environmental planning tools (e.g., LEP, Overseer) are not simple to implement, as they require farmers to prepare and enter a large and complicated set of data into the model. Some tools may require farmers to implement several complex spatial analysis processes (e.g., map overlay, multicriteria analysis) to define environmental issues on a farm. These analysis are challenging tasks without appropriate supporting tools and the results achieved from these analysis are often difficult to interpret (Synge et al., 2013). In fact, land and environmental planning is a spatially complex problem, since it requires the integration of a wide range of geographic information (e.g., soil, land use types, climate variables) to define issues and allocate and plan resource use. Without an appropriate spatial decision support system (DSS), the process is intimidating for farmers, as they are overwhelmed with information (Synge et al., 2013). An adaptive spatial-based DSS incorporating spatial analysis tools and techniques would provide models with the capability to capture, store, manipulate, analyze, manage and visualise land resources and environmental data and information (Sugumaran & Degroote, 2010). This makes the results more transparent to the various decision-makers through the use of different forms of visualization (such as interactive maps, graphs and reports). Despite the fact that various DSS tools and applications have been developed, most applications for the farm-scale are not spatially-explicit systems and limited in encouraging the participation and contribution of farmers in the modelling process. A spatial-based DSS that has a transparent underlying approach and model's outcomes and allows farmers to actively be involved in and contribute to the planning process would better support and encourage farmers in the development of more sustainable future farmed landscapes.

2.3.3. Spatial data for land and environmental planning at the farm scale in New Zealand

Most land and environmental data for New Zealand has been created and mapped at regional or catchment scales (Table 2.1). Apart from the topographical data (digital elevation model - DEM) that is widely available and has a resolution suitable for farm-scale application, most data used for farm-scale modelling is considered to be at a "poor level", given that the spatial scale at which the data was collected and mapped is not capable of obtaining the level of variation required across the farm (Burkitt & Bretherton, 2022). For instance, the S-map data that is at a nominal scale of between 1:30,000 and 1:50,000 is appropriate to represent soil variability at greater than ~500 m length, however, is not detailed enough to represent soils at the scale of paddocks or sub-paddocks (Grealish, 2017; Landcare Research, 2023). In addition, S-map data is limited for farm-scale applications due to its poor coverage, especially the hill country and steep-land areas (i.e., currently covers only 37.8% of NZ soil). Similarly, the New Zealand Land Cover Database (LCDB) data that was mapped at 1:50,000 can describe well the land cover pattern in a catchment or a region but is limited in capturing that of farm scale. For example, LCDB information with a minimum mapping unit of 1ha, is not able to represent the small woodblocks or water bodies, which may play an important role in providing ecosystem services for a farm. The same situation is seen in the land use capability (LUC) data. This fundamental layer is widely used in land resources planning and assessment, however, is not suitable for the farm scale application. In addition to these primary land resources data, there is a comprehensive dataset covering 72 environmental variables that was developed by Landcare Research (McCarthy et al., 2021). The spatial resolution of this data set i.e., 100m is suitable for national and regional scale applications but not that of farm scale as this alters the representation of micro topographic and environmental pattern in a complex farmed landscape. For instance, the 100m data resolution means that each cell (i.e., 1ha) will have the same soil, slope, aspect, and altitude values, whereas in a highly complex hill country farm, a range of soils, slopes, aspects, and altitudes can be found over short distances (e.g., 5-10m). Good quality and appropriate farm-scale data may be available elsewhere through the work done by local regional councils, research institutions, and government agencies. However, a major barrier that prevents the use of these data is that they are not publicly available and cover a limited number of farms. Most farm plans are private between the landowner and Regional Council and not available to the public as they contain personal financial details.

Table 2.1: Spatial data for land and environmental modelling available in New Zealand

Data	**Scale/Resolution**	**Source**
Digital Elevation Model (DEM)	8-25m	Land Information New Zealand, University of Otago, Landcare Research
	30m – 90m	The Shuttle Radar Topography Mission (SRTM)
The New Zealand Land Cover Database (LCDB), Land Use and Carbon Analysis System (LUCAS)	1:50000	Landcare Research
Soil	≥ 1:50000	Soil Bureau bulletins and Soil Survey Reports, New Zealand Land Resource Inventory (NZLRI)
Digital soil property (S-map)	1:30000 – 1:50000	Landcare Research
Land use capability (LUC)	1:50000	New Zealand Land Resource Inventory (NZLRI)
Environmental data/ Ecosystem services	100m (raster), 1:50000 (shapefile)	Landcare Research
New Zealand Monitor Farm Data	Farm-scale	Ministry of Agriculture and Forestry (MAF), Overseer
Other land and environmental data (e.g., soil, LUC, LiDAR DEM)	Farm-scale	Local regional councils; Research Institutions; Government agencies; Private consulting firms

Figure 2.2 demonstrates the spatial variation in land cover, land use capability, and soil pattern in a farm presented at regional scale derived from LCDB and NZLRI (Figures 2.2a and 2.2c) and farm scale data obtained from field survey and mapping (Figures 2.2b, 2.2d, and 2.2e). It can be seen that data at regional scale has been highly simplified showing a homogenous pattern of land cover, soils, and LUC.

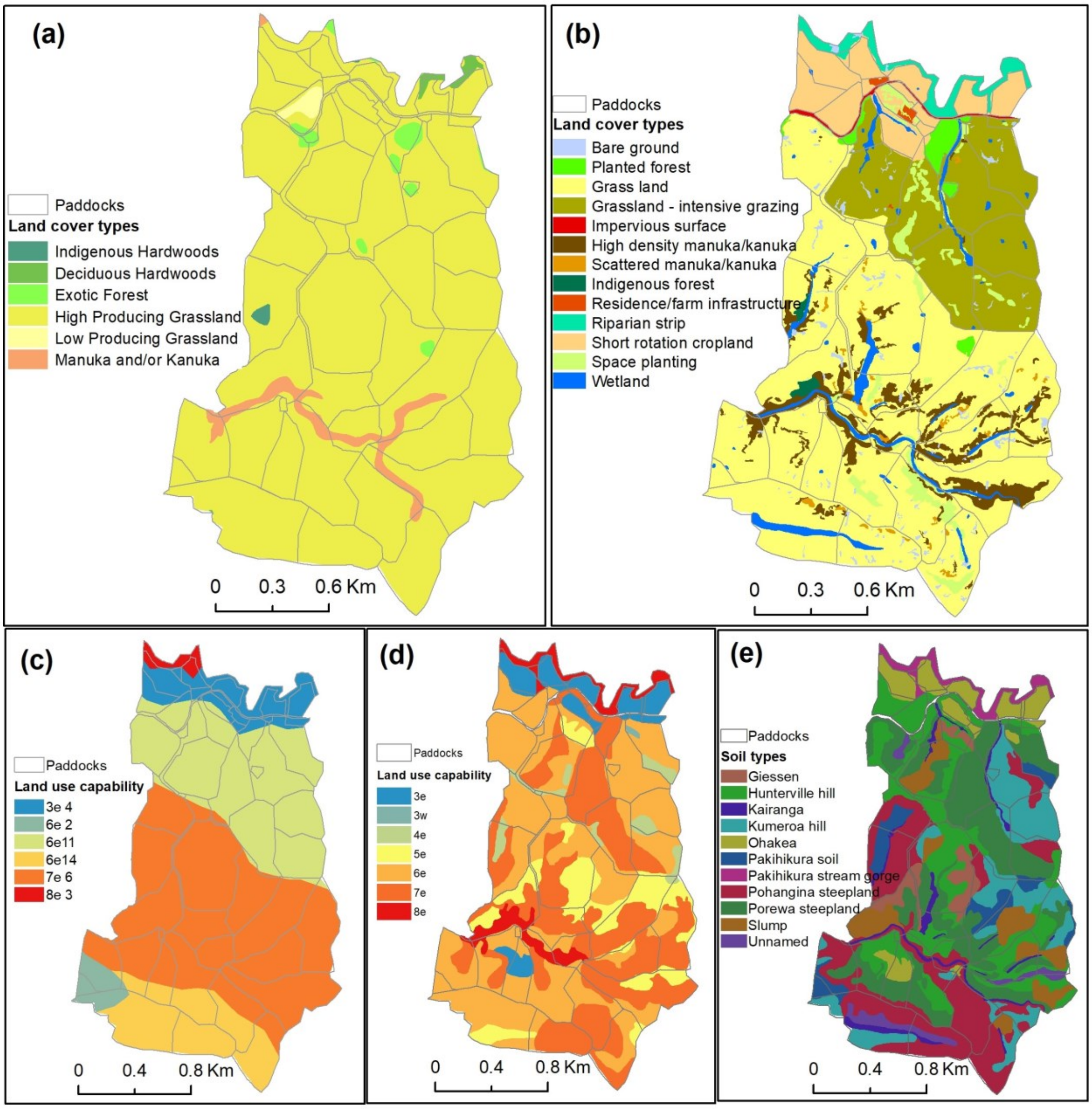

Figure 2.2. Illustration of land cover and land use, soils, and land use capability data at regional/catchment scales (a, c) and farm scale (b, d, e).

Besides, regional data covers only a limited number of LULC classes and soil types and exhibits an inaccurate data pattern compared to farm-scale data. For example, the LCDB data for the farm does not show LULC classes that are described in the farm-scale data such as wetland, bare ground (i.e., bare soil), and short-rotation cropland. The regional scale LUC data demonstrates that class 7e covers a large area in the central part of the farm, whereas, farm-scale data reveals that this area is actually made up of various LUC classes, ranging from 4e to 8e. Whilst LULC data and soils are major input for the assessment of ecosystem services, regional scale data is not able to capture the complexity of the farmed landscape and hence, using this data to quantify the value and distribution of ecosystem services is inappropriate. For this reason, spatial data more suitable for farm scale mapping and modelling were created, when possible, by the author.

2.3.4. Why have multifunctional landscapes on hill country farms?

Landscape simplification is significant in the hill country landscapes in NZ, as there has been extensive conversion of the natural vegetation to pastoral land associated with the expansion of agriculture since European settlement (McGlone, 1989) (Figure 2.3). The area under pasture has increased rapidly from less than 70,000 hectares in 1861 to 1.4 million hectares in 1881, 4.5 million hectares in 1901, and 7.7 million hectares in 2016 (Beef and Lamb, 2019b; MfE, 1997). The conversion of natural ecosystems (e.g., forest, shrubs) to pasture has led to a degradation of landscape functions in the sense that provisioning services (e.g., grazing production) are dominant and increasing, whereas regulating services are weak and declining. In other words, the human need to produce food has eroded the capacity of the ecosystems to produce other essential services (e.g., regulating services) (Rodríguez et al., 2006). The negative impacts of landscape intensification on hill country are well documented, such as the impacts on the provision of freshwater (Caruso et al., 2013), soil and plant biodiversity (Laliberté & Tylianakis, 2012; Schon et al., 2011) or soil biogeochemical cycling of nutrients (Wakelin et al., 2013).

Figure 2.3. Example of New Zealand hill country landscapes: high simplification with low regulating services (left); low simplification with high regulating services (right). Photographed by Duy X. Tran in 2019.

It is suggested that the issues that originate from landscape simplification due to agricultural intensification could only be solved by taking into account the redesign of agricultural landscapes (Landis, 2017). The goal of the approach suggested in this paper is to redesign (or plan) the agricultural landscape to achieve a better balance between ecological, cultural and production functions (Landis, 2017). The cultural and production functions reflect the capability of the landscape to produce goods and services that support human demand from a socio-economic perspective (Jorgensen & Fath, 2008). Whereas maintaining and improving the ecological functions of the landscape is thought to increase biodiversity and landscape connectivity, which has important conservation and landscape resilience implications, including the ability to adapt to climate change and disturbance (Biggs et al., 2012; Killion et al., 2018; Lovell & Taylor, 2013; Selman, 2009). The creation of this kind of landscape is expected to be an effective solution to solve the problems related to landscape simplification in NZ hill country farms. The justification for this is that a multifunctional agricultural landscape that is made up of a mosaic of natural habitat areas and agricultural production areas could help to maximise the balance of ecological and socio-economic demands and minimise the conflicts between them (Scherr & McNeely, 2008). This allows the landscape to provide multiple services and achieve multiple objectives (both agricultural production demand and environmental standards) (Kato & Ahern, 2009; Rallings et al., 2019). By diversifying farming activities, farmers can secure various income sources whilst at the same time promoting the cultural and natural heritage (Kremen et al., 2012). For instance, a sustainable multifunctional agricultural landscape may provide the option to develop agritourism or environmental education. Consequently, this contributes to an added income for farmers and increases public interest in the social and environmental values that the farms bring to the community. However, the challenge comes in determining how to implement the multifunctional landscape approach as a practical application to develop a sustainable agricultural landscape where different land use and land cover types (e.g., wetland pasture, forest, and horticulture) co-exist and the land use pattern is appropriate to maintain and promote sufficient heterogeneity so that different landscape functions work properly (Cumming et al., 2014; Kirchner et al., 2015).

2.4. A conceptual framework for sustainable agricultural landscape planning

In this paper, we propose a conceptual framework for sustainable agricultural landscape planning (Figure 2.4) that integrates the concept of multifunctional landscapes with a geodesign approach. An integration of an EBM approach with geodesign framework for landscape planning at the farm scale demonstrates novelty of this research, considering that planning frameworks developed in previous studies often focused on the implementation of an EBM approach at regional and national scales, and there is no considerable linkage between EBM and the geodesign process (Ahern, 2005; Huang et al., 2019; Kato & Ahern, 2009). The geodesign processes in this framework adapted the approach outlined by Steinitz, (2012), which comprises six phases. These phases are: (1) Landscape description, (2) Landscape process; (3) Landscape evaluation; (4) Future landscape scenarios development; (5) Impact assessment of alternative landscape scenarios; and (6) Decision-making. One limitation of the original geodesign framework (Steinitz, 2012) is that it was initially developed for the use in landscape architecture and is more suitable for urban landscapes design (i.e., built-environment), and its application to farmed landscapes with a dominance of agricultural land is limited. Because urban landscapes and agroecological landscapes are highly different, mostly due to the pattern and structure of land use/land cover and population, and socio-economic activities, a direct application of the urban landscape design approach to farmed landscape design is not suitable. As such, the integration of an EBM approach and its associated concepts into geodesign proposed in this study enables the adapted framework to better suit the agroecological/rural landscapes. By creating a framework that fully integrates the basic concepts of a multifunctional landscape and an ecosystem services approach and clearly outlining the implementation of designing multifunctional farmed landscapes, this study can make a unique contribution to the field of landscape planning and environmental management.

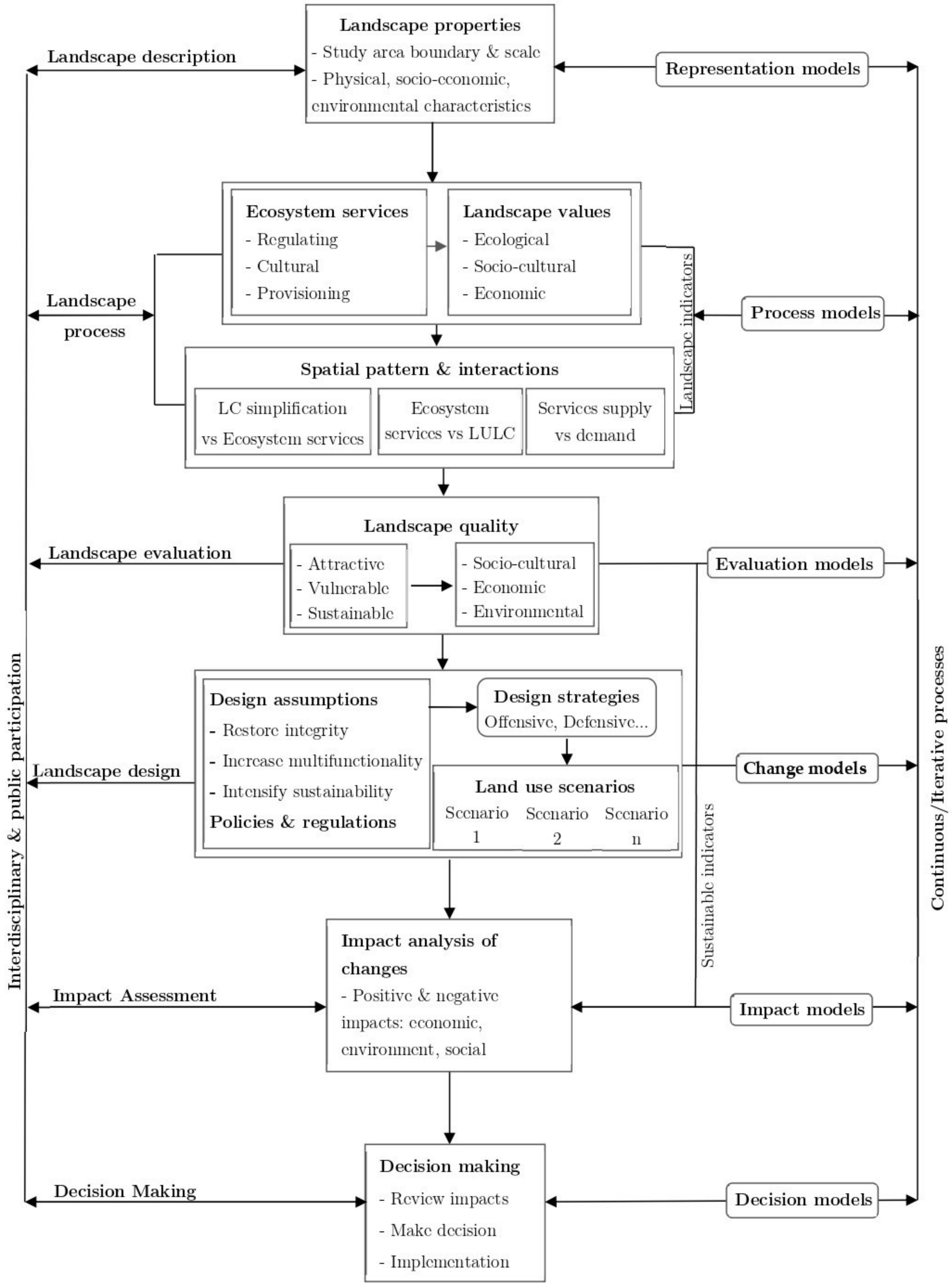

Figure 2.4. A conceptual framework for a multifunctional landscape-based geodesign for sustainable landscape planning, adapted from Steinitz, (2012).

2. 4.1. Landscape description

The landscape description phase is used to describe a general picture of the study area. The first task is to define an appropriate boundary for the study area. It is suggested to consider both the social and ecological boundaries (i.e., boundaries that cover both the ecological and socio-political/cultural functions of the landscape) when defining the boundary for the study area (Bergsten et al., 2014; Dallimer & Strange, 2015). The ecological boundary of the study area may be determined based on ecological processes or biophysical constraints (e.g., land management unit, catchment or sub-catchment boundaries) (Schonewald, 2000). The cultural functions of the landscape sometimes may not align with the boundary of the ecological functions, so it is recommended to work with the "people of the place" to properly define an appropriate boundary (Dallimer & Strange, 2015). In NZ, a catchment group is a community network of farmers who operate in a particular catchment. They are increasingly committed to tackling environmental issues and responding to a long-term sustainable development plan for the catchment (Beef and Lamb, 2019a; NZ Landcare Trust, 2019). Working with such groups offers the potential to assist in developing a relevant cultural boundary.

Once the study area boundary is defined, the next step is collecting necessary physical and socio-economic data, especially data for characterising ecosystem services and environmental issues (e.g., soils, topography, LULC, climate). In the case of NZ hill country, the lack of data is a limiting factor for analysis. To navigate around this requires an integration of multiple data sources that may come from the government, research institutions, remote sensing and field surveys. In fine-scale applications, such as those undertaken at the farm and paddock scales, information provided by farmers (e.g., stocking unit, grazing rotation) is an important source of data. The integration of local and global data to model ecosystem services is therefore a valuable option to address data deficiencies in remote and data-poor areas (Cerretelli et al., 2018). In addition, data are normally archived in different formats, standards and scales, so data standardization is an important step to make sure multiple data layers can be appropriately integrated and used.

A representation model (e.g., a raster-based 2D data model) is used to organise and visualise data collected for the study area through space and over time. For example, maps visualise LULC types of a farm or rainfall and temperature patterns in a catchment from 20–30 years ago to the present. This gives a general understanding of the landscape (from the past to the present) and provides necessary input for the other stages of the framework. Data resolution and availability will affect all other processes of landscape design, as the difference in the resolution and level of data accuracy in the input process could lead to completely different results. For instance, small landscape features (e.g., small plots of shrubs or ponds) play an important role in a farm, such as providing biodiversity, water resources and shade for stocks. However, these features are often eliminated in the low-resolution data (e.g., LULC at the catchment or smaller scale), so ecosystem services provided by these features may not be quantified when using such coarser data.

2.4.2. Landscape process/operation

The landscape process phase aims to define key processes in the study area that include both physical/ecological drivers and socio-economic drivers. The first step is spatially and quantitatively characterising major ecosystem services. This provides insights into the landscape operation in which important landscape characteristics are examined. An example of possible ecosystem services supply by NZ hill country farmed landscapes and relevant indicators to quantify them is presented in Table 2.2. It is critical to note that for a farm scale study the number of ecosystem services may differ significantly when comparing it with other farms. This is due to the variations in the farmed landscape (i.e., land cover and land use), land management practices, and the preferences/opinions of land users (farmers in this context). For instance, the provision of manuka honey may be not available on some farms where manuka trees have been cleared for pasture development.

Table 2.2: Example of possible ecosystem services (ES) provided by the New Zealand hill country landscapes.

	ES	Indicators/Sub-indicators	Units/Measurements
Provisioning	Stock feed production	Pasture productivity	Pasture yield (kg Dry matter/ha/yr)
	Timber production	Timber productivity	Volume of harvest (tons/ha/yr)
	Provision of manuka honey	Honey production	Honey yield (kg/ha/yr)
	Fresh water supply	Water availability for irrigation or drinking	Water supply (m^3/yr)
Supporting/ Regulating	Erosion control	Capacity of landscape for retaining sediments	Retained soil (ton/ha/yr)
	Flood regulation	Rainfall absorbed by soil	Runoff (mm/ha/yr)
	Drought mitigation	Capacity of landscape for retaining moisture	Drought severity (mm/ha/yr)
	Carbon sequestration	Landscape capacity to trap/absorb carbon	Sequestered carbon (ton/ha/yr)
	Nutrient retention	Part of nutrient retained by the soil	Retained N and P (kg/ha/yr)
	GHG emissions mitigation	Amount of GHG emissions regulated	CO_2, N_2O, CH_4 (tons/ha/yr)
	Forest biodiversity	Landscape capacity to support natural habitats	Native/natural forest (%/ha)
	Plant habitat	Rare, endemic, and indicator plant species	Conservation Value index
Cultural	Landscape aesthetics	Landscape naturalness Landscape complexity Landscape disturbance Landscape coherence	Proportion of landscape elements/attributes; % of area in correspondence
	Cultural heritage	Historic land use value and diversity Historic element value and diversity	Historic land use, number of land use change Types and number of heritage sites
	Educational	Attractive landscape element/features for educational activities	Educational activities suitability
	Recreation and ecotourism	Attractive landscape for recreation activities	Recreation activities suitability

Sources: adapted and revised from (Ausseil et al., 2012; Dominati et al., 2014; Dominati et al., 2016, 2019; Maseyk et al., 2018; van den Belt & Blake, 2014; Swaffield & McWilliam, 2013; Stanik et al., 2018; MEA, 2005).

In addition, some farmers may see the presence of manuka trees on their farm as scrub and areas which are covered by manuka can be perceived as disturbed landscape which has little value aesthetically, whereas other farmers may see these areas as a beautiful natural landscape with high value aesthetically. As such, it is important that the ecosystem framework demonstrated here serves as a reference for future work and is not seen as providing "a must" list which all case study farms in hill country must achieve. We suggest that consultation with field experts and people of the place is an essential step to determine relevant types and number of ecosystem services that can exist or be promoted on an individual farm.

It is important that ecosystem services supply is estimated in monetary units so that the overall benefit that a landscape provided can be easily measured. Various economic valuation methods have been used for estimating the value of ecosystem services, such as market prices, replacement cost and provision cost (Dominati et al., 2014). For instance, the market price method can be applied directly to convert several ecosystem services (e.g., pasture and timber production, carbon sequestration) to appropriate monetary units. Many indirect use services (e.g., drought mitigation, flood mitigation, nutrient retention) may require using provision cost or replacement cost methods to transfer their qualities to monetary value. Additionally, the economic value of landscape aesthetics in an area can be evaluated by estimating people's willingness to pay for visiting heritage or tourist sites distributed in the landscape.

After that, the spatial interaction between the provision of ecosystem services and landscape simplification and LULC dynamics are analysed to determine how these processes are linked to each other. A substantial number of studies have stated that the provision of ecosystem services has been significantly affected by LULC dynamics (Arowolo et al., 2018; Crespin & Simonetti, 2016; Kreuter et al., 2001; Mendoza-González et al., 2012; Polasky et al., 2011; Yi et al., 2017). Quantifying these relationships will be a key to transferring a multifunctional landscape design to a future land use plan. Landscape indicators that reflect the landscape simplification (i.e., agricultural intensification) well (e.g., the proportion of cropland and semi-natural land obtained from LULC data (Meehan et al., 2011), the variations in ecosystem services provision (e.g., ecosystem services change index (Cabral et al., 2016) or multifunctionality index (Maestre et al., 2012)) and spatial regression analysis will be used to characterise the spatial interactions between the change in LULC and variations in ecosystem services.

Quantifying and mapping ecosystem services can help farmers recognise and understand the multiple values of their farms. This is an advantage compared to using land cover information, as many ecosystem services may not be directly quantified by using land cover data alone (Louise, 2010). Understanding major landscape processes and the interaction between them is the key basis for designing a sustainable multifunctional landscape.

2. 4.3. Landscape evaluation

The landscape evaluation phase seeks to assess whether the landscape is working well or not (Di Lucia et al., 2018), in other words, assessing the overall quality of the landscape (Muir, 1999). In a multifunctional landscape this can be understood as assessing the quality of goods and services that a landscape provides to humans and the environment. To determine landscape quality, an evaluation model that utilises comprehensive indicators will be used to evaluate the attractiveness, vulnerability and sustainability of the study area. Attractiveness refers to the advantages that landscapes may have for a specific land use purpose or for socio-economic activities (e.g., suitable soil and climate conditions for fruit production). The vulnerability relates to characteristics that negatively contribute to socio-economic development or the environment (e.g., impacts of extreme climate and steep slopes on agricultural production, or negative effects of agricultural intensification on water quality and biodiversity). Sustainability reflects the landscape’s capacity for steadily supplying long-term ecosystem services that are critical for maintaining human and environmental well-being (e.g., a landscape that has different ecosystem functions and services that co-exist and balance) (Wu, 2013).

Landscape assessment indicators, which can be of various types, including single (e.g., GHG emissions mitigation index), multiple (e.g., a combined-index integrating several parameters, such as soil erosion control, carbon sequestration and drought mitigation), static (the sustainable threshold being classified into a fixed category) and dynamic (the sustainable threshold being subjected to the dynamic interaction between indicators) (Banos-González et al., 2016; Huang et al., 2019), and come from various sources (e.g., expert consultant, environmentalist, empirical analysis, law and regulation) (Steinitz, 2012), could be used to assess past and present situations of a study site, monitor the design process and compare design alternatives (Huang et al., 2019). Hence, choosing appropriate indicators is important for the success of a landscape design project. Suitable landscape indicators should satisfy several requirements, such as the capability to reflect a wide range of ecosystem services to analyse the trade-offs between ecosystem services provision and land use change options (Albert et al., 2016), providing reliable, detailed, understandable, comparable and spatially explicit information to support decision-making (Niemeijer & De Groot, 2008), and providing cost-effective indicators by utilising available data or employing low-cost generated data and models (Heink et al., 2016).

Landscape evaluation models also need to reside within the geographical context in the sense that assessment indicators should recognise and align with existing legitimised environmental strategy and policy and reflect major landscape processes in the study area. For example, in the case study of hill country in NZ, water quality, soil erosion control, drought mitigation, pasture productivity and GHGs emission mitigation could be used as some of the indicators for landscape sustainability assessment.

2.4.4. Future landscape scenarios development

Based on the results achieved from the landscape evaluation process, change models will be used to define a series of alternative future scenarios for the proposed multifunctional landscapes. In this stage, stakeholders can follow the scenarios developed by scientists or propose their scenarios (a user-defined plan) for the future landscape. Alternative scenarios for future landscape design can be implemented by applying the following procedure:

First, the information on landscape process (characters, services and values) as well as major socio-economic drivers and environment issues are used to define how the landscape should be changed. Determining the expected future landscape is based on several assumptions, such as the preferences of local people, the landscape functions or services that the future landscape will be capable of providing, and the implications of policies and regulations (Babí Almenar et al., 2018). In agricultural landscapes, the design goal for future landscapes is mainly based on the level of agricultural intensification (or landscape simplification) (Ekroos et al., 2014). Landscapes that have been highly simplified may need to be redesigned in order to restore integrity between provisioning, supporting, regulating and cultural services, whereas the likely design goal for less simplified landscapes is to increase provisioning services while maintaining current levels of other services (Landis, 2017). Climate change scenarios can be integrated in this step to measure how the changes in climate variability can affect the landscape operation through the interaction with landscape functions.

Afterwards, a design strategy that could take an offensive approach (where the design goal is utilising the advantageous or attractive landscape characteristics to develop a future landscape), or a defensive approach (where the development of a future landscape is based on one that avoids vulnerability or risks), or a combination of these approaches, will be used to create a specific change model to simulate future change for the landscape (Steinitz, 2012). There are different methods of designing for landscape change, such as rule-based, optimised, and agent-based approaches (see (Steinitz, 2012) (pp. 56–59) for further details). Among these, the use of multi-criteria decision-making (MCA) can be an efficient method to propose future landscape scenarios in the study area, as the creation of a future landscape can be regarded as a complex MCA process (Pohekar & Ramachandran, 2004). Each land use scenario or option often requires multiple objectives (e.g., erosion control, carbon sequestration, pasture productivity, GHGs emission) and the final decision will be a compromise between the interests of the different stakeholders involved in the design process. The results from these approaches are maps showing the future landscape with the distribution and pattern of different LULC types. Associated with each LULC map will be the provision of ecosystem services and landscape multifunctionality maps. For each scenario and stage, different alternatives can be created and reassessed iteratively until consensus is achieved.

2.4.5. Impact assessment

In the impact assessment of alternative landscape options, the criteria and indicators used in landscape evaluation will be applied to assess the positive and negative impacts (benefits, risks, and sustainability) of the future landscape. In a geodesign project, an environmental impact assessment is often implemented to characterise the consequences of the proposed change. In the context of developing a multifunctional agricultural landscape, the impact assessment is related to quantifying the costs and benefits (including both socio-economic and environmental costs) of recovering landscape functions or re-designing the landscape to increase landscape diversification (or landscape multifunctionality). The results of this stage include maps and statistical data showing the cost–benefit ratio of each alternative landscape option. For instance, associated with each land use scenario will be maps showing ecosystem services provision and value of carbon sequestration, GHGs emissions, erosion control, drought mitigation and pasture productivity, as well as the total benefit (value) of that scenario. This includes the cost to implement such a landscape (e.g., loss of pastoral area, fencing cost, tree planting cost). This will be critical for the decision-making stage.

2.4.6. Decision-making

In the last phase, the scenario analysis and group discussion will be conducted with the public, experts, and stakeholders. The results of the future landscape scenario development and impact analysis will be utilised for discussion, and this will from a basis for making the final decision. According to Steinitz (2012), participants in the geodesign process might give different answers, including “Yes”, “Maybe” and “No”, in response to proposed scenarios. If decision-makers agree with one of the proposed plans, the next stage is to develop the implementation plan. In case stakeholders are not sure about their decision, further study or analysis is needed to provide more information to help them decide. Sometimes decision-makers may not approve the designed landscape. If this is the case, it is necessary to get comments and feedback on why this is so. This will be valuable information to integrate into the landscape project in the future.

The proposed framework in this research inherits the major advantages exhibited by a geodesign approach. These include the fact that it can be a continuous procedure, a multidisciplinary or transdisciplinary approach, and a participatory collaborative planning technique. Moreover, this framework integrates concepts drawn from landscape ecological theory (such as incorporating information on landscape functions and ecosystem services, landscape simplification and landscape pattern). This means that the theory provides the scientific context to informed and collaborative decision support processes for farm systems that are faced with the need to change in response to environmental pressures and market influences. Because the framework proposed in this study is comprehensive, a full implementation of the framework is an ideal which enables the best outcome to be achieved. The primary condition that allows a full application of this framework to be achieved is having fundamental farm-scale data and a geodesign application (i.e., spatial decision support system) incorporating all necessary tools and models. However, this is an ideal situation that is difficult to achieve by all farms and farmers in the hill country. Therefore, it is suggested that a modification or simplified version of the conceptual framework that reduces the complexity and implementation cost is required to meet the specific environmental context and socio-economic situation of a case study.

2.5. Conclusions

This paper reviewed the major challenges facing NZ hill country farms and proposed an approach for sustainable agricultural landscape planning. The significant issues facing hill country farming include land use changes and deforestation, soil erosion, agricultural intensification, climate change and the impacts of changes in consumers' preferences. These challenges are considerations for farmers striving towards the long-term sustainable development of NZ's hill country. Currently, landscape simplification associated with agricultural intensification is a significant feature of hill country farms.

This may reduce the landscape's capacity to mitigate and adapt to the environmental challenges and climate change effects. Therefore, we have suggested that designing a more sustainable multifunctional landscape is a possible solution to tackle the issues facing NZ hill country. The development of multifunctional agricultural landscapes can contribute towards innovative future farming systems that can deal with emerging environmental issues (Bretagnolle et al., 2018). In addition, the design of multifunctional landscapes can improve their resilience to change and disturbance (Kimberly, 2019), which will be crucial for ongoing sustainability in NZ hill country.

This is one of the first studies to propose a geodesign framework for sustainable multifunctional agricultural landscape planning in NZ. By integrating a multifunctional landscape approach in a geodesign context we offer a solution to address some of the implementation problems that have restricted uptake. Considering landscape planning in a design-driven perspective, geodesign embraces collaborative planning (among different stakeholders) as the key to landscape design. It also enables the incorporation of stakeholder values and aspirations as a central element to this process. By dividing the landscape design process into different phases and utilising geospatial technologies (e.g., human–computer interaction), geodesign allows important stakeholders to be effectively involved and contribute to the planning process. In addition, geodesign enables the use of multiple sources of relevant spatial and temporal resolution data for landscape planning, especially in large-scale applications, as well as being better at dealing with different aspects of land use planning.

The proposed framework in this paper considers the major concepts associated with a multifunctional landscape approach, including landscape functions and services, landscape supply and demand, the value of ecosystem services, sustainable landscape indicators, spatial patterns and interactions. This facilitates a comprehensive implementation of the multifunctional landscape approach in land use planning and management. A landscape ecological approach has been talked about conceptually for landscape sustainability but has not been widely applied practically in NZ. Therefore, the comprehensive integration of an ecosystem services approach in landscape planning offers a solution to address some of the limitations faced by current land use planning and management practices in NZ (Dominati et al., 2019; van den Belt & Blake, 2014). The proposed approach and associated framework can provide a scientific basis towards the development of a future commercial land and environmental planning tool. This will hopefully give farmers and rural professionals more options to conduct useful land use planning at the farm scale.

We believe that the proposed conceptual framework of an integrated landscape ecological (the scientific theory behind a multifunctional landscape concept) and geodesign approach will be a valuable reference for future work about agricultural landscape planning. Ideas around creating multifunctional farm landscapes have been discussed (Dalgaard et al., 2007; Hassink et al., 2016; Milestad & Björklund, 2008), the role that geodesign can play in future planning has been explored (Slotterback et al., 2016; Wu, 2013) and frameworks for developing sustainable landscape based on an integration of geodesign and landscape ecology have been proposed (Huang et al., 2019; Wu, 2019). However, there is a lack of a detailed framework that can demonstrate how concepts associated with the generation of multifunctional landscapes can be incorporated into a geodesign process to create a planning tool at the farm scale. Hence, the approach proposed in our paper, which covers a comprehensive description of a type of geodesign process applied to the management of a multifunctional agricultural landscape, will significantly contribute to environmental management studies and illustrate the potential of this type of approach for global application.

Although the framework proposed in this paper demonstrates a comprehensive approach for agricultural landscape planning that can be applied to NZ hill country farms, we acknowledge that future work needs to consider and investigate the issue regarding the financial resources required to support the farmers to overcome their economic concerns associated with changes in land use. Farmers may recognise and be motivated by the great value that extra ecosystem services can provide and agree with a proposed landscape design, but a barrier to implementation of this design might be the lack of the long-term support that is needed to enable them to be able to afford the cost of implementation and to follow the suggested revised land use and environmental plan. For instance, increasing native woody vegetation on a farm provides a great range of ecosystem services, but it may potentially affect economic profit in the short term due to the fact that it would decrease land available for grazing and has a low growth rate (McWilliam et al., 2017), and thus have less earning capacity in its early life stages. A solution to this is for policymakers in NZ to consider payment for ecosystem services. In many countries a wide range of regulating and supporting services are estimated in terms of economic value, and the farmers (i.e., landowners) are able to get a payment for these services (Asquith et al., 2008; Bradley, 2002; Mouchet et al., 2017). Currently, farmers in NZ can only receive payment for carbon sequestration services, so there are no strong incentives to encourage farmers to implement a land use plan that promotes multiple ecosystem services on their farm. An approach such as the one outlined in this paper can help to demonstrate a proof of concept to policy-makers so that they recognise the greater environmental value that farmers can provide by designing future landscapes for multifunctionality and ecosystem services and therefore build financial support into future policy-making.

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3. A comprehensive spatially explicit analysis of agricultural landscape multifunctionality using a New Zealand hill country farm case study

Abstract

Although a large number of studies have been carried out to measure landscape multifunctionality and associated ecosystem services (ES), comprehensive spatially explicit assessments at the farm scale are limited. This research applies a wide range of spatial models, tools, and methods to spatially quantify the provision of multiple ES as well as the pattern of landscape multifunctionality in farmed landscapes. To quantify the provision of multiple ES provided by the landscape, the bio-physical models provided by InVEST (e.g., Nutrient Delivery Ratio and Sediment Delivery Ratio models) and land use land cover-based assessments using spatial analysis tools in ArcGIS were employed. The Analytic Hierarchy Process was applied to calculate the landscape multifunctionality index which is an integration of multiple ES supply. Hot spot analysis using Getis Ord Gi* statistics was utilised to examine the spatial distribution of multiple ecosystem services. A hill country farm in New Zealand is chosen as a case study because it is a good example of a diverse landscape that is facing significant environmental issues due to intensive agricultural production. Our study reveals that the provision of ES and the pattern of landscape multifunctionality is highly variable across the farm. Both positive and negative relationships among ES are found and the interactions between them are mainly reflected in three ES bundles: the agricultural land, the indigenous forest and wetlands, and the mixed land uses. Furthermore, our study demonstrates that the quality of landscape is significantly dependent on the landscape management goals and preferences of the farmers so involving them into the process of ES and landscape multifunctionality assessment at a farm scale is essential step to obtain more comprehensive results. Results from this study enable important questions to be answered regarding the spatial variation of ES provision and how land use and land management goals relate to the value and quality of landscape multifunctionality. This can provide valuable information to design future multifunctional landscapes and inform decision making in relation to sustainable land use management.

Keywords: Spatial analysis; Ecosystem services; Agricultural intensification; Landscape planning; Land use land cover; Sustainable agriculture

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3.1. Introduction

Multifunctional landscapes supply a wide range of goods and services to society, including provisioning, supporting/regulating, and cultural services (Bolliger et al., 2011). Agricultural landscapes with a high level of multifunctionality are recognised as hot spots of ecosystem services provision and therefore can provide multiple benefits to promote landscape health and human well-being such as clean water and biodiversity provision, carbon sequestration, climate change mitigation, food security and livelihood diversification (Garcia-Martin et al., 2017; Fagerholm et al., 2020). However, the expansion and intensification of agricultural land has significantly simplified and modified the landscape, resulting in biodiversity loss and land degradation (Duru et al., 2015; Emmerson et al. 2016; Hooper et al., 2012). Consequently, important ecosystem services can be lost with associated impacts on the functioning and resilience of the landscape and environment (Emmerson et al., 2016). In order to mitigate the negative impacts of agricultural production on the environment, appropriate management of the key functions and services provided by the landscape is required (Barrios et al., 2018;

Gordon et al., 2010; Macintosh et al., 2019). Landis (2017) suggested that determining the provision of ecosystem services associated with levels of landscape simplification provides a useful basis from which to develop and propose landscape design goals and management strategies. Also, recreating multifunctional landscapes that can support the provision of multiple ecosystem services is suggested as a long-term solution for sustainable and resilient agricultural systems (Frei et al., 2020; Helming & Wiggering, 2013; Nyström et al., 2019). This means that to achieve sustainable landscape planning and management, it is useful to quantify the quantity and pattern of ecosystem services supply and their interactions as well as the level and spatial distribution of landscape multifunctionality (MFC) (Tran et al., 2020; Wittman et al., 2017; Willemen, 2010).

Several methods have been applied to quantify landscape multifunctionality such as the “multiple ecosystem services landscape index” (MESLI) used for mapping the quantity of ecosystem services supply (Rodríguez-Loinaz et al., 2015), the “ecosystem services richness index” for presenting the total number of ecosystem services (Powers et al., 2020), and a number of landscape diversity indices such as the Simpson’s reciprocal index (SRI) and Shannon’s H’ index aimed at quantifying both the ecosystem services supply and their richness (Stürck and Verburg, 2017). Despite their usefulness, a major limitation of these methods is that they do not integrate human perceptions and preferences into the process of landscape multifunctionality evaluation. Given that the value of landscapes is strongly dependent on human awareness, it is important that the mapping and assessment of landscape multifunctionality takes into account human needs and desires (Fry, 2001; Solecka et al., 2022). This is particularly important in a farm scale study because the overall value of the farmed landscape may differ significantly by property since it is dependent on the management goals and priorities of the landowners (Quinn et al., 2013). Also, obtaining farmers participation in the landscape evaluation process is a useful way to obtain more farm-scale data, which is usually poor and not readily available (Tran et al., 2022). Despite the relevance of these factors, studies that incorporate the participation and contribution of farmers into the process of ecosystem services and landscape multifunctionality mapping at a farm scale are limited to date.

Although the number of farm-scale studies that have involved ecosystem services mapping and assessment have been increasing in recent years, most of them tend to focus on provisioning and some supporting/regulating services, whereas a comprehensive assessment of ecosystem services that considers a range of provisioning, supporting/regulating, and cultural services or landscape aesthetics has been somewhat limited (Blesh et al., 2019; Botzas-Coluni et al., 2021; Hipólito et al., 2018; Nicholson et al., 2017; Rawluk & Saunders, 2019; Pornaro et al., 2021). As a result, existing studies tend to only provide a partial understanding of the value and quality of landscape multifunctionality, and the trade-offs people make between different types of ecosystem services. For example, a landscape that has a high value for provisioning services may have a low value for landscape aesthetics. To understand the overall value of the landscape, both types of services must be quantified. In addition, many studies that apply an ecosystem services approach to farm system design and planning often use the whole farm or land management unit as the geographic unit of analysis, whereas the spatial pattern of ecosystem services across different parts of the farm is not fully examined (Bullock et al., 2021; Dominati et al., 2021; Dominati et al., 2019; Quinn et al., 2013; Tessier et al., 2021). In landscapes where topography and land use land cover (LULC) are complex, patterns of ecosystem services provision and their interactions vary across space. As such, the information obtained from analysis of the aggregated average values for the whole farm is not adequate to develop farm management plans that inform localised practices that reflect the spatial variation across the farm.

The primary objective of this study is to spatially and quantitatively assess the provision of multiple ecosystem services and landscape multifunctionality in agricultural landscapes at a scale useful for illustrating trade-offs between ecosystem services and informing decision making on-farm. To demonstrate this approach, a hill country and steep-land farm in New Zealand (NZ) was selected as a case study. The hill country farmed landscape in NZ is a good example of landscape simplification and modification due to the extensive conversion of natural vegetation to pastoral land (Mackay et al., 1993). This process has shifted the supply of ecosystem services from primarily regulating to primarily provisioning. Therefore, comprehensive mapping and assessment of ecosystem services is essential to understand the status of the landscape and the quality of landscape health and multifunctionality. Doing this will provide important information to help farm environmental planning by the farmers. It will also provide information about the impact of changes in management practices on ecosystem services. The hill country landscape in NZ is highly complex and spatial data for environmental modelling is scarce, so obtaining high resolution data for farm-scale modelling is time-consuming and expensive. This is also a typical challenge in many rural landscapes and marginal land around the world (Gottero & Cassatella, 2017; Sallustio et al., 2018). For this reason, we will demonstrate how various types of data and tools can be efficiently used and integrated to create an effective framework for undertaking a comprehensive spatially explicit assessment of ecosystem services and landscape multifunctionality at the farm scale. This approach has potential for wider application thus demonstrating capability to inform global agricultural landscape planning and management studies and practices.

3.2. Data and the study area

The case study is a 380 ha sheep and beef farm located in the North Island of NZ (Figure 3.1a). The farm is covered by various LULC types: grassland (74%), indigenous vegetation (10%), cropland (8%), exotic forest (6%), and other LULC classes (2%) (e.g., residence and farm infrastructure, wetland, and bare ground) (Figure 3.1b). The major soil group at the study site is Pallic soils (Ustepts) (52%), followed by Brown soils (Udepts) (37%), and Gley soils (Aquepts) (8%) (Figure 3.1c). The case study is classed as hill country and steep-land given that approximately 40% of the farm situates on slopes of 15-25^{o} and a further 27% on slopes greater than 25^{o}. The remaining 33% of the farm is on land with slopes of less than 15^{o}. Significant changes in elevation occur across the farm (Figure 3.1d).

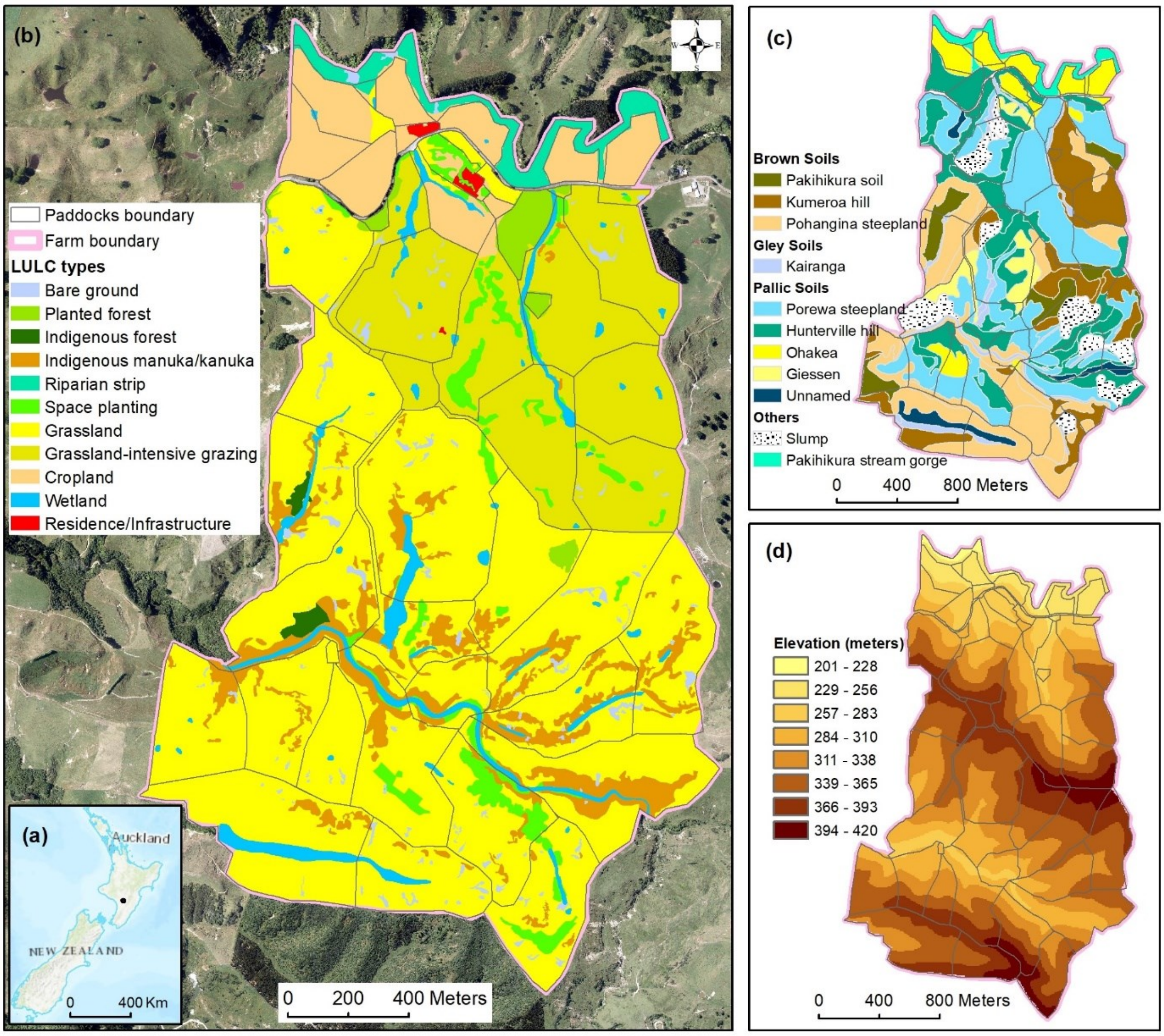

Figure 3.1. Location of the farm (a); land use and land cover classes (LULC) in 2020 (b); soil types (c); and elevation (d). Data sources: Field survey and mapping (a-c) and Land Information New Zealand (d).

In this research, different types of data and information were utilised to quantify the ecosystem services in the study site (Table 3.1). They were obtained from three main sources: (1) publicly available data from international agencies (e.g., remotely sensed data of vegetation, Google Earth images), (2) data from New Zealand government organizations and government-funded projects (e.g., climate, topography), and (3) data from field surveys and GIS mapping (e.g., soils, LULC, farm stocking information). Soils and LULC data were acquired through a field survey and mapping because publicly available data in NZ are too coarse for farm-scale modelling and analysis.

Table 3.1: Ecosystem services indicators and major data used in the research

ES	Indicators	Sub Indicators/Measurements	Data used
Provisioning	Stockfeed production	Pasture yield	Farm stocking information [1], Normalized Difference Vegetation Index [2] (NDVI), land cover and land use [3] (LULC), trees information [4]
	Provision of timber	Planted forest for timber production	
	Provision of manuka honey	Manuka cover for honey production	
Supporting/ Regulating	Erosion control	Sediment loss	LULC, climate[5], soil data[6], Digital Elevation Model [7] (DEM), Carbon stock look-up tables[8]
	Water flow regulation	Water yield	
	Carbon sequestration	Soil and vegetation carbon stock	
	Water purification	Nitrate leaching	
	Provision of natural habitat	Natural LULC	
Landscape aesthetics	Ease of farming	Availability of water bodies	Aerial photo, LULC, DEM, erosion data
		Slope and erosion	
		Agricultural land pattern	
		Aspects of terrain slope	
	Landscape diversity	LULC diversity	LULC, DEM, survey questionnaire, field surveying
		LULC complexity	
		Relief complexity	
	Landscape naturalness	Natural vegetation and wetlands	LULC, aerial photo, field surveying
		Absence of disturbing elements	

Data sources: [1] Survey questionnaires, [2] Google Earth Engine, [3] Classified from aerial imagery (Land Information New Zealand - LINZ) and Google Earth Imagery, [4] Survey questionnaires and LULC data, [5] National Institute of Water and Atmospheric Research (NIWA), [6] Farm scale land resources surveying, [7] LINZ, [8] Ministry for Primary Industries (MPI).

3.3. Research methods

An overview of research methods and procedures applied in this study is presented in Figure 3.2. A wide range of data and information were used to quantify multiple ecosystem services using InVEST and GIS-based models. After this stage, the Analytic Hierarchy Process (AHP) method was applied to map landscape multifunctionality, which involved integrating multiple ecosystem services. Afterwards, the interactions between ecosystem services (e.g., synergies, trade-offs, and bundles of ecosystem services) and spatial pattern of landscape multifunctionality were evaluated. Through the interpretation of the findings associated with this analysis, the relevance of the information derived for landscape planning and management practices can be determined.

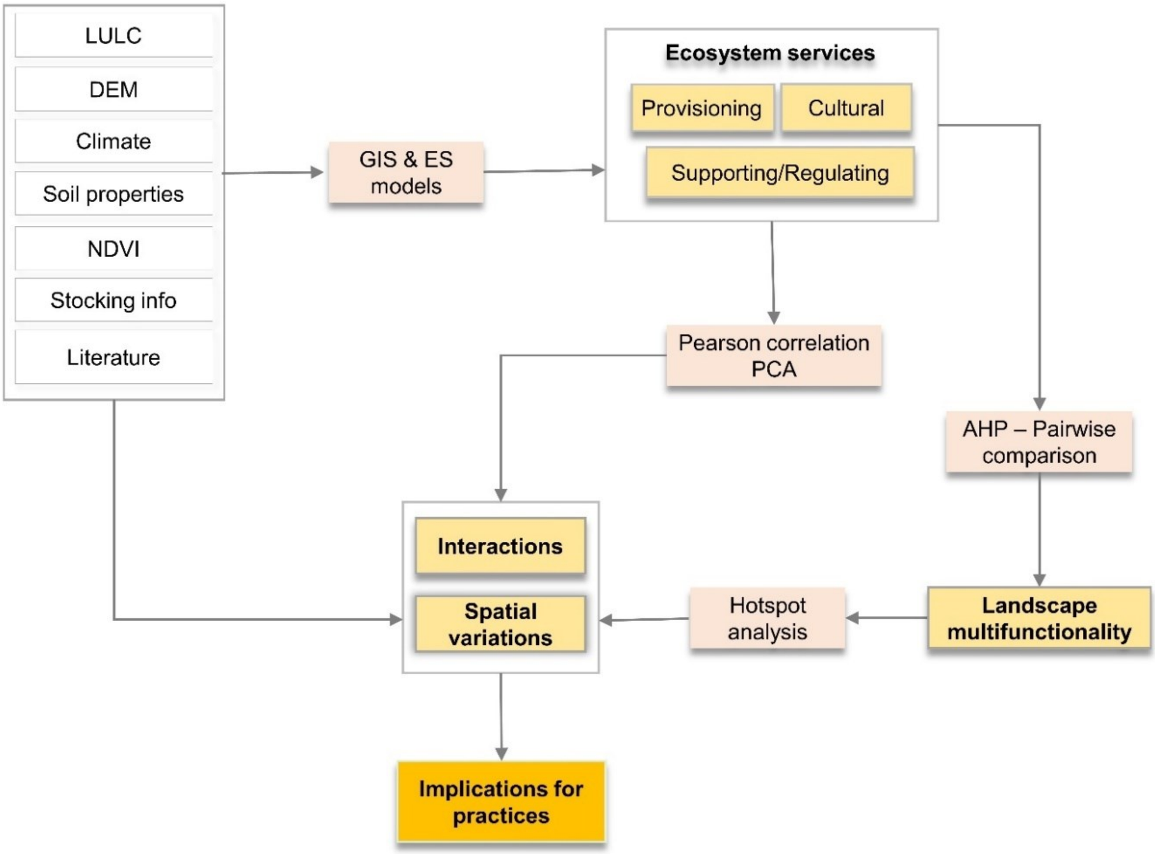

Figure 3.2. An overview of the analysis of spatial-based landscape multifunctionality. LULC: land use land cover; DEM: Digital Elevation Model; NDVI: Normalized Difference Vegetation Index; GIS: Geographic Information System; ES: Ecosystem services; PCA: Principal Component Analysis; AHP: Analytical Hierarchy Process.

3.3.1. Land use/Land cover mapping

Remotely sensed data and aerial photos are the key source of information that enables the creation of fast and up to date LULC maps at various scales (Rogan & Chen, 2004). For a small area (e.g., farm scale study), it is important that a LULC map contains fine detail as this allows for better assessment of LULC change and aids ecosystem services evaluation (Kandziora et al., 2013). In the case of NZ hill country farms where the landscape is heterogeneous, NZ aerial photos obtained from LINZ and Google Earth (GE) images will be a major source of information used to map LULC classes. The advantage of using GE is that it provides the latest satellite imagery that has very high spatial resolution (less than 1m), so this enables small LULC objects (e.g., individual buildings, water bodies, trees, small shrubs) to be mapped (Malarvizhi et al., 2016). Google Earth also enables the use of images taken at different time periods which will be very useful to perform land use change detection (Malarvizhi et al., 2016). In this study images captured over the period 2005-2019 will be used to determine LULC classes for the study site. The minimum mapping unit is 0.01 ha (100 m^2) so this is able to capture small woodlots, water bodies (ponds and dams), and erosion scars in the case study. Both GE and LINZ data are available free of charge and can be accessed online. Data downloaded from these providers will be assigned an appropriate spatial reference that is compatible with the NZ spatial reference system (i.e., NZGD2000 Transverse Mercator). The on-screen digitising method available in ArcGIS was used in association with aerial photograph interpretation and ground truthing to derive the LULC classes for the study site. This method takes more time than automated or semi-automated classification techniques (e.g., object-based classification, supervised classification), but it will provide a more accurate result (Davenport et al., 2017). Since LULC maps will be used to quantify several ecosystem services in the study site, very detailed LULC classes are mapped, these are residence/farm infrastructure, planted (i.e., exotic) forest, space planting, riparian strip, indigenous (i.e., native) forest, indigenous manuka/kanuka (scattered manuka/kanuka, high density manuka/kanuka), grassland (low intensive pasture, high intensive pasture), short rotation cropland, water bodies, and bare ground (Figure 3.1b).

3.3.2. Ecosystem services modelling

The ecosystem services framework demonstrated in Chapter 2 presents a list of possible ecosystem services that hill country farms may provide. However, types and number of ecosystem services is farm-specific as it is dependent on the farmed landscapes, farm size, and farmer's interest. For instance, the case study is small and considered not suitable for eco-tourism activities. In addition, modelling a large number of ecosystem services is time-consuming and expensive, especially the cultural services, because doing this requires more data and increases the complexity of the analysis. The framework was therefore simplified, and the cultural ecosystem services are not fully modelled. Only some services related to landscape aesthetics were selected and modelled as an example of cultural ecosystem services. Eleven ecosystem services within three categories (provisioning, supporting/regulating, and landscape aesthetic services) were defined and mapped in the study area (Table 3.1). Relevant indicators and sub-indicators for these selected services were defined based on published literature which focus on the ecosystem services provision in NZ and the hill country landscape (Dominati et al., 2016; Dominati et al., 2014; Dominati et al., 2021; Dominati et al., 2019; Powers et al., 2020; Tran et al., 2020; Tran et al., 2022; van den Belt & Blake, 2014; Swaffield & McWilliam, 2013; Brown & Brabyn, 2012[a,b]).

3.3.2.1. Provisioning services

Pasture productivity

Our study mapped the pasture yield by integrating the stocking information provided by the farmers and a remotely sensed vegetation index (i.e., Normalized Difference Vegetation Index (NDVI)) (Tran et al., 2022). Annual dry matter yield (DMY) by paddock was obtained based on information associated with "stock units", "stock carrying capacity", and "pasture utilisation" (Beef and Lamb NZ, 2022). The Pearson correlation between pasture yield and long-term vegetation data (i.e., mean NDVI from 2016 to 2021) was evaluated ($r = 0.7$, $p < 0.002$) (Figure S3.1), demonstrating that the NDVI data can be used to estimate the pasture yield. Once this had been established the DMY value per pixel was distributed based on the proportion of the NDVI of the pixel relative to the mean NDVI value of the paddock. Spearman correlation analysis was carried out to evaluate the accuracy of the pasture yield map. Fifty random points across the farm were created using ArcGIS (Table S3.1). A printed map that visualised the locations of these points was provided to the farmer, and he ranked the pasture yield in these locations using a scale from 1 (lowest) to 10 (highest) based on his own experiences. A good correlation between the DMY derived from the model and DMY estimated by the landowner was found ($r = 0.76$, $p < 0.0001$), demonstrating that the pasture yield pattern derived from the model is strongly aligned with one that was estimated by the farmer in the field (Figure S2).

Provision of timber and manuka honey production

In a managed production forest that is homogenous in terms of tree species, tree age, and management practices, a simple method using wood production rates can be used to estimate timber production (Powers et al., 2020). Considering that the focus of this study is on quantifying the current ecosystem services, a straight-forward estimation of timber yield based on LULC data and tree information obtained from the farmer, and information associated with the annual growth rate for tree species from published literature was used to estimate timber yield (Berg, 2008; Pizzirani et al., 2019). The proportion of planted forest area per geographic unit presents the relative value of timber production service. For example, the timber production service is at a maximum when the whole area is covered by planted forest and there is no provision service when there are no planted trees in the landscape.

Manuka (*Leptospermum scoparium*) is an indigenous tree species in NZ. In addition to its ecological value such as setting the stage for indigenous forests to regrow, preventing soil erosion and damage from grazing animals, and supporting biodiversity, manuka supplies nectar for honey production by farmed honeybees (Ausseil et al., 2018). With the ability to provide both ecological and economic value, manuka honey production is recognised as an alternative land use option for NZ hill country which contributes to sustainable agricultural development in this area (Bennik, 2009). As such, quantifying the capability of the landscape for manuka honey production is necessary to better understand the value of a landscape. Given that manuka honey production is directly related to the presence of manuka tree cover in the landscape, LULC data was used to determine the potential provision of manuka honey production in the study area. Specifically, the pattern of manuka honey provision was estimated as the proportion of manuka tree cover per geographic unit (i.e., $100m^2$).

3.3.2.2. Supporting/Regulating services

Erosion control

Control of erosion rate (also known as sediment retention) is a regulating service defined as “the difference between the potential and the actual soil loss” and is mostly a function of ground cover by plants and the land use management practices (Guerra et al., 2014; Maes et al. 2013; Steinhoff-Knopp & Burkhard, 2018). This is one of the key ecosystem services given its impacts on the ecosystem and environment such as water quality, agricultural productivity, soil biodiversity and carbon stock (Dominati et al., 2010). In this study, the overland sediment retention (i.e., surficial erosion) derived using the InVEST Sediment Delivery Ratio (SDR) model was applied to quantify the sediment retention values (Hamel et al., 2015). This model uses the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) to calculate the amount of annual sediment loss from each pixel. The model inputs for the USLE calculation require a range of data, biophysical parameters, and empirical coefficients. To achieve better model outcomes, we adapted methods and coefficients drawn from the published literature that were developed for NZ (Klik et al., 2015., Donovan 2022) (Table 3.2). Because the model only quantifies surficial erosion (i.e., water/sheet-wash), other types of erosion (e.g., soil slip erosion, gully, or stream bank erosion) are excluded due to model limitations. Given that soil slip erosion contributes significantly to the sediment loss but was excluded in the USLE model, we digitised soil slip scars through visual interpretation of high-resolution aerial photos. Areas of soil slip erosion were then integrated with the surficial erosion maps. Considering that soil slip erosion often led to a significant amount of soil loss in the hill country landscape in NZ (Basher, 2013; Trustrum et al., 1984) we assigned the maximum erosion value to soil slip erosion areas, which is equal to the normalised value of 1 in the surficial erosion pattern (i.e., minimum retention value).

Table 3.2: Cover-management factor for different land use land cover (LULC) classes and soil erodibility factor (K) for different soils in the study area

Cover-management factor		**Soil erodibility factor**	
LULC classes	C values	Soil texture	K values
Residence	0	Silty clay loam	0.67
Planted forest	0.005	Silty loam	0.38
Space planting	0.005	Fine sandy loam	0.38
Riparian strip	0.005	Sandy loam	0.27
Indigenous forest	0.005	Sandy clay loam	0.45
Scattered manuka/kanuka	0.05		
High density manuka/kanuka	0.05		
Cropland	0.1		
Low producing grassland	0.01		
High producing grassland	0.01		
Lake/pond	0		
Bare ground	1		
Impervious surface	1		

Water flow regulation

The annual water yield for the farm was quantified using the InVEST Annual Water Yield model. This model estimates the water yield using climatic information associated with annual precipitation and potential evapotranspiration, plant available water content, plant root depth, a DEM, soil depth, and LULC information (Tallis et al., 2011). Long-term average annual precipitation and potential evapotranspiration (1998–2018) were collected at the two nearest weather stations (1.5 – 2 kilometers from the farm) provided by NIWA. Soil characteristics data for the study area were estimated from the field survey. Plant and land use characteristics (e.g., root depth, land cover) were derived from LULC data that show different vegetation cover types on the farm that allow an estimate of the average root depth value to be derived. The selection of data input and relevant coefficients were carried out following the InVEST model's instructions (Sharp et al., 2020) (Table 3.3).

Table 3.3: Biophysical parameters linked to land use land cover (LULC) classes used for modelling water yield in the study area

LULC classes	**root_depth**	**Kc**	**lulc_veg**
Residence/farm infrastructure	200	0.15	0
Planted forest	2500	1	1
Space planting	1000	0.92	1
Riparian strip	1500	1.3	1
Indigenous forest	2500	1.3	1
Scattered manuka/kanuka	1000	1.3	1
High density manuka/kanuka	1000	1.3	1
Low intensive pasture	500	0.97	1
High intensive pasture	500	0.97	1
Short rotation cropland	400	1.05	1
Water bodies	300	0.65	0
Bare ground	200	0.15	0
Impervious surface	200	0.15	0

Definitions: root_depth (root restricting layer depth), Kc (plant evapotranspiration coefficient), lulc_veg (a land cover type of vegetation).

Carbon stock

Carbon stock was estimated based on vegetation and soil carbon. Vegetation carbon includes all vegetation biomass carbon sinks such as riparian strips, planted forests, natural forests, and shelterbelts. The carbon look-up tables published by the NZ government were employed to measure forest carbon stock (MPI, 2017). Carbon stock in non-forest ecosystems (e.g., wetlands, riparian strips, pole planting, shelterbelts, small woodlots, and revegetation of retired land) was evaluated based on the guidelines developed by Landcare Research in collaboration with SCION, NIWA and AgResearch (Burrows, 2018). For soil carbon, the national average soil carbon stocks for the different LULC types, published by Kirschbaum et al. (2009) were used in this study. Total carbon stock was then calculated using the raster calculator function in ArcGIS.

Freshwater purification

In this study we used nitrogen leaching as a proxy for the purification of freshwater, given that a high value of nitrogen exported to the stream represents a low supply of freshwater (Ausseil et al., 2013). The InVEST nutrient delivery (NDR) model was employed to quantify the flow of non-point source nutrients exported to the waterways on the farm (Zhang et al., 2021). The InVEST NDR model uses a “simple mass balance approach”, estimating the flow of a mass of nutrients across space based on the landscape characteristics such as LULC, topography (DEM), runoff potential (precipitation), and associated nutrient loading rate and retention efficiency (see Zhang et al., 2021). Sources of nutrient across the landscape, also called nutrient loads, were determined based on the input of farm information provided by the landowner. Information associated with the maximum retention efficiency for each LULC class was adapted from published literature (Ledein et al., 2007; Trodahl, 2018) and InVEST model documentation (Sharp et al., 2020) (Table 3.4). The NDR model provides a map of the nitrogen export for actual LULC. Given that the nitrogen that is exported is an inverse indicator for the freshwater purification (Powers et al., 2020), this map was converted to the freshwater supply map using the raster calculator function in ArcGIS.

Table 3.4: Biophysical coefficients for different land use land cover (LULC) classes used for modelling Nitrogen leaching

LULC classes	**load_n***	**eff_n**	**crit_len_n**	**rooth_depth**
Residence/farm infrastructure	8.5	0.5	10	200
Planted forest	4.1	0.8	300	2500
Space planting	25	0.8	200	1000
Riparian strip	8.5	0.85	300	1500
Indigenous forest	8.5	0.85	300	2500
Scattered manuka/kanuka	25	0.85	300	1000
High density manuka/kanuka	17	0.8	300	1000
Low intensive pasture	56	0.7	150	500
High intensive pasture	84	0.6	150	500
Short rotation cropland	120	0.5	25	400
Water bodies	8.5	0.85	10	300
Bare ground	0	0.05	10	200
Impervious surface	0	0.05	0	200

*Definitions: load_n (the nitrogen loading), eff_n (maximum nutrient retention efficiency), crit_len_n (the distance after which it is assumed that this LULC type retains the nutrient at its maximum capacity), root_depth (root restricting layer depth). *Nitrogen loading is farm specific as it is dependent on farm management practices (i.e., different between farms).*

Forest biodiversity/Natural habitat provision

A comprehensive assessment of forest biodiversity at the farm scale requires extensive field survey information related to species richness and their distribution across space (Brockerhoff et al., 2017). Because obtaining this data is time consuming and expensive (Le Clec'h et al., 2018), LULC data associated with forest land cover types can be used as a proxy to estimate forest biodiversity. Given that the contribution of LULC to biodiversity is not similar in all types, this study applied a condition index of natural land cover as an indicator to weight the levels of significance which different LULC types contribute to forest biodiversity (Ausseil et al., 2013). For instance, indigenous vegetation and wetlands make the highest level of contribution to biodiversity values (Table 3.5).

Table 3.5: Contribution of land use land cover (LULC) classes to biodiversity

LULC classes	**Condition index of natural land cover**	**Level of contribution to biodiversity**
Indigenous forest	1.0	Very high
Indigenous manuka/kanuka	0.5	Moderate
Planted forest	0.3	Some/Low
Wetland	0.8	High
Grassland	0.05	Very Low
Other LULCs	0.0	No contribution

3.3.2.3. Landscape aesthetics

The ability to map and assess landscape aesthetics provides valuable insights to understand the socio-cultural value of a landscape (Kalinauskas et al., 2021). While most ecosystem services associated with provisioning and regulating categories are widely accepted and used, defining and quantifying landscape aesthetic experiences can be complex and challenging processes (Swaffield & McWilliam, 2013). Most studies that focus on socio-cultural ecosystem services assessment often involve regional or national scales and public land use and conservation areas (Brown & Brabyn, 2012[a,b]; Fairweather & Swaffield, 2002; Kerr & Swaffield, 2012), whereas farm-scale study is overlooked. At a farm-scale, landscape aesthetics are a reflection of the farmers perception, experience, and appreciation of their farmed landscape. The aesthetics value of landscapes is primarily based on subjective feelings and human nature (Daniel et al., 2012; Tribot et al., 2018) so perception-based assessments are often used to interpret human preference for a particular landscape (Klein et al., 2015). Discussions with the landowners were carried out to understand what they valued about the landscape. This reveals that they favor aspects of their farm landscapes which are easy to farm, and that they also appreciate opportunities on their land for recreational activities such as tramping and sightseeing. Although a wide range of indicators have been used to assess the quality of landscape aesthetics (Tveit et al., 2006; Swaffield and McWilliam, 2013), landscape diversity and landscape naturalness have been reported to be key determinants for landscape aesthetics (Frank et al., 2013; Peña et al., 2015; Hermes et al., 2018; Kalinauskas et al., 2021). The assessment of landscape diversity and landscape naturalness was developed based on studies conducted by Hermes et al. (2018) and Kalinauskas et al. (2021).

In addition to these indicators, we considered "ease of farming" that reflects the landscape's attractiveness for pastoral farming as an indicator to evaluate landscape aesthetics from a farmer's perspective. Because the aesthetics value of landscapes is primarily based on subjective feelings and human nature (Daniel et al., 2012; Tribot et al., 2018), and place preference is driven by a range of reasons (e.g., recreational, identification, ecological, spiritual, economic) (Richardson & Stock, 2022), it is not surprising that farmers perceive areas which are easy to farm as their desired landscapes. Previous studies have demonstrated that the reactions and preferences of humans towards landscapes is strongly dependent on the purpose for which land is used and the interaction between land users and landscapes (Kaplan, 1979). It has been shown that farmers preferences in terms of what constitutes a desirable agricultural landscape are variable. Research has shown that within rural landscapes pastoral aesthetics can be characterised as an environment that is perpetually green, peaceful, comforting, and productive (Schauman, 2007) and in some areas, it has been documented that farmers prefer agricultural landscapes that display what can be described as "care", and that this aesthetic experience was supported by elements in the landscape such as straight crop rows, uniform green, and weed-free fields (Nassauer, 1988). Whilst in other areas, the farmer's perception may involve "neat and tidy aesthetics" which reflect a field (landscape) that allows for their ease of management (Chapman et al., 2019). Studies of landscape aesthetics based on photographic assessment indicate that farmers have a unique perspective, for instance, "seeing beauty in the same ordered and controlled arable agricultural landscapes that almost all other publics find monotonous and boring" (Burton, 2012, p.51). The aesthetics experience in a farmed landscape is noted to be complex with sometimes farmers exhibiting polar opposite responses depending on their production system. Von Bonsdorff (2005) suggested that aesthetics appreciation of farmers in an agricultural landscape is inseparable from personal interests and linked to practicing agriculture. For instance, some conventional farmers who observe the rectilinear patterns of conventional farming landscape as "tidy", might see the organic farming landscape as "messy", reflecting cultural and social beliefs about "neglect and laziness". In contrast, organic farmers see this landscape as diverse and functional and they might perceive the conventional farming landscape as "boring, uninspiring, and representing no understanding of nature" (Egoz et al., 2001). In the context of hill country farms, the topography and physical settings has created very complex and heterogenous landscapes. As such, the homogenous areas with landscape pattern and structure that make the pasture easy to manage is an attractive landscape that farmers appreciate, as is the case with this studies case study farmer. This can be attributed to the practical use of landscapes that contribute to the well-being of farmers and their family. As such, including this indicator is essential to being able to better quantify the cultural values within the farmed landscapes. To quantify the suitability of the landscape for pasture production and grazing, we considered the availability of water bodies, the terrain's slope and level of erosion, the agricultural land pattern, and the aspects (directions) of terrain slope, based on the key roles that these factors play in grazing management (Lambert, 1976; Radcliffe, 1982). With this in mind, we selected three indicators which are ease of farming, landscape diversity, and landscape naturalness to map the landscape aesthetics associated with the case study farm (Table 3.6). Considering that our objective is mapping the spatial pattern of landscape aesthetics, the selection of indicators and sub-indicators also needs to ensure these can be mapped (spatially explicit) and that the necessary data to do so are available. For most of the ecosystem services metrics and indicators, the absolute data values were classified into different categories (i.e., 10 classes) and then normalised to a relative scale from 0 to 1, in which higher values represented the greater supply of ecosystem services. For the assessment of the suitability of terrain aspect for pasture farming practice, the scores were estimated based on the relative impact of aspects on pasture production (i.e., mean pasture yield by aspects). As such, the scores of 0.5, 0.65, 0.8, and 1.0 were assigned for North and Northeast, East and Northwest, West and Southwest, and South, Southeast, and Flat terrain, respectively. Doing this allows the data that have different measurement units to be aggregated for mapping landscape multifunctionality. These characterised sub-indicators and metrics were then aggregated using the weighted overlay function in ArcGIS.

Table 3.6: Landscape aesthetics indicators/sub-indicators and measurements

Indicators	**Sub-indicators**	**Metrics**	**Data used**
Ease of farming	Availability of water bodies	Proximity to water bodies	LULC
	Slope and erosion	Slope and erosion levels	DEM, USLE
	Agricultural land pattern	Largest Patch Index	LULC
	Aspects of terrain slope	Aspects of terrain slope	DEM
Landscape diversity	LULC diversity	Shannon Diversity Index	LULC
	LULC complexity	Edge-Density of patches	LULC
	Terrain complexity	Terrain Ruggedness Index	DEM
Landscape naturalness	Land cover naturalness	Percentage of natural vegetation and wetlands	LULC
	Absence of disturbing elements	Percentage of bare soil, impervious surface, slump	LULC, Aerial photos

Definitions: LULC: land use/land cover, DEM: Digital Elevation Model, USLE: Universal Soil Loss Equation

3.3.3. Mapping landscape multifunctionality using GIS and the Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) has been widely used in landscape quality mapping and assessment (Hermes et al., 2018; Kalinauskas et al., 2021; Khomalli et al., 2020; Quinn et al., 2013; Vizzari, 2011). The AHP is a prioritization technique used to identify the relative importance of multiple paired criteria to achieve a stated goal (Saaty, 1980). In this research, AHP was employed to characterise landscape multifunctionality as an integration of multiple ecosystem services. In the first stage, the hierarchy of the landscape multifunctionality mapping process was defined. The highest level presents the overall quality of landscape multifunctionality, the second level is three broad ecosystem services categories (i.e., provisioning, supporting, cultural), the third level is eleven indicators representing the three ecosystem services categories, and the fourth level of the hierarchy signifies the sub-indicators which were used to measure a specific ecosystem service.

In the second stage, the relative priorities (i.e., weights) of the ecosystem services for each hierarchical level are identified through pair-wise comparisons. As the AHP method considers only two criteria at a time when comparing evaluation criteria to assign possible weights, it is easier for the decision makers to express their preferred structure (i.e., order of criteria priority) than evaluating multiple landscape functions simultaneously. To evaluate how management goals and priorities contribute to the landscape quality, two weighting preferences (i.e., priority scenarios) were considered: an equal weighting and a landowner-based scenario. The first scenario assumes that all ecosystem services are important and contribute significantly and equally to landscape quality. As such, weights are assigned equally across all levels of ecosystem services metrics. This scenario can be seen as a sustainable landscape management goal as the weightings reflect the balance between the three categories of ecosystem services. In the second scenario the weightings are made based on the goal for pastoral production. The landowner ranked the ecosystem services in terms of importance based on his preferences. The results from the pairwise comparison are metric weights for the ecosystem services indicators and sub-indicators (Table 3.7). For detailed information of the pairwise comparison and sub-metrics weighted values see supplementary material (Table S3-S10). Each ecosystem service was prepared as a map layer and the total multifunctionality was integrated using the raster calculator tool in ArcGIS (version 10.8). The results from this step are MFC maps for the overall landscape and for each category of ecosystem services (i.e., provisioning, regulating, and landscape aesthetics services).

Table 3.7: Ecosystem services categories (ES) and metric weights for the two options: equal weighting and landowner weighting

	Metrics	**Equal weighting**		**Landowner weighting**	
		ES	Metrics	ES	Metrics
Provisioning	Stockfeed production (SP)	0.34	0.34	0.78	0.78
	Provision of timber (PT)		0.33		0.07
	Provision of manuka honey (MH)		0.33		0.15
Supporting/ Regulating	Erosion control (EC)	0.33	0.20	0.11	0.29
	Water flow regulation (WR)		0.20		0.22
	Carbon sequestration (CS)		0.20		0.06
	Freshwater purification (FW)		0.20		0.37
	Natural habitat (NH)		0.20		0.06
Landscape aesthetics	Ease of farming (EF)	0.33	0.34	0.11	0.45
	Landscape diversity (LD)		0.33		0.45
	Landscape naturalness (LN)		0.33		0.10

3.3.4. Hot Spot Analysis using Getis-Ord Gi* statistic

Hot spot analysis using the *Optimized Hot Spot Analysis* tool in ArcGIS (ESRI, 2022) was applied to explore the spatial clustering of landscape multifunctionality. In this study, a hot spot indicates a "specific location where a high number of ecosystem services co-occur and are provided at high levels" and cold spots show the areas with low levels of ecosystem services supply (Saidi & Spray, 2018). This tool utilises the Getis-Ord Gi* algorithm (Getis & Ord, 2010) to characterise the existence of significant hot spots (high MFC clusters) and cold spots (low MFC clusters) in the landscape. The Hot Spot

Analysis tool calculates the Getis-Ord Gi* statistic for each feature in a dataset. The results including z-scores and p-values reveal where features with either high or low values cluster spatially. Higher positive z-scores identify locations with more intense clustering of high values (i.e., hot spots) and lower negative z-scores represent locations with clusters of low values (i.e., cold spots) (ESRI, 2022). Because hot spot analysis uses vector data (point or polygon features), a grid cell of polygons (10mx10m) that is converted from the MFC maps of provisioning, regulating, and landscape aesthetics services was used as the geographic unit of analysis.

3.3.5. Statistical analysis

We used Pearson correlations, an indicator for the strength of the linear relationship between two variables (Williams et al., 2020), to assess the relationships between all pairs of 11 ecosystem services. The Pearson correlation values (r) will be classified as strong ($r \geq 0.5$), moderate ($r \geq 0.3$), and weak correlations ($r < 0.3$) (Akoglu, 2018). ArcGIS Pro (version 2.9) was used to calculate the Pearson correlations and visualise the results. The relationships between ecosystem services were further examined using principal component analysis (PCA) which is a multivariate data analysis technique used to explore variation among multiple variables (Jolliffe & Cadima, 2016). Because the Pearson's correlation analysis revealed correlation among the ecosystem services, the aim of PCA in this study is to investigate variation among the 11 ecosystem services by reducing them to fewer principal components. Factor loadings from the PCA can be used to identify ecosystem services grouped into "bundles" which can be interpreted in terms of ecosystem service "synergies" and "trade-offs". A synergy is defined as "a situation where the use of one ecosystem service directly increases the benefits supplied by another service", whereas a trade-off is "the simultaneous reduction in one ecosystem service and the enhancement of another" (Raudsepp-Hearne et al., 2010). Ecosystem services bundles are defined as "a set of associated ecosystem services that are linked to a given ecosystem and that usually appear together repeatedly in time and/or space" (Raudsepp-Hearne et al., 2010). All analysis were carried out at the pixel level (i.e., 10m x 10m cell size or grid cells of 100 square meters resolution).

3.4. Results

3.4.1. Ecosystem services provision

Overall, the ecosystem services provision varies greatly across the landscape (Figure 3.3) and the pattern of ecosystem services supply is strongly related to the LULC pattern (Figure 3.1b). Pattern of pasture yield, water yield, and ease of farming services are relatively similar which are highest in the north and lowest in the south-central of the farm. This is opposite to pattern of other ecosystem services; those are often found to be highest in the areas covered by woody vegetation and wetlands.

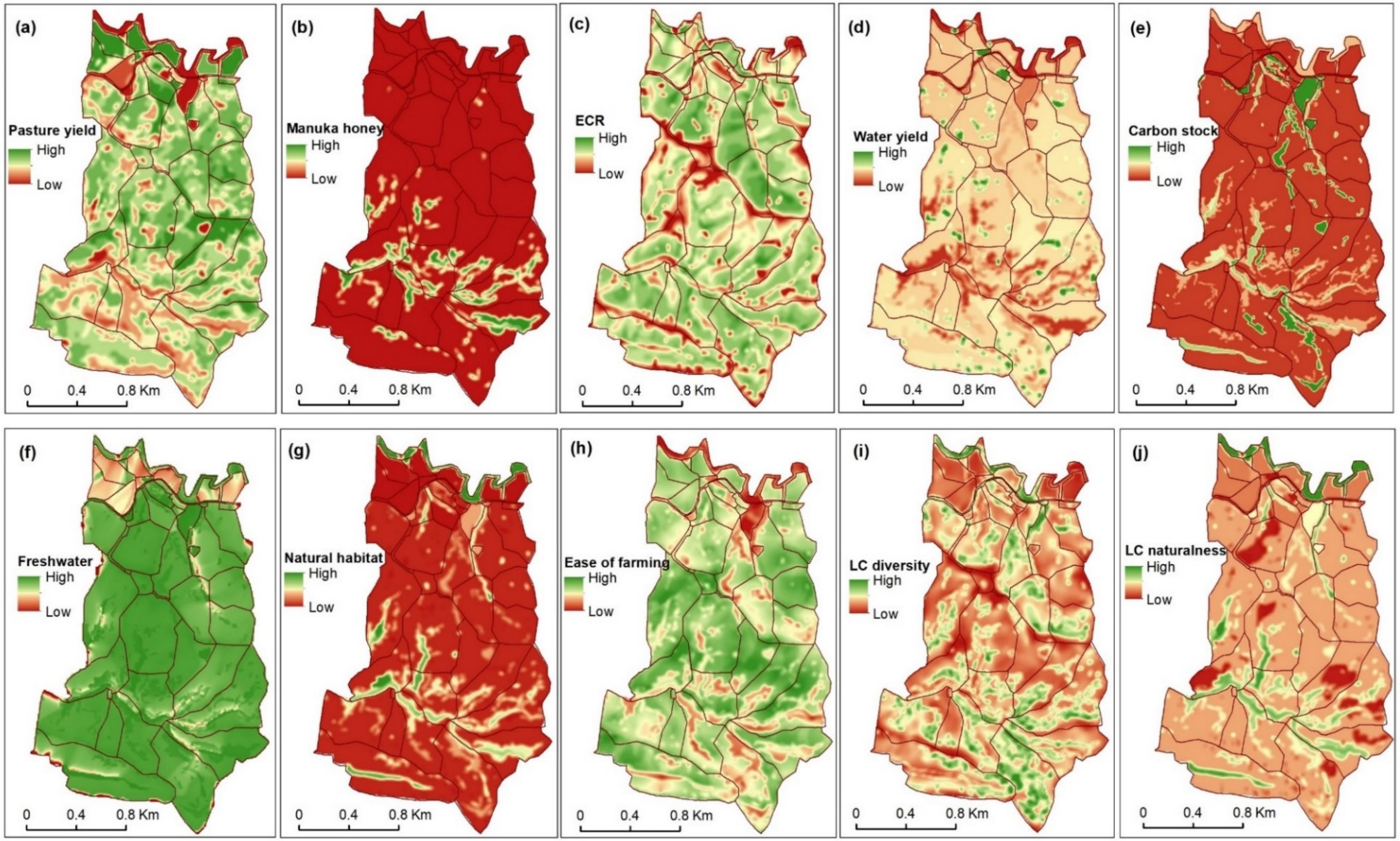

Figure 3.3. The spatial pattern of ecosystem services for the case study: (a) Stockfeed production, (b) Provision of manuka honey, (c) Erosion control, (d) Water flow regulation (e) Carbon sequestration, (f) Freshwater purification, (g) Provision of natural habitat, (h) Ease of farming (i) Landscape diversity, (j) Landscape naturalness. The timber production service is not presented here as it occupies only a small area of the landscape.

Among the ecosystem services quantified in the study area, ease of farming, freshwater purification, water supply, and stockfeed production have the highest mean value (0.71, 0.68, 0.65, and 0.6, respectivelly), which indicates that these services are the ones most constantly provided across the farm. In contrast, the provision of manuka honey and timber have the lowest mean values (0.07 and 0.01), and also the lowest variation compared to other services. For detailed information associated with the distribution of 11 ecosystem services values in the study area such as the max, min, mean, median is described in the box plots in Figure 3.4.

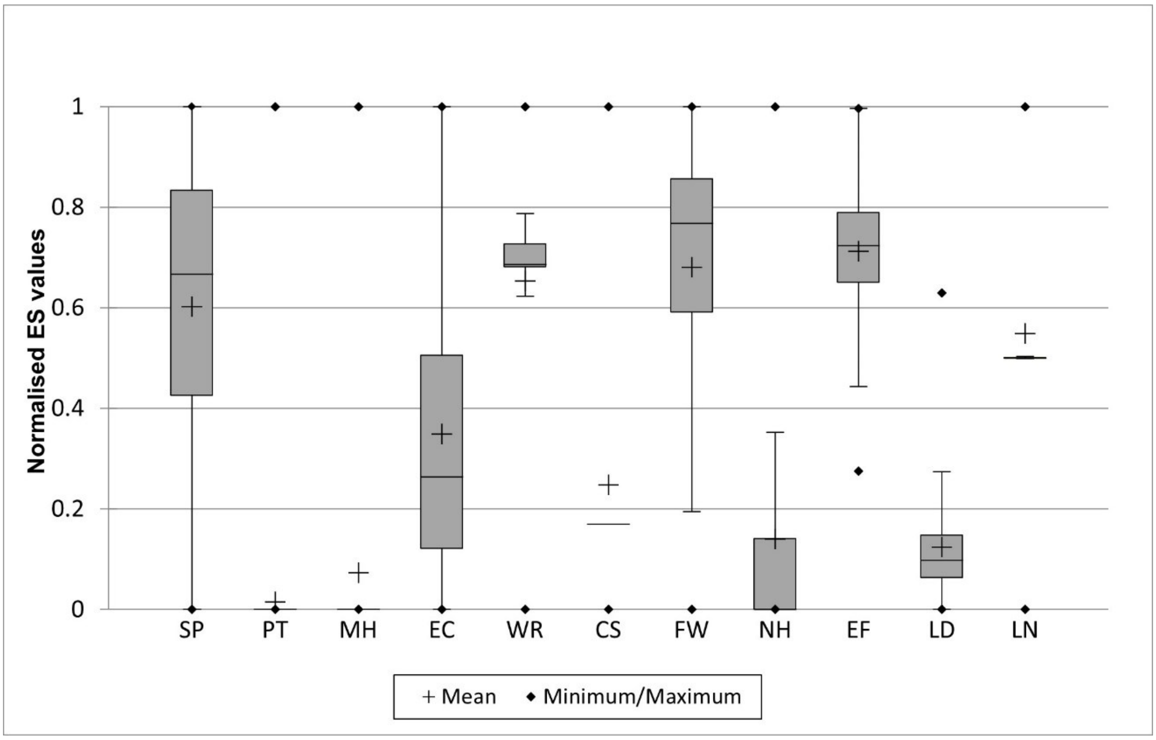

Figure 3.4. The normalised value of ecosystem services: Stockfeed production (SP), Provision of timber (PT), Provision of manuka honey (MH), Erosion control (EC), Water flow regulation (WR), Carbon sequestration (CS), Freshwater purification (FW), Natural habitat (NH), Ease of farming (EF), Landscape diversity (LD), Landscape naturalness (LN). The box plots present maximum (upper fence), median (horizontal line inside the box), mean (the plus sign), minimum (lower fence), and the middle 50% of ecosystem services values (the rectangle box).

3.4.2. Synergies and trade-offs between ecosystem services

The results from the Pearson correlation analysis show both positive and negative relationships between ecosystem services pairs and most of the correlations are statistically significant ($p < 0.01$) (see Figure 3.5x). Of all ecosystem services pairs, strong positive correlations are seen in six pairs whereas, strong negative correlations can be observed in five ecosystem services pairs. Moderate positive correlations are somewhat more common, showing that six pairs of ecosystem services have positive correlations and nine pairs show negative correlations.

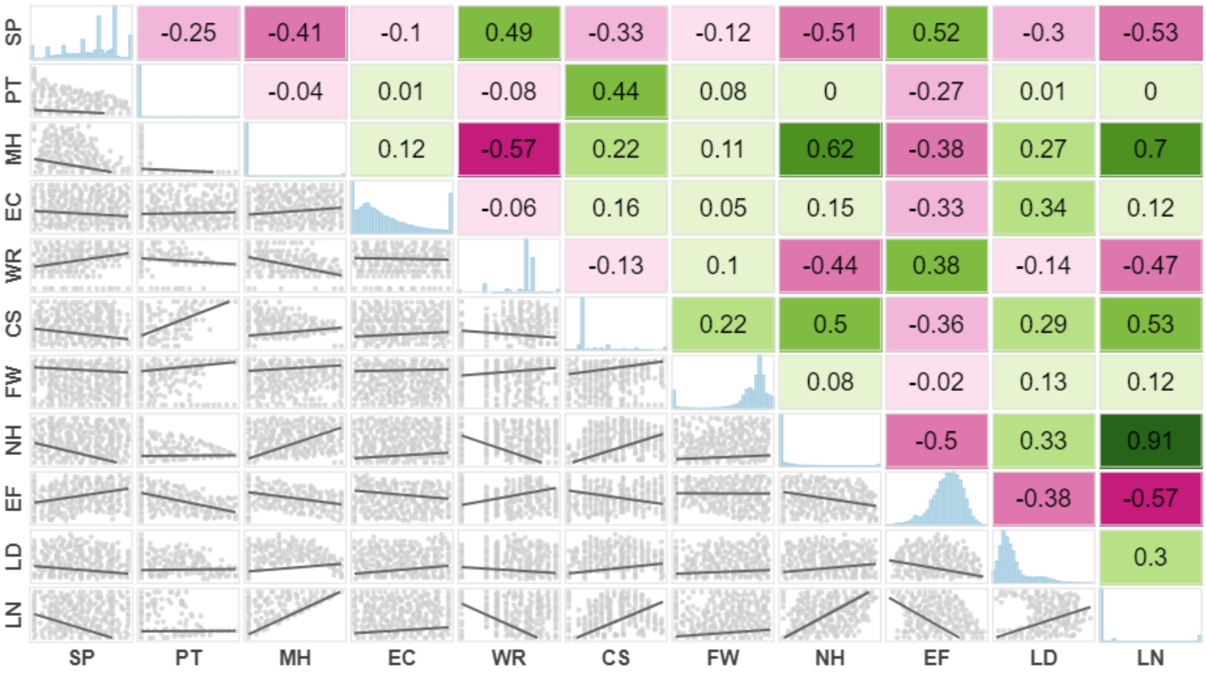

Figure 3.5. The Pearson correlation coefficients matrix between ecosystem services (ES) pairs: Stockfeed production (SP), Provision of timber (PT), Provision of manuka honey (MH), Erosion control (EC), Water flow regulation (WR), Carbon sequestration (CS), Freshwater purification (FW), Natural habitat (NH), Ease of farming (EF), Landscape diversity (LD), Landscape naturalness (LN). Each cell in the lower left of the diagonal shows a bivariate scatterplot for each pair of services. Points represent normalised values of ES. The black lines in the lower left of the diagonal present the trend (positive and negative) of the relationship between two variables in each pair of ES. Each cell in the upper right of the diagonal shows Pearson correlation coefficients for each pair of ES (green for the positive correlations and pink colors for the negative correlations). All correlations that are different from zero are statistically significant ($p < 0.01$).

Among those having low correlations, 10 pairs are positively correlated, and six pairs are inversely correlated. These results demonstrate how the supply of one ecosystem service may relate to another in the landscape. For instance, a correlation between NH and LN (*r = 0.91, p <0.01*) indicates that the provision of natural habitat is strongly compatible with landscape naturalness. Whereas a correlation between SP and NH (*r = -0.51, p < 0.01*) shows that pasture production is not compatible with the provision of natural habitat.

The relationships between the 11 ecosystem services were further examined using principal component analysis (PCA). Information obtained from the PCA analysis for the first five components is presented in Table 3.8. For a fully description of the PCA analysis such as the eigen values, component loading, and the contribution of the variables, see Table S3.10 and Figure S3.3.

Table 3.8: Result of the principal component analysis for the first five factors

	F1	F2	F3	F4	F5
Eigen value	4.13	1.41	1.24	1.03	0.92
Variability (%)	37.54	12.80	11.28	9.41	8.34
Cumulative %	37.54	50.34	61.61	71.02	79.36
	Factor loadings				
Water flow regulation (WR)	**-0.62**	0.34	0.15	0.21	0.47
Stockfeed production (SP)	**-0.72**	-0.08	0.17	0.03	0.38
Ease of farming (EF)	**-0.73**	-0.19	-0.22	0.25	0.13
Provision of timber (PT)	0.23	**0.75**	-0.36	-0.33	-0.16
Freshwater purification (FW)	0.17	0.21	-0.40	**0.81**	-0.19
Erosion control (EC)	0.28	0.27	**0.76**	0.07	-0.14
Carbon sequestration (CS)	**0.61**	**0.51**	-0.16	0.02	0.44
Landscape diversity (LD)	**0.50**	0.20	0.49	0.36	-0.04
Provision of manuka honey (MH)	**0.73**	-0.42	-0.06	0.13	-0.09
Landscape naturalness (LN)	**0.82**	-0.23	-0.10	-0.05	0.40
Natural habitat (NH)	**0.85**	-0.21	-0.03	0.02	0.30

Significant values that meet $r \geq 0.5$ are in bold.

Table 3.8 shows that the first two principal components explain 50.34% of the total variance in the 11 ecosystem services. The first component (F1) is negatively associated to the first bundle (WR, SP, and EF) and positively related to other ecosystem services.

This indicates the synergies between water supply, pasture production, and the landscape coherence for farming and the trade-offs between these and other ecosystem services. In contrast, the second and third bundles (PT, FW, EC, CS, LD and MH, LN, NH) that are associated with the presence of woody vegetation (exotic and indigenous forest) or wetlands ecosystems are shown to be a rich producer of ecosystem services.

3.4.3. Spatial pattern of landscape multifunctionality

The spatial pattern of overall landscape multifunctionality and multifunctionality by categories of ecosystem services for two weighting preferences (i.e., management goals) are illustrated in Figure 3.6. These maps show the overall spatial variation in MFC quality (Figure 3.6a and 3.6e), and the MFC quality for the provisioning, supporting, and aesthetics categories of ecosystem services (Figure 3.6b-d) based on the equal weighting of the 11 ecosystem services, and the same for the AHP weights based on landowner priorities (Figure 3.6f-h). In the equal weighting scenario (Figure 3.6a), high MFC scores can be seen in the northeast and across a west-east strip in the south of the farm. Those landscapes are often high in both provisioning, supporting/regulating, and aesthetic services. Areas with the lowest MFC values are situated in the northwest and the south of the farm and are strongly aligned to the results obtained from landowner's weighting (Figure 3.6e). In some parts of the farm, the two weighting options show opposite patterns, such as the north-end and middle-eastern part of the farm. These areas have the highest MFC values and also the highest provisioning services values (i.e., stockfeed production) based on the landowner preference. The area covered by exotic forest in the northeast of the farm shows high MFC for the equal weighting scenario, but low MFC with the landowner's weightings. Most areas in the landscapes in both weighting scenarios show good alignment for supporting services.

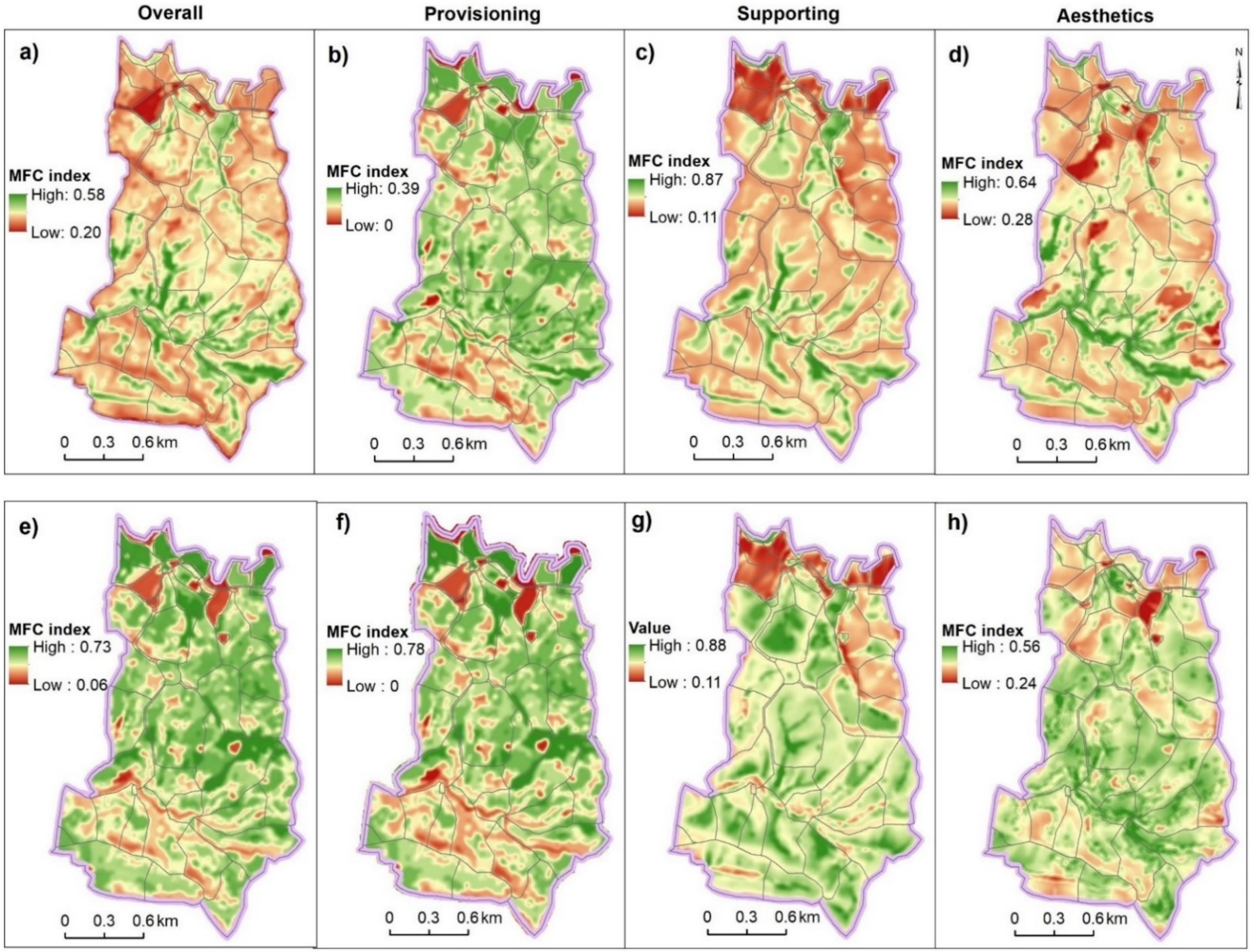

Figure 3.6. Landscape multifunctionality (MFC) quality in the study area based on equal weighting (3a-d) and landowner weighting (3e-h). Higher score indicates a higher MFC level, suggesting that the landscape can supply more ecosystem services.

The variations in MFC by LULC type and the slope of the terrain are shown in Table 3.9. In the equal weighting scenario, mean values of MFC in the areas covered by trees and wetlands are higher than those used for stockfeed production. This is also reflected in the multifunctionality of supporting and landscape aesthetic services. However, an inverse pattern is observed when looking at the MFC mapped using the farmer's weightings. Because the services related to stockfeed production are weighted much higher than the others, landscape multifunctionality for the whole landscape and that of the provisioning service group are very high for the grassland and cropland areas.

Table 3.9: Mean value of landscape multifunctionality by land use land cover types

	Equal weighting				**Landowner's weighting**			
LULC types	MFC	PS	SS	AES	MFC	PS	SS	AES
Riparian strip	0.36	0.04	**0.51**	**0.52**	0.17	0.08	0.50	0.38
Grass land	0.36	0.23	0.40	0.46	**0.50**	**0.50**	0.52	**0.44**
Exotic forest	**0.42**	**0.29**	**0.56**	0.40	0.22	0.14	**0.61**	0.34
Space planting	**0.42**	0.21	**0.56**	**0.50**	**0.49**	0.47	***0.64***	***0.47***
Indigenous manuka	***0.46***	***0.31***	**0.53**	**0.54**	0.38	0.34	**0.58**	**0.45**
Cropland	0.32	**0.26**	0.28	0.43	***0.55***	***0.61***	0.33	0.40
Wetland	**0.45**	0.22	**0.58**	***0.55***	0.46	0.44	**0.58**	**0.45**
Intensive grassland	0.36	**0.24**	0.39	0.44	**0.53**	**0.55**	0.51	0.43
Indigenous forest	**0.40**	0.08	***0.60***	**0.54**	0.22	0.13	**0.59**	**0.45**
Slope classes	MFC	PS	SS	AES	MFC	PS	SS	AES
0 – 7	0.36	0.23	0.38	**0.47**	0.47	0.48	0.44	0.43
8 – 15	0.36	***0.24***	0.39	0.46	***0.51***	**0.52**	0.48	0.43
16 – 25	**0.37**	***0.24***	0.41	0.46	**0.50**	**0.51**	**0.53**	0.43
25 – 35	***0.38***	0.21	**0.46**	0.46	0.45	0.44	**0.58**	0.43
> 35	**0.37**	0.15	***0.49***	**0.47**	0.36	0.31	***0.61***	0.43

Definitions: Overall landscape multifunctionality (MFC), Provisioning services (PS), Supporting services (SS), Landscape aesthetics (AES). Values that are greater than the mean are highlighted in bold and the highest values are in italics.

It is important to note that both the equal weighting and landowner's weighting maps resulted in a high value for the supporting service in the LULC types associated with woody vegetation or wetlands. The mean MFC scores by slope group clearly demonstrate that the multifunctionality values under the farmer's weightings tend to be higher in the slopes between 8-15^{o} and 16-25^{o}. For both weighting scenarios, landscape aesthetics values are relatively similar in all slope groups, whereas provisioning services are high in steep-lands (slope $> 25^{0}$).

Insight into the spatial clustering of landscape multifunctionality among ecosystem services groups is shown using hot spot analysis (Figure 3.7). The maps obtained by using equal weighting show that hot spots (high quality MFC) are mainly clustered in the central area of the farm, both north and south. In contrast, cold spots (low quality MFC) are in the northwest and the south. Using AHP weights based on landowner preferences, hot spots for all the ecosystem services are highly clustered in the centre of the farm. The north of the farm presents hot spots of provisioning services (high MFC) but cold spots of supporting services and landscape aesthetics (low MFC). Hot spot and cold spot patterns of provisioning services are well aligned between the two weighting scenarios. In terms of area, there are more hot spots in the equal weighting scenario (181.12 ha) than in the landowner's weighting scenario (151.60 ha). Whereas the areas of cold spots for all categories in the landowner's weighting scenario remain higher than the equal weighting scenario (162.87 ha and 136.07 ha, respectively).

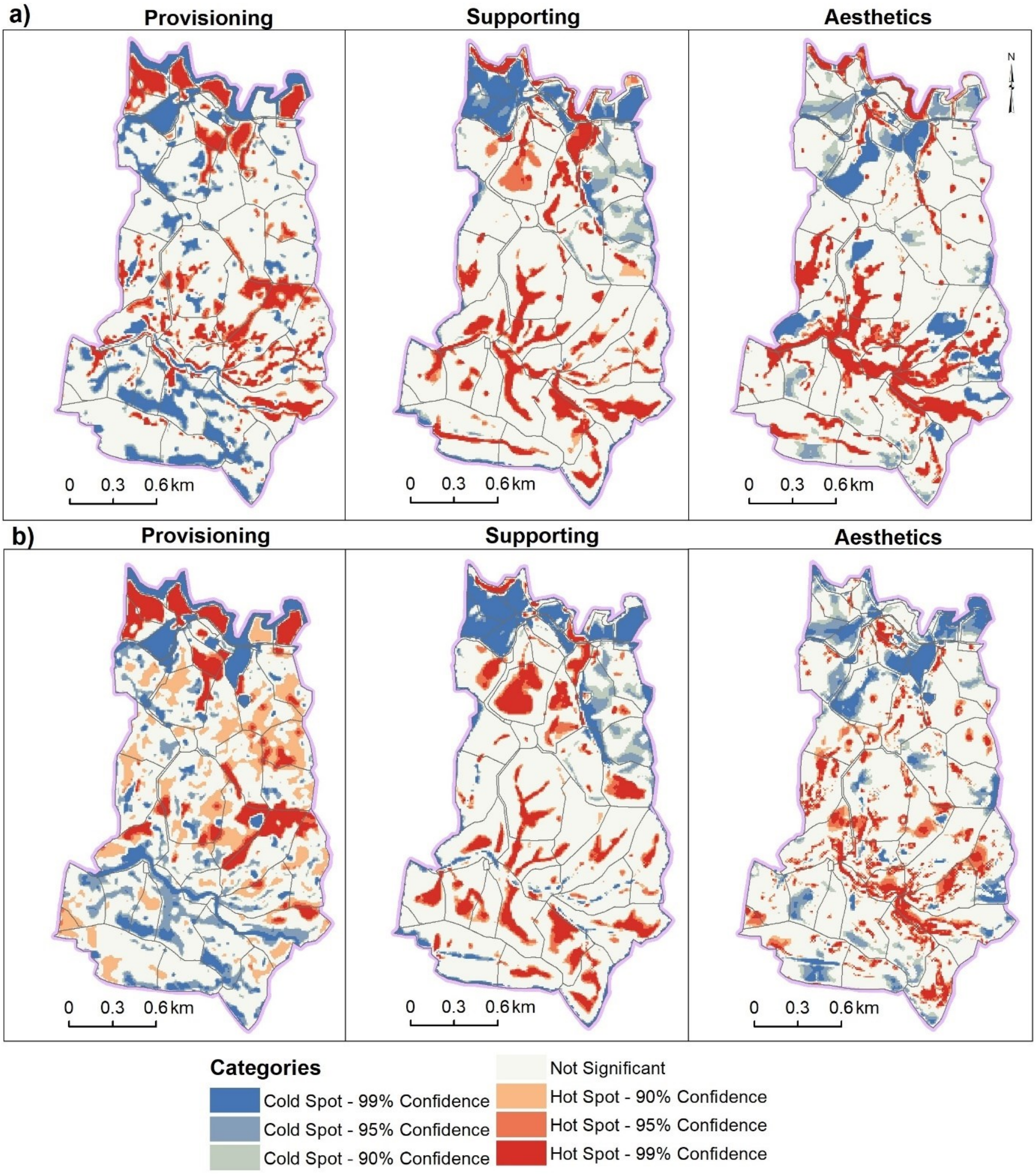

Figure 3.7. Hot spots and cold spots of ecosystem services provision in the study area: a) equal weighting and b) landowner's weighting scenarios

3.5. Discussion

3.5.1. Ecosystem services mapping at the farm scale, uncertainties, and limitations

A major challenge facing farm-scale analysis is the lack of empirical data to capture the complexity of ecosystem services (Andersson et al., 2015) or field verification information to assess and validate model outcomes (Tran et al., 2022). The realities of obtaining these data that are expensive and time consuming, mean that it is often not feasible. In order to undertake more practical landscape planning and management at a farm-scale, integrating different sources of data, utilising various tools and models, and taking advantage of local experts and landowners' knowledge are suggested as ways to generate a comprehensive assessment of ecosystem services provision (Stritih et al., 2019). While some bio-physical landscape processes can be calculated using topographical and climatic data, place-based local knowledge can play an important role in successfully mapping the ecosystem services which are strongly associated with anthropologic activities (Hölting et al., 2020; Paulin et al., 2020; Plieninger et al. 2019). In our study, important information provided by the farmer such as nutrient use, stocking rate, and tree age, etc., has enabled us to quantify several ecosystem services including the purification of freshwater, stockfeed production, and carbon stock. Also, applying modern geospatial technologies has proven efficient to deal with a lack of relevant data when quantifying ecosystem services at the farm scale. For instance, the long-term (i.e., time-series) NDVI data obtained from Google Earth Engine can provide reliable information that reflects the pasture yield pattern of a farm because it captures both seasonality (Amies et al., 2021; Baldi et al., 2008) and variations due to changes in grazing management (Wall et al., 2012). Also, social media information such as textual metadata and image posts can be used to map landscape aesthetics (Fox et al., 2021), and machine learning and hyperspectral remote sensing data can be applied to model soil carbon (Guo et al., 2021). Therefore, it is useful to develop effective protocols to acquire information from farmers and to utilise the advanced geospatial technologies in farm-scale ecosystem services assessment.

A limitation of this study is the lack of experimental data for ecosystem services model calibration and validation. If field data such as soil carbon stock, nutrient concentration, and natural habitat samples are available, more accurate information on the provision of ecosystem services across the farm can be mapped. Therefore, this limitation needs to be overcome in the future for farm scale modelling. This study focuses on modelling the supply of current ecosystem services whereas change in ecosystem services over time (i.e., temporal variation) is neglected. It is suggested that future studies consider evaluating changes in ecosystem services associated with different land use change scenarios and management practices. Also, farm-scale analysis should examine variations in the relationship between ecosystem services by different levels of agricultural intensification and by different land use combinations. Such analyses will provide useful information to help understand how land use change may influence the value and pattern of ecosystem services and provide farmers more choices for improving the land use and management of their farms (Heinze et al., 2022).

Although some landscape aesthetics services were modelled in this study, these are not comprehensive enough to capture the socio-cultural ecosystem services that may be provided by a hill country farm. Some aesthetics services such as imageability, visual quality (visual scale), and historicity were not quantified, and an integration of Māori values and perspectives into the socio-cultural ecosystem services is lacking. Several studies have reported a comprehensive socio-cultural and landscape aesthetics experiences at various scales in NZ with relevant indicators and methods to map these services. For instance, Brown and Brabyn (2012[a,b]) applied public participation through GIS (PPGIS) and GIS-based landscape character classification to examine social landscape values at the regional (Otago and Southland) and national level. Also, Kerr and Swaffield (2012) combined the Q-sort method with a choice experiment to assess cultural service values of small rivers and streams in Canterbury. Harmsworth and Awatere (2013) presented an ecosystem services framework that was based on Māori knowledge, values, and perspectives. Recently, advanced geospatial technologies such as automated landform classification and crowdsourcing or textual volunteered geographic information have been used in NZ as an efficient tool to quantify landscape aesthetics

(Egorova, 2021; Németh et al., 2021). It is suggested that these studies can provide valuable reference that enables future work to carry out a more comprehensive assessment of socio-cultural ecosystem services provision on hill country farms.

3.5.2. Complexity and variation in ecosystem services provision and landscape multifunctionality pattern

The results from the ecosystem services and landscape multifunctionality mapping demonstrate that, even in a farm landscape, the pattern of ecosystem services supply and landscape multifunctionality vary greatly across space (Figures S3 and 3.3). Clearly, the LULC explains a substantial part of the variation in the spatial pattern of ecosystem services provision for the case study. Landscapes associated with a low level of simplification such as those covered by indigenous trees and wetlands that are located in the middle-south of the farm tend to supply more ecosystem services than the areas which are highly simplified and modified for pasture production. In contrast, areas with a high level of landscape simplification such as the northern paddocks provide a higher value of stockfeed production service. In addition, differences in the pattern of ecosystem services and MFC are also related to the degree of terrain slope (Table 3.9), for example, the provision of supporting services are on steep-land areas are higher than the flatter parts of the farm. Given a hill country landscape is highly heterogenous, information associated with the spatial relationship between landscape pattern and structure and the performance of different land uses to supply a range of ecosystem services across the landscape is useful to fully understand this variation (Tran et al., 2022).

This study also demonstrates that the value of landscapes is subjective relative to the land management goals which are reflected by the preferences of the landowner and the weighting that he places on the different ecosystem services (Table 3.7 and Figure 3.6). As such, we suggest that integrating landowner views and preferences in a farm scale study is necessary to empower the landowner in the decision-making and assessment process. This is in line with conclusions drawn from previous studies who stated that the engagement and participation of the landowner is an efficient way to promote the application of an ecosystem services approach in decision making (Cowling et al., 2008; Fish et al., 2016). We also recommend that in addition to the overall MFC index which provides a broad indication of landscape quality, the examination of multifunctionality by ecosystem services category in relation to land use type is useful for understanding and explaining this multifunctionality. This process enables the landowner to determine the status (e.g., strengths and weaknesses) of the individual ecosystem services on the farm and the categories that most influence these and this provides a basis for making decisions about how best to improve the overall MFC (Floridi et al. 2011; Quinn et al., 2013).

The Pearson corelation and PCA assessment between ecosystem services show both synergies and trade-offs among the different ecosystem services. Trade-offs are clearly seen between the stockfeed production service (e.g., pastoral production) and most of the other services (excluding the water yield and aesthetic for pastoral farming). This conclusion is aligned with previous studies, highlighting that promoting pasture production will significantly reduce the provision of other services, especially supporting and regulating services such as erosion control, carbon sequestration, nutrient retention, and provision of biodiversity (Le Clec'h et al., 2019; Powers et al., 2020; Wu et al., 2017). Similarly, our analysis shows the synergies between supporting services and landscape aesthetics, which come from natural land covers (e.g., erosion control, provision of natural habitat, landscape naturalness). Whilst agricultural production is often seen as creating negative impacts on ecosystem services provision other than provisioning services, this study reveals that different types of agricultural production show different trade-offs between ecosystem services. For example, in this case manuka trees for the production of honey significantly promotes the supply of other ecosystem services such as the purification of freshwater, erosion control, landscape diversity, and landscape naturalness. In addition, exotic forestry also demonstrates a positive relationship with most ecosystem services, although the synergies are not as strong as for indigenous forest. The synergy between landscape diversity and regulating services (i.e., freshwater provision, erosion control, and carbon stock) demonstrates that a diverse and complex landscape with a mix of different land use types can provide multiple ecosystem services. This shows the importance of providing landowners with a range of alternative land use options that can promote agricultural production whilst also creating positive impacts on the provision of ecosystem services. Therefore, providing information associated with the synergies and trade-offs among ecosystem services and the performance of different LULC across the landscape for the provision of different ecosystem services is critical for landowners when making decision about the best use of different areas of the farm, in the context of the landowner's overarching goals for the business.

3.5.3. Applications in land and environmental planning and management in a farmed landscape

The results from the landscape multifunctionality and ecosystem services mapping provide several opportunities for land and environmental planning and changes to management practices. Information associated with the spatial pattern of ecosystem services provision as well as the synergies and trade-offs between them provide the land manager with an understanding of the state of landscape quality and its ability to deal with associated environmental challenges. For instance, by looking at the map of landscape multifunctionality and ecosystem services hot spots, land managers can determine areas which supply more ecosystem services than others and vice versa. This information can be used to prioritise specific areas where changes in land use or management practices are required. In other words, it can help with the development of spatial-based management goals, to enhance the provision of desired ecosystem services. Because the level of landscape multifunctionality and the provision of ecosystem services vary across the landscape, different management goals and strategies are required to optimise the supply of ecosystem services in different areas. For example, the planting of manuka trees in areas where there is low pasture yield will increase regulating services, but may not significantly reduce profit, as this land use change has limited impact on the farm's total pasture production and will generate additional income from manuka honey (Dominati et al., 2019). Also, the space planting of poplar trees had a high value for both supporting services and landscape aesthetics. This is because the space planting of poplar trees on steep slopes that are grazed by livestock can help to increase landscape multifunctionality by promoting a number of ecosystem services such as erosion control, carbon sequestration, landscape diversity, and improve animal performances (Dodd et al., 2008; Dominati et al, 2014). In contrast, in the areas which are highest in the provision of stockfeed production but low in provisioning services (e.g., the northern paddocks of the farm), changes to non-agricultural production land will increase the provision of multiple ecosystem services. However, this is not a practical solution because doing this will significantly reduce the farm's productivity. As such, the farmer is more likely to retain this land for stockfeed production and apply mitigation strategies to reduce environmental impacts such as changing crop management to improve soil carbon sequestration (Stanley et al., 2018), creating nutrient buffer strips to reduce nutrient loss (Anderson et al., 2020), and diversifying types of crops to increase temporal (i.e., seasonal) multifunctionality (Finney & Kaye, 2017). This can increase regulating services and reduce environmental impacts whilst maintaining farm's productivity.

Results from our study can provide an important basis from which to develop an integrated farm plan which focuses on multiple goals such as agricultural production, the mitigation of environmental impacts, and cultural/social aspiration. Although this study was undertaken on a single farm, the findings provide valuable insights for land use planning and management that can be generalised to a wider context. To date, most environmental farm plans applied in NZ often target a specific environmental management goal such as a "soil conservation plan" with a primary focus on erosion control, a "forestry-oriented environmental farm plan" with a goal of establishing production forestry, or a "riparian plan" with a major focus on water quality (Blaschke & Ngapo, 2003). As such, applying these traditional methods to develop a comprehensive integrated farm plan that covers various environmental issues is challenging due to lack of information to develop multiple options for land use and management. NZ farming systems, like many across the world facing environmental challenges, are transitioning to more sustainable integrated systems (Pearson, 2020; Turner et al., 2020), and an ecosystem services-based planning and management approach has the capacity to inform strategic farm planning that will meet multiple management goals (Dominati et al., 2016; Mackay et al., 2018). Whilst the landscapes of this farm are typical of those across NZ hill country and the challenges which are facing the case study are common for most hill country farm systems (Tran et al., 2020), the methodology and findings presented in our study can be broadly applied to other areas. The synergies, trade-offs, and variations in ecosystem services across the farmed landscape demonstrated in this study provide valuable references to landowners on other hill farms to think about their own context and apply the same concepts for developing comprehensive farm plans. Although the absolute values of ecosystem services supply may differ from farm to farm, the pattern of the ecosystem services provision across space and relationships between them are relatively similar in areas having the same LULC and topography pattern (Tran et al., 2022). This suggests that other farms can consider similar land use strategies and practices that were applied to this case study to improve the ecosystem services supply and environmental quality. More importantly, results illustrated in the case study may encourage the wider application of an ecosystem services approach at the farm scale. Considering that ecosystem services assessment for each farm is time-consuming and expensive, it is more feasible if this is done in a way that involves multiple farms and farmers (e.g., within a catchment) and in collaboration with local government agencies.

3.6. Conclusions

This study presents one of the first attempts to quantify the spatially explicit nature of landscape multifunctionality at a farm scale to provide information to support farmer decision making. The results show that the pattern of landscape multifunctionality is highly variable across the farmed landscapes, and the interaction between ecosystem services is complex, showing both synergy and trade-off relationships. Our study found a strong association between the ecosystem services provided by woody vegetation and wetlands. Also, most of the regulating/supporting and aesthetics services were compatible with the provision of timber and manuka honey production. In contrast, the main trade-off was found to be between ecosystem services associated with pasture production (stockfeed production, ease of farming, water supply) and all other services. This information provides effective land use options which can enhance multiple ecosystem services across the farmed landscape simultaneously. Also, information associated with the spatial pattern of ecosystem services provision enables a better understanding of the variation in the pattern of ecosystem services across the farm and therefore, allows the land manager to tailor decision making to the strengths and weaknesses of the landscape.

In addition to using a wide range of spatial analysis tools and methods, our study incorporated the views and preferences of the farmer into the process of mapping landscape multifunctionality and this might help to promote the applications of an ecosystem services approach to sustainable planning and management of farmed landscapes. This approach will enable landowners to have the capability to better adapt their future farming systems to the various environmental challenges such as soil erosion, water quality reduction, GHGs emissions, and biodiversity loss. This can also contribute to informing research and policy actions at other scales such as the catchment and regional scales to achieve sustainable development goals aimed at maintaining and promoting the long-term provision of multiple ecosystem services. Given that integrating ecosystem services concepts into decision-making is still limited in NZ (Greenhalgh and Hart, 2015), our study that demonstrates the necessities and advantages of an ecosystem services approach could promote the use of this approach by decision-makers in the future. Although the geographic focus of this study is a case study in NZ, we believe that the methodology and findings presented in our study can be broadly applied to other areas in the world because the challenges which are confronting hill country farms in NZ are typical of issues facing many farm systems worldwide.

Whilst the focus of this paper is more about quantifying landscape multifunctionality and the patterns and interactions of ecosystem services, the practical applications of the results to farmed landscape planning and management are not fully demonstrated. Therefore, our next step is to look at land use performance across the farm to optimise the land use mosaic to increase ecosystem services overall. We will use the results from this study to design scenarios for landscape changes, and model different scenarios based on different goals. We will then evaluate ecosystem services in alternative land use scenarios to support land management in agricultural landscapes.

Author Contributions: Duy X. Tran: Conceptualization, Methodology, Data collection, Formal analysis, Writing- original draft preparation, Visualization. Diane Pearson: Conceptualization, Writing - review & editing. Alan Palmer: Data collection, Writing - review & editing. John Lowry: Writing - review & editing; Visualization. David Gray: Writing - review & editing. Estelle J. Dominati: Writing - review & editing. All authors contributed to a portion of the research. The overall percentage contributed by Duy X. Tran is approximately 80% (see Appendix 1).

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Supplementary materials

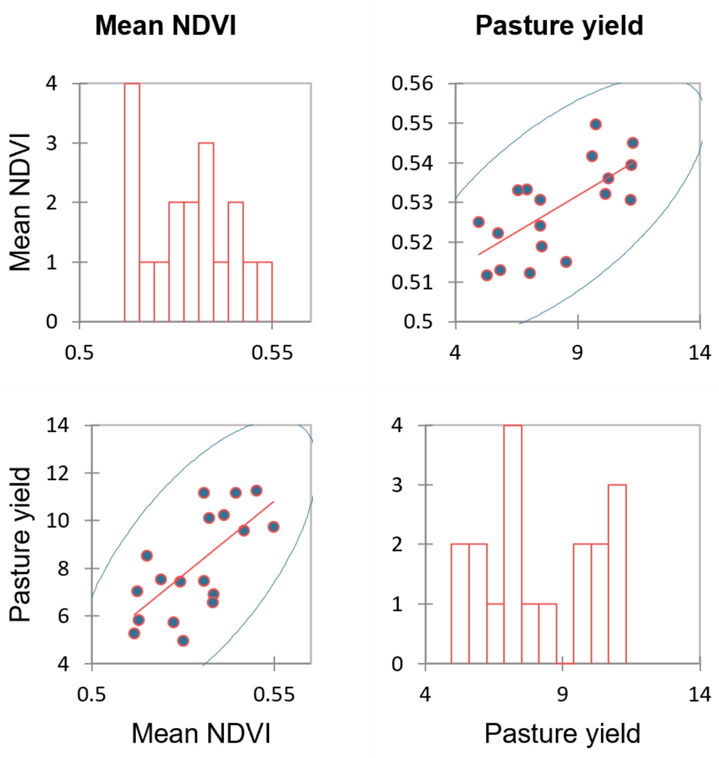

Figure S3. 1: Correlation between mean NDVI (5 years) and pasture yield (tonnes/ha/yr) by paddocks in the study area (*r = 0.697, p< 0.002*).

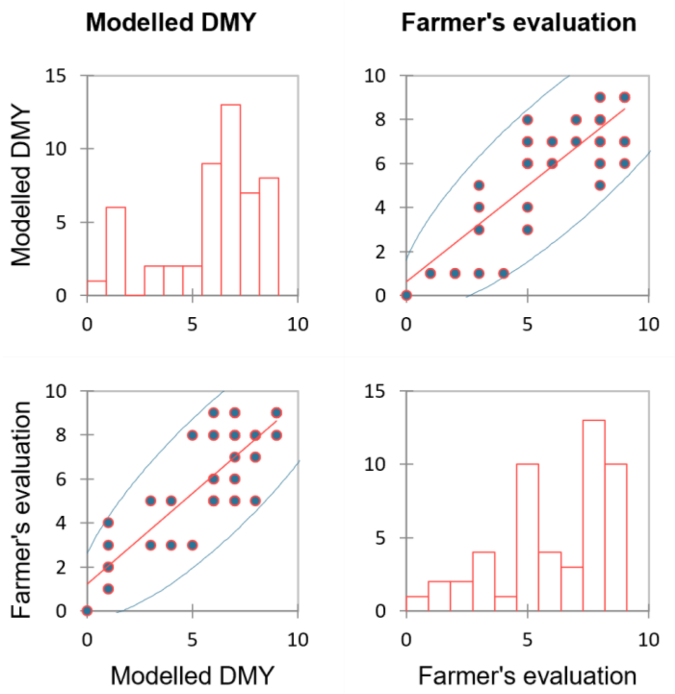

Figure S3. 2: Correlation between pasture yield ranking obtained from the model and evaluation by the farmer's experience ($r = 0.76$, $p < 0.0001$).

Table S3. 1: Location of pasture yield samples for the accuracy assessment

Samples ID	Lat	Long	DMY	DMY rank	Farmer's rank
0	-39.9559	175.684	1389	1	1
1	-39.9587	175.693	12500	9	9
2	-39.9495	175.691	12500	9	9
3	-39.9428	175.685	9722	5	3
4	-39.9513	175.685	8333	6	8
5	-39.9551	175.686	1389	1	1
6	-39.9628	175.681	11111	8	7
7	-39.9573	175.683	9722	7	8
8	-39.9568	175.689	9722	7	8
9	-39.9515	175.68	1389	1	2
10	-39.9585	175.679	1389	1	3
11	-39.9479	175.687	9722	7	5
12	-39.9602	175.685	9722	7	5
13	-39.9416	175.689	11111	8	5
14	-39.9567	175.68	8333	6	5
15	-39.9603	175.68	5556	4	3
16	-39.9577	175.688	11111	8	8
17	-39.9616	175.679	8333	6	6
18	-39.9491	175.687	12500	9	8
19	-39.9535	175.692	8333	6	8
20	-39.9441	175.688	9722	7	7
21	-39.9472	175.682	11111	8	8
22	-39.9473	175.689	11111	8	8
23	-39.9609	175.678	8333	6	9
24	-39.9418	175.681	5556	4	5
25	-39.9589	175.688	1389	1	4
26	-39.9594	175.684	8333	6	6
27	-39.9548	175.692	9722	7	10
28	-39.9511	175.683	6944	5	8
29	-39.9613	175.69	11111	8	8
30	-39.9598	175.682	4167	3	3

31	-39.9602	175.676	9722	7	9
32	-39.9611	175.684	9722	7	9
33	-39.9406	175.684	12500	9	10
34	-39.9397	175.684	0	0	0
35	-39.9525	175.693	12500	9	8
36	-39.9578	175.694	8333	6	5
37	-39.951	175.693	12500	9	10
38	-39.9529	175.681	9722	7	8
39	-39.9404	175.682	12500	9	10
40	-39.9556	175.68	1389	1	2
41	-39.9396	175.681	12500	9	10
42	-39.9508	175.686	9722	7	6
43	-39.9624	175.687	8333	6	5
44	-39.9436	175.692	8333	6	5
45	-39.9428	175.691	11111	8	7
46	-39.9493	175.689	9722	7	6
47	-39.9461	175.686	4167	3	5
48	-39.9434	175.68	9722	7	8
49	-39.9413	175.685	9722	7	5

Table S3. 2: Pairwise comparison matrix between categories of ecosystem services (landowner's weighting)

	Provisioning	Supporting	Landscape aesthetics
Provisioning	1.00	7.00	7.00
Supporting	0.14	1.00	1.00
Landscape aesthetics	0.14	1.00	1.00
Sum columns	1.29	9.00	9.00

Table S3. 3: Normalised pairwise comparison matrix calculated from Table S3.2

	Provisioning	Supporting	Landscape aesthetics	Criteria Weights
Provisioning	0.78	0.78	0.78	0.78
Supporting	0.11	0.11	0.11	0.11
Landscape aesthetics	0.11	0.11	0.11	0.11
Sum columns	1.00	1.00	1.00	1.00

Table S3. 4: Pairwise comparison matrix between provisioning ecosystem services (landowner's weighting)

	Stockfeed production	Timber production	Provision of manuka honey
Stock feed production	1.00	9.00	7.00
Timber production	0.11	1.00	0.33
Provision of manuka honey	0.14	3.00	1.00
Sum columns	1.25	13.00	8.33

Table S3. 5: Normalised pairwise comparison matrix for provisioning ecosystem services calculated from Table S3.4

	Stockfeed production	Timber production	Provision of manuka honey	Criteria Weights
Stockfeed production	0.80	0.69	0.84	0.78
Timber production	0.09	0.08	0.04	0.07
Provision of manuka honey	0.11	0.23	0.12	0.15
Sum columns	1.00	1.00	1.00	1.00

Table S3. 6: Pairwise comparison matrix between supporting ecosystem services (landowner's weighting)

	Erosion control	Water flow regulation	Carbon sequestration	Freshwater purification	Provision of natural habitat
Erosion control	1.00	1.00	5.00	1.00	5.00
Water flow regulation	1.00	1.00	3.00	0.33	5.00
Carbon sequestration	0.20	0.33	1.00	0.20	1.00
Freshwater purification	1.00	3.00	5.00	1.00	5.00
Provision of natural habitat	0.20	0.20	1.00	0.20	1.00
Sum columns	3.40	5.53	15.00	2.73	17.00

Table S3. 7: Normalised pairwise comparison matrix for supporting ecosystem services calculated from Table S3.6

	Erosion control	Water flow regulation	Carbon sequestration	Freshwater purification	Provision of natural habitat	Criteria Weights
Erosion control	0.29	0.18	0.33	0.37	0.29	0.29
Water flow regulation	0.29	0.18	0.20	0.12	0.29	0.22
Carbon sequestration	0.06	0.06	0.07	0.07	0.06	0.06
Freshwater purification	0.29	0.54	0.33	0.37	0.29	0.37
Provision of natural habitat	0.06	0.04	0.07	0.07	0.06	0.06
Sum columns	1.00	1.00	1.00	1.00	1.00	1.00

Table S3. 8: Pairwise comparison matrix between landscape aesthetics services (landowner's weighting)

	Ease of farming	Landscape diversity	Landscape naturalness
Ease of farming	1.00	1.00	5.00
Landscape diversity	1.00	1.00	5.00
Landscape naturalness	0.20	0.20	1.00
Sum columns	2.20	2.20	11.00

Table S3. 9: Normalised pairwise comparison matrix for landscape aesthetics services calculated from Table S3.8

	Ease of farming	Landscape diversity	Landscape naturalness	Criteria Weights
Easy of farming	0.45	0.45	0.45	0.45
Landscape diversity	0.45	0.45	0.45	0.45
Landscape naturalness	0.09	0.09	0.09	0.09
Sum columns	1.00	1.00	1.00	1.00

Table S3.10: PCA analysis results

Eigenvalues

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Eigenvalue	4.13	1.41	1.24	1.03	0.92	0.62	0.52	0.42	0.33	0.22	0.15
Variability (%)	37.54	12.80	11.28	9.41	8.34	5.65	4.77	3.86	2.97	2.04	1.35
Cumulative %	37.54	50.34	61.61	71.02	79.36	85.01	89.78	93.64	96.61	98.65	100.00

Factor loadings

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
SP	**-0.72**	-0.08	0.17	0.03	0.38	-0.24	0.31	-0.32	-0.21	0.08	-0.04
PT	0.23	**0.75**	-0.36	-0.33	-0.16	-0.07	0.20	-0.15	0.15	0.18	0.03
MH	**0.73**	-0.42	-0.06	0.13	-0.09	-0.19	0.25	-0.22	0.30	-0.18	-0.04
EC	0.28	0.27	**0.76**	0.07	-0.14	-0.47	-0.06	0.13	0.06	0.05	0.05
WR	**-0.62**	0.34	0.15	0.21	0.47	0.11	-0.27	-0.15	0.31	-0.04	-0.01
CS	**0.61**	**0.51**	-0.16	0.02	0.44	-0.09	0.15	0.22	-0.13	-0.24	-0.05
FW	0.17	0.21	-0.40	0.81	-0.19	-0.17	-0.13	-0.10	-0.11	0.05	0.01
NH	**0.85**	-0.21	-0.03	0.02	0.30	-0.02	-0.09	0.09	0.04	0.26	-0.23
EF	**-0.73**	-0.19	-0.22	0.25	0.13	-0.08	0.31	0.38	0.19	0.11	0.07
LD	**0.50**	0.20	**0.49**	0.36	-0.04	0.49	0.31	-0.03	-0.02	0.06	0.03
LN	**0.82**	-0.23	-0.10	-0.05	0.40	-0.02	-0.09	-0.07	-0.03	0.09	0.28

Significant values that meet r ≥ 0.5 are in bold.

Contribution of the variables (%)

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
SP	12.41	0.51	2.35	0.09	15.65	9.40	18.03	23.47	14.14	2.70	1.25
PT	1.24	40.14	10.33	10.22	2.88	0.75	7.80	5.37	7.10	13.70	0.45
MH	12.76	12.27	0.29	1.58	0.80	6.04	12.16	11.46	27.28	14.23	1.11
EC	1.91	5.15	46.30	0.44	2.09	35.63	0.75	4.02	0.98	1.20	1.53
WR	9.32	8.33	1.85	4.44	24.30	2.04	13.80	5.08	29.91	0.82	0.12
CS	8.88	18.28	2.16	0.03	21.00	1.43	4.15	11.21	5.17	26.15	1.55
FW	0.69	3.02	12.65	64.11	3.93	4.70	3.45	2.30	4.01	1.08	0.06
NH	17.53	3.22	0.08	0.04	9.97	0.05	1.50	2.01	0.59	29.75	35.25
EF	13.03	2.53	3.86	6.02	1.86	1.15	18.68	33.55	10.51	5.24	3.57
LD	5.99	2.73	19.31	12.75	0.17	38.72	18.15	0.25	0.09	1.35	0.49
LN	16.22	3.80	0.82	0.29	17.35	0.09	1.53	1.28	0.22	3.77	54.62

Squared cosines of the variables

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
SP	**0.51**	0.01	0.03	0.00	0.14	0.06	0.09	0.10	0.05	0.01	0.00
PT	0.05	**0.57**	0.13	0.11	0.03	0.00	0.04	0.02	0.02	0.03	0.00
MH	**0.53**	0.17	0.00	0.02	0.01	0.04	0.06	0.05	0.09	0.03	0.00
EC	0.08	0.07	**0.57**	0.00	0.02	0.22	0.00	0.02	0.00	0.00	0.00
WR	**0.38**	0.12	0.02	0.05	0.22	0.01	0.07	0.02	0.10	0.00	0.00
CS	**0.37**	0.26	0.03	0.00	0.19	0.01	0.02	0.05	0.02	0.06	0.00

FW	0.03	0.04	0.16	**0.66**	0.04	0.03	0.02	0.01	0.01	0.00	0.00
NH	**0.72**	0.05	0.00	0.00	0.09	0.00	0.01	0.01	0.00	0.07	0.05
EF	**0.54**	0.04	0.05	0.06	0.02	0.01	0.10	0.14	0.03	0.01	0.01
LD	**0.25**	0.04	0.24	0.13	0.00	0.24	0.10	0.00	0.00	0.00	0.00
LN	**0.67**	0.05	0.01	0.00	0.16	0.00	0.01	0.01	0.00	0.01	0.08

Definitions: Stockfeed production (SP), Provision of timber (PT), Provision of manuka honey (MH), Erosion control (EC), Water flow regulation (WR), Carbon sequestration (CS), Freshwater purification (FW), Natural habitat (NH), Ease of farming (EF), Landscape diversity (LD), Landscape naturalness (LN). Values in bold correspond for each variable to the factor for which the squared cosine is the largest.

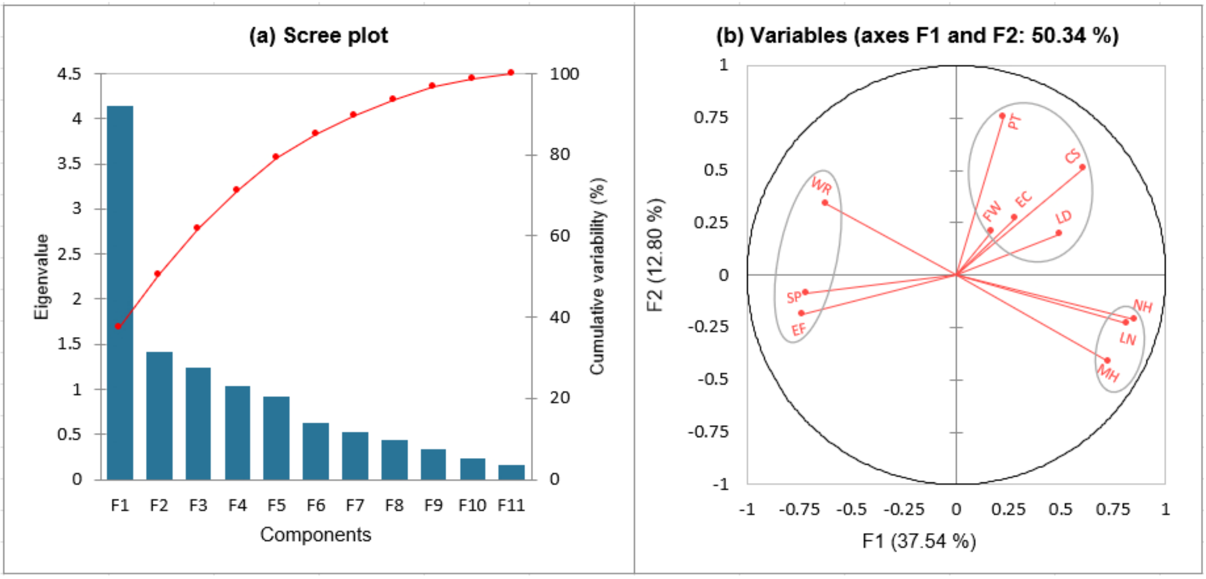

Figure S3. 3: Principal component analysis (PCA) of ecosystem services for the case study farm (N = 416 grid cells). The scree plot (a) shows the relationship between the increasing principal components of each metric and the cumulative proportion of variance explained. The PCA presents the first two components showing bundles of ES and their association to the components (b): Stockfeed production (SP), Provision of timber (PT), Provision of manuka honey (MH), Erosion control (EC), Water flow regulation (WR), Carbon sequestration (CS), Provision of Freshwater purification (FW), Natural habitat (NH), Ease of farming (EF), Landscape diversity (LD), Landscape naturalness (LN).

4. Quantifying spatial non-stationarity in the relationship between landscape structure and the provision of pasture productivity, sediment retention, and water yield: an example in the New Zealand hill country

Abstract

Knowing how landscape structure affects the provision of ecosystem services (ES) is an important first step toward better landscape planning. Because landscape structure is often heterogenous across space, modelling the relationship between landscape structure and the provision of ES must account for spatial non-stationarity. This paper examines the relationship between landscape structure and the provision of ES using a hill country and steep-land case study in New Zealand. Indicators derived from land cover and topographical data such as Largest Patch Index (LPI), Contrast Class Edge (CCE), Edge Density (ED), and Terrain slope (SLOPE) were used to examine the landscape's structure and pattern. Measures of pasture productivity, soil erosion control, and water supply were derived with InVEST tools and spatial analysis in a GIS. Multiscale Geographically Weighted Regression (MGWR) was used to evaluate the relationship between indicators of landscape structure and the provisioning of ES. Other regression models, including Ordinary Least Square (OLS) and Geographically Weighted Regression (GWR), were carried out to evaluate the performance of MGWR. Results showed that landscape patterns significantly affect the supply of all mapped ES, and this varies across the landscape, dependent on the pattern of topographical features and land cover pattern and structure. MWGR outperformed other OLS and GWR in terms of explanatory power of the ES determinants and had a better ability to deal with the presence of spatial autocorrelation. Spatially and quantitatively detailed variations of the relationship between landscape structure and the provision of ES provide a scientific basis to inform the design of sustainable multifunctional landscapes. Information derived from this analysis can be used for spatial planning of farmed landscapes to promote multiple ES which meet multiple sustainable development objectives.

Keywords: Landscape planning; Land use land cover change; Multiscale Geographically Weighted Regression (MGWR); Sustainable agricultural development; Farm environmental planning.

Based on:

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4.1. Introduction

Land use and land cover (LULC) change, especially deforestation and land clearing associated with agricultural intensification, has simplified landscape functions and services other than those associated with food provisioning. This has in turn reduced the capability of agricultural landscapes to mitigate change and disturbances (Dainese et al., 2017; Paredes et al., 2021; Poveda et al., 2012) and has created a variety of negative impacts on the environment such as soil erosion, water pollution, and biodiversity loss (Kanianska, 2016). One potential solution that could help address the environmental sustainability challenges presented by farming systems dominated by monocultures is to move towards the creation of multifunctional agricultural landscapes which are capable of delivering multiple ecosystem services (Nieto-Romero et al., 2014). By restoring important ecosystem functions and services within the farm system through planning and design of the functionality within the system, there is an opportunity to mitigate environmental problems whilst ensuring socio-economic demands associated with production are realised (McGranahan, 2014; Vihervaara et al., 2010).

In designing multifunctional landscapes, it is essential to determine the best landscape configuration where different LULC types co-exist, and the LULC pattern is appropriately arranged to support multiple landscape functions and services (Kirchner et al., 2015). To assist with this process, it is useful to quantify the relationship between landscape structure and the supply of ecosystem services under different land uses and management (Lamy et al., 2016). This knowledge helps inform options for potential modification to the LULC to optimise land use and management in the most suitable places to attain desired ecosystem services. For example, if a desired outcome is to decrease soil erosion, what changes to landscape structure need to be made to increase the supply of sediment retention service?

A technique commonly adopted to determine the relationship between landscape pattern and the provision of ecosystem services is the Ordinary Least Squares (OLS) regression model (Duflot et al., 2017; Lamy et al., 2016; Redhead et al., 2020). Other models such as stepwise regression, Pearson correlation analysis, and Partial Least Squares Regression (PLSR) model have also been used to illustrate this relationship (Xia et al., 2021; Yohannes et al., 2021). These models assume that the relationship between dependent and explanatory variables is stationary (i.e., constant) across the study area so they are also called global models (Fotheringham et al., 1997; Myers, 1990). However, because the distribution of landscape pattern and ecosystem services provision is heterogeneous across space (Grêt-Regamey et al., 2014), global models may not accurately represent this relationship in cases where there is local spatial variability (Su et al., 2014; Degefu et al., 2021). When the relationship between explanatory variables and response variables varies across space the relationship is referred to as non-stationary (Brundson et al., 1996). In such cases, a spatial regression model suited to modelling heterogeneous spatial variables is more appropriate.

Various types of spatial regression models, including Geographical Weighted Regression (GWR), Spatial Error Model (SEM), Spatial Lag Model (SLM), and Spatial Autoregressive Model (SAM) have been used to quantify the spatial dependency and association between the provision of ecosystem services and underlying factors (Degefu et al., 2021; Fernández, 2019; Labrière et al., 2015; Sannigrahi et al., 2020). Among these models, GWR has been shown to be a more efficient method than others in explaining model variance while addressing spatial non-stationarity in ecosystem services determinants (Dahal et al., 2021; Gao et al., 2021; Jarvis et al., 2017; Li et al., 2017; Sannigrahi et al., 2020; Sun et al., 2020). However, a limitation of GWR is that it assumes that stationarity in the relationship between explanatory variables and dependent variables varies at the same spatial scale (Fotheringham et al., 2017). Often, however, the scale of these processes varies (Su et al., 2020). For example, the effects of terrain slope or aspect on vegetation growth may be influential at a fine scale (e.g., paddock scale (10s of metres)), whereas the impacts of rainfall on vegetation growth are often more influential at a broader scale (e.g., farm scale (100s of metres)). This drawback of GWR is thought to restrict the capability of the model to capture the nature of geographic processes because the relationship of each explanatory variable to the response variable is usually not independent of geographic scale (Fotheringham et al., 2017).

Multiscale Geographically Weighted Regression (MGWR) is an extended version of GWR developed to address multi-scale relationships between explanatory and response variables (Oshan et al., 2019). In addition to the advantages inherited from GWR, the novelty of MGWR is that it allows the relationship between the corresponding and dependent variables to be modelled at multiple spatial scales so the model can better characterise real-world processes (Oshan et al., 2019). MGWR has recently been successfully employed to investigate spatial non-stationarity in several applications such as the incidence of COVID-19 (Iyanda et al., 2020; Mollalo et al., 2020), housing prices

(Hong & Yoo, 2020), and tourism (Shabrina et al., 2020). Applications of MGWR in landscape sciences are still relatively under explored.

To date, many studies associated with landscape planning and management, based on ecosystem services have been conducted at catchment, regional, or national scales, whilst local scales or farm-scale studies have been limited (Dang et al., 2021; Longato et al., 2021; Malinga et al., 2015; Tran et al., 2020). Although findings from coarser scale studies provide useful information for regional (or nationwide) landscape planning, management, and policy formulation, they usually are not accurate enough to be used for farm-scale decision making and farm management (Quinn et al., 2013). Although a few farm-scale studies associated with ecosystem services assessment have been conducted recently, it is notable that (1) the focus on quantifying the relationship between landscape composition and configuration and the provision of ecosystem services is neglected, and (2) results from most current studies are often reported for the whole farm, whereas spatial heterogeneity in ecosystem services across the farm are not well presented (Boeraeve et al., 2020; Bullock et al., 2021; Campos et al., 2019; Dominati et al., 2021).

This paper focuses on a hill country and steep-land farm in New Zealand (NZ) as a case study. NZ hill country and steep-land occupies 10 million ha (~37%) of the total NZ land area (Cameron, 2016). In NZ hill country, native forest was converted extensively to pastoral land between 1860 and 1920 (Blaschke et al., 1992). Changes to land cover have favoured the supply of provisioning services (meat, fibre, and wood) over the supply of other essential services such as supporting and regulating services (e.g., erosion control, nutrient retention, carbon sequestration, forest biodiversity). Supporting and regulating services play a fundamental role in the resilience of farm systems themselves and the resilience of the landscape in dealing with environmental challenges resulting from agricultural intensification such as nutrient leaching, soil erosion, water pollution, and biodiversity decline (Tittonell, 2014). One solution to address environmental issues challenging NZ hill country is the creation of "multifunctional agricultural landscapes" where multiple ecosystem services are restored and revitalised (Tran et al., 2020). Being able to quantify the relationship between the provision of ecosystem services and landscape structure is an essential first step toward the design of multifunctional landscapes as this can help inform which areas of land can be converted to other LULCs.

4.2. Material and methods

4.2.1. Study area

A sheep and beef farm situated in the Manawatu-Wanganui region of the North Island, NZ, was selected for this study (Figure 4.1). The farm covers 380 ha of various slope classes: flat to undulating land (0 – 7°) (10.5%), rolling land (8 -15°) (22.6%), hill country (16 - 25°) (39.8%), and steep-land (> 25°) (27.1%) and is 330m above sea level with elevation ranging between 201 and 420m. Rock types include colluvium over alluvial gravels in the flat land and dominantly massive mudstone and unconsolidated to weakly consolidated sands in the hill and steep-land.

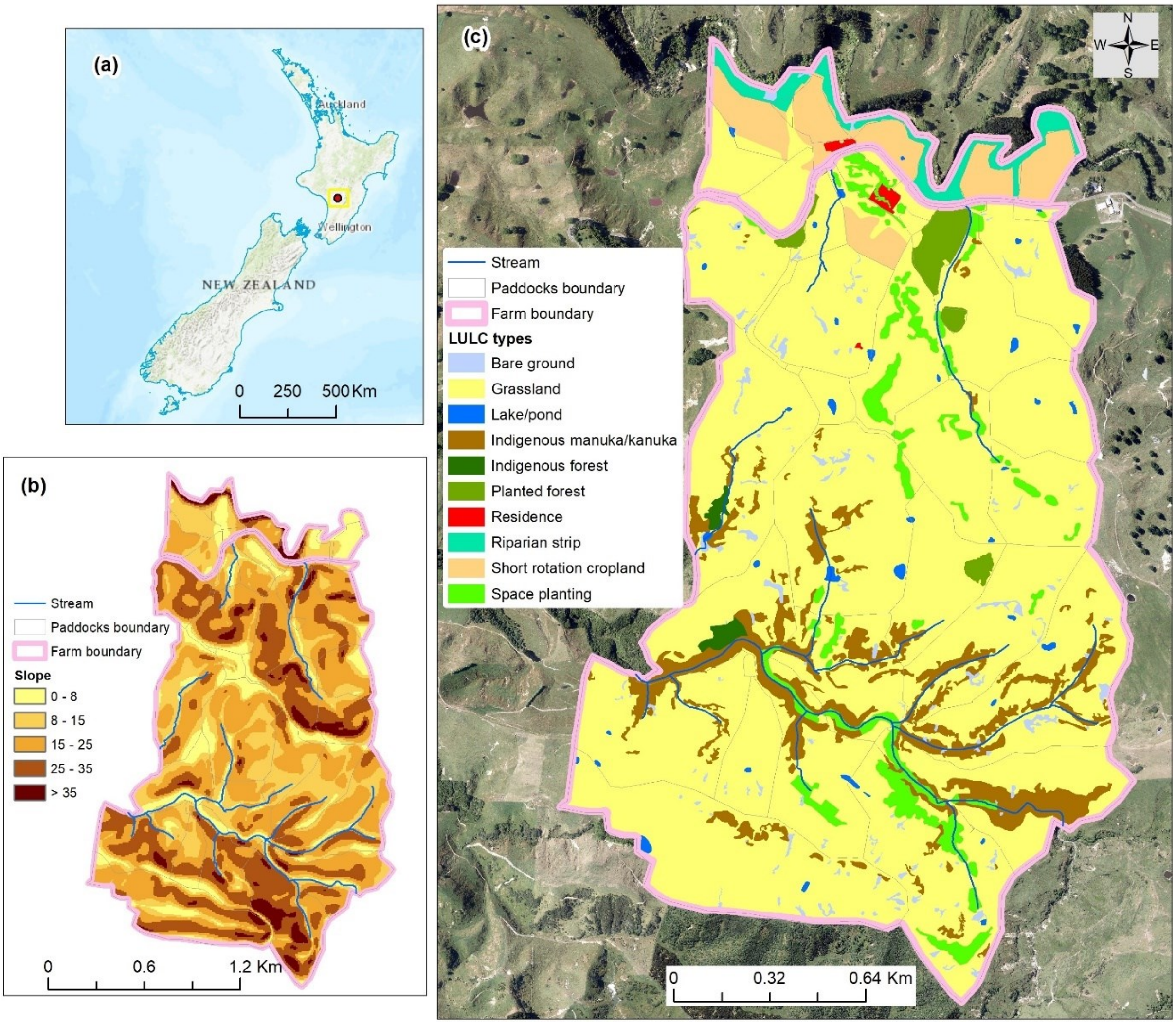

Figure 4.1. Location of the farm in New Zealand (a); slope map (b); and land use land cover (LULC) map in 2020 (c) of the farm. Data sources: Location and LULC data of the farm were obtained from field survey and mapping; slope classes were classified from DEM data downloaded from Land Information New Zealand data portal.

Average annual temperature in the Pakihikura region where this farm is located is 12 °C, and rainfall is 1140 mm. The farm is situated on typical hill country and steep-land which is heterogeneous in topographic features (e.g., slope groups, landforms) and land use capability (LUC). The LUC assessment includes the Land Resource Inventory information: geology, soil, slope, erosion and vegetation mapped in the field (Lynn et al., 2009). Major soil groups in the study site are Pallic Soils (Ustepts), followed by Brown Soils (Udepts), and Gley Soils (Aquepts). A farm in this landscape requires a range of different land use and management practices to optimise the use of all landscape resources. Sustainable agricultural practices are increasingly promoted in the hill country to reduce environmental impacts and mitigate climate change.

4.2.2. Data collection and processing

Relevant data were collected from different sources (Table 4.1). High-resolution aerial photos (~1 meter) obtained from Land Information New Zealand (LINZ) and Google Earth (GE) image were used to classify ten LULC classes. These were residence/farm infrastructure, planted forest, space planting, riparian strip, indigenous forest, indigenous manuka/kanuka, grassland, short rotation cropland, water bodies (lake/pond), and bare ground (Figure 4.1c).

Table 4.1: Data and information used for the study

Data	Data types/resolution	Sources
Land use land cover	Shapefile, 1m	Classified from aerial imagery (LINZ) and Google Earth Imagery
Digital Elevation Model (DEM)	Raster, 8m	LINZ
Slope, watershed, stream	Raster, 8m	Model from DEM data
Climate data (precipitation, evapotranspiration)	Census, point dataset	NIWA
Boundary (farm, paddock)	Shapefile	Horizons
Farm stocking information	Census	Survey questionnaires
Land use capability and soil mapping	Shapefile, census	Farm scale land resources surveying
Vegetation indices (NDVI)	Raster, 10m	Google Earth Engine

LINZ is Land Information New Zealand, NIWA is National Institute of Water and Atmospheric Research (New Zealand).

Ninety-three soil profile samples were described to map the attributed soil types and associated soil characteristics (e.g., soil classes, soil types, texture, drainage). The first step of the soil survey was to understand and map the geology. Apart from the broad ridge tops and colluvial footslopes, the soils are formed directly into the bedrock.

Afterwards, we selected small sub-catchments in which clusters of soil profiles were dug to sample each landscape position in a manner similar to Tonkin (1994). We then tested the pattern that emerged by describing profiles farther afield, taking into account slope, aspect, and erosion history. Main soil boundaries were determined and drafted during the fieldwork then were refined and additional boundaries were added using the Georeferencing and Digitizing tools in ArcGIS (version 10.8). High resolution aerial photo and slope and aspect maps were used as base information to determine and adjust soil boundaries. Additional information relating to farm management such as animal types, stocking rate, and stock distribution was provided by the land manager through participation in a questionnaire survey. The survey questions are listed in the Table S4.1. Sentinel 2 vegetation data (Normalised Difference Vegetation Index (NDVI)) from 2015 to 2020 were obtained from Google Earth Engine.

4.2.3. Spatially explicit ecosystem services

Ecosystem services that were quantified include pasture productivity, sediment retention, and water yield. Although the NZ hill country provides other ecosystem services (Dominati et al., 2014), we focused on three ecosystem services that have the most direct impact on hill country farm systems. These were quantified using InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models and spatial analysis tools in ArcGIS. InVEST includes spatially-explicit models to quantify a wide range of ecosystem services at various scales of analysis (i.e., multiple spatial resolutions) (Sharp et al., 2020). Pasture productivity is the most important provisioning service in the NZ hill country landscape due to the dominance of pasture-based farming (e.g., 70% of the NZ grassland or 18% of NZ's total area) (Kerr, 2016). Spatially quantifying potential pasture productivity is necessary as the pasture yield can be highly variable within a single paddock and understanding this spatial variation allows the application of more effective pasture management (Dennis et al., 2015). This study generated pasture yield maps for the study farm by applying an estimated approach that integrates livestock carrying capacity and a remotely sensed vegetation index (NDVI). Information associated with stock units, stock carrying capacity, and pasture utilisation were used to estimate the annual dry matter yield (DMY) by paddock (See Beef and LambNZ (2021) for methods). Then, the relationship between DMY and long term NDVI in the pastoral area was analysed, the correlation between the two ($r=0.7$, $p<0.05$) demonstrated the relevance of using NDVI for pasture yield estimation (See Amies et al., 2021 for more details).

Soil erosion is one of the most critical environmental issues in NZ hill country, especially on steep-land (Basher, 2013). Understanding the relationship between landscape pattern and sediment retention is central to reducing soil erosion in hill country because this knowledge can be used for land use planning and targeting management practices that optimise the capability of the landscape to reduce sediment export to streams and other waterways (Jones et al., 2008). Overland sediment retention defined as "the difference between sediment export from the bare soil and export from the actual land cover class" was estimated by using the InVEST Sediment Delivery Ratio (SDR) model (Hamel et al., 2015). This model computes annual soil loss from each pixel using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and calculates SDR, which is the proportion of actual soil loss reaching the stream. InVEST SDR model inputs were DEM, LULC, soil texture, and precipitation. The result is expressed as tonnes of sediment retained for each cell, or total sediment retained by each watershed/sub-watershed.

The quantity and pattern of water flow from hill country can significantly affect nutrient and sediment loss, and therefore influence its capacity to provide quality freshwater for human consumption and agricultural production in the lower catchment (Ausseil et al., 2013; Quinn et al., 1997). An understanding of the relationship between water supply and landscape pattern on hill country may provide useful information to reduce the negative impacts of agricultural production on water quality. The average annual water yield for the farm was calculated using the water balance model incorporated in the InVEST Annual Water Yield tool (Tallis et al., 2011). This tool estimates water yield using annual precipitation and potential evapotranspiration, a DEM, soil depth, land cover and land use characteristics (Tallis et al., 2011).

Results obtained from these models are GIS rasters (10m resolution) showing sediment retention, pasture yield, and water yield per hectare for each pixel (Figure 4.2). These derived ecosystem services were the dependent variables for the regression analysis. Absolute ecosystem services values were normalised to a 0-1 scale, with higher values representing the greater supply of the ecosystem services.

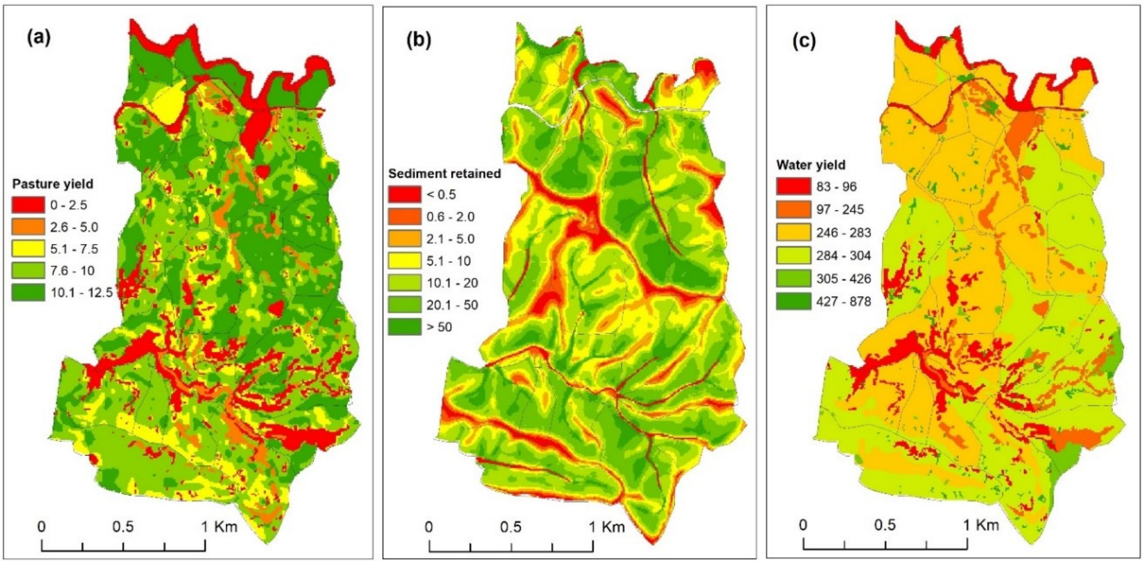

Figure 4.2. Spatial patterns of ecosystem services provision in the study area: (a) Pasture yield (tonnes DM ha^{-1} year^{-1}), (b) Sediment retention (tonnes ha^{-1} year^{-1}), and (c) Water yield (mm ha^{-1} year^{-1}).

4.2.4. Landscape structure indicators

LULC data was used to derive landscape metrics for landscape composition and configuration (see McGarigal, 2017 for more details). Six landscape structure indicators are considered explanatory factors influencing the supply of ecosystem services. These were: Largest Patch Index (LPI), Edge Contrast Index (CCE), Edge Density (ED), Diversity (SHDI), Slope (SLOPE), and Distance to stream (DIST) (Table 4.2). These indicators were derived using Zonalmetrics tool (Adamczyk and Tiede, 2017).

Table 4.2: A list of the indicators used to present landscape structure pattern maps

Indicators	**Description**
Largest Patch Index (LPI)	"Percentage of the landscape comprised by the largest patch of the corresponding LULC class" ($0 < \text{LPI} < 100$)
Contrast Class Edge (CCE)	"Percentage of the edge length of the focus class shared with contrast classes within the statistical zone"
Edge Density (ED)	"Total length of edge of a certain LULC class per unit area" (m/ha). ED ≥ 0, without limit
Diversity (SHDI)	"Shannon diversity index (SHDI) per zone, based on the selected classes".
Terrain slope (SLOPE)	Slope degree of LULC class
Distance to stream (DIST)	The Euclidean distance from a pixel to nearest stream

Edge Density (ED) and Largest Patch Index (LPI) are common indicators used to characterise landscape composition (Sertel et al., 2020), whilst Edge Contrast Index (CCE) is an indicator of landscape configuration (Cushman et al., 2008), and Shannon diversity index (SHDI) is commonly used to evaluate landscape heterogeneity (Perović et al., 2015). In this study, LPI and ED were calculated for agricultural land cover (cropland and grassland) to measure the dominance or fragmentation of agricultural land. For the Edge contrast index (CCE), we assumed that the *focus class* is agricultural land cover, and the *contrast class* is tree cover such as planted forest, riparian strip, space planting, and indigenous woody vegetation. This is because the configuration of these two land cover classes is expected to be most related to the provision of ecosystem services. In addition to these metrics, degree of terrain slope (SLOPE) and distance to stream (DIST) were used because of the important role of topography in sediment retention (Woznicki et al., 2020) and pasture production (Radcliffe, 1982). Landscape structure indicator maps were derived using the Zonalmetrics tool developed by Adamczyk and Tiede (2017) and ArcGIS spatial analyst toolbox (version 10.8) (Figure 4.3).

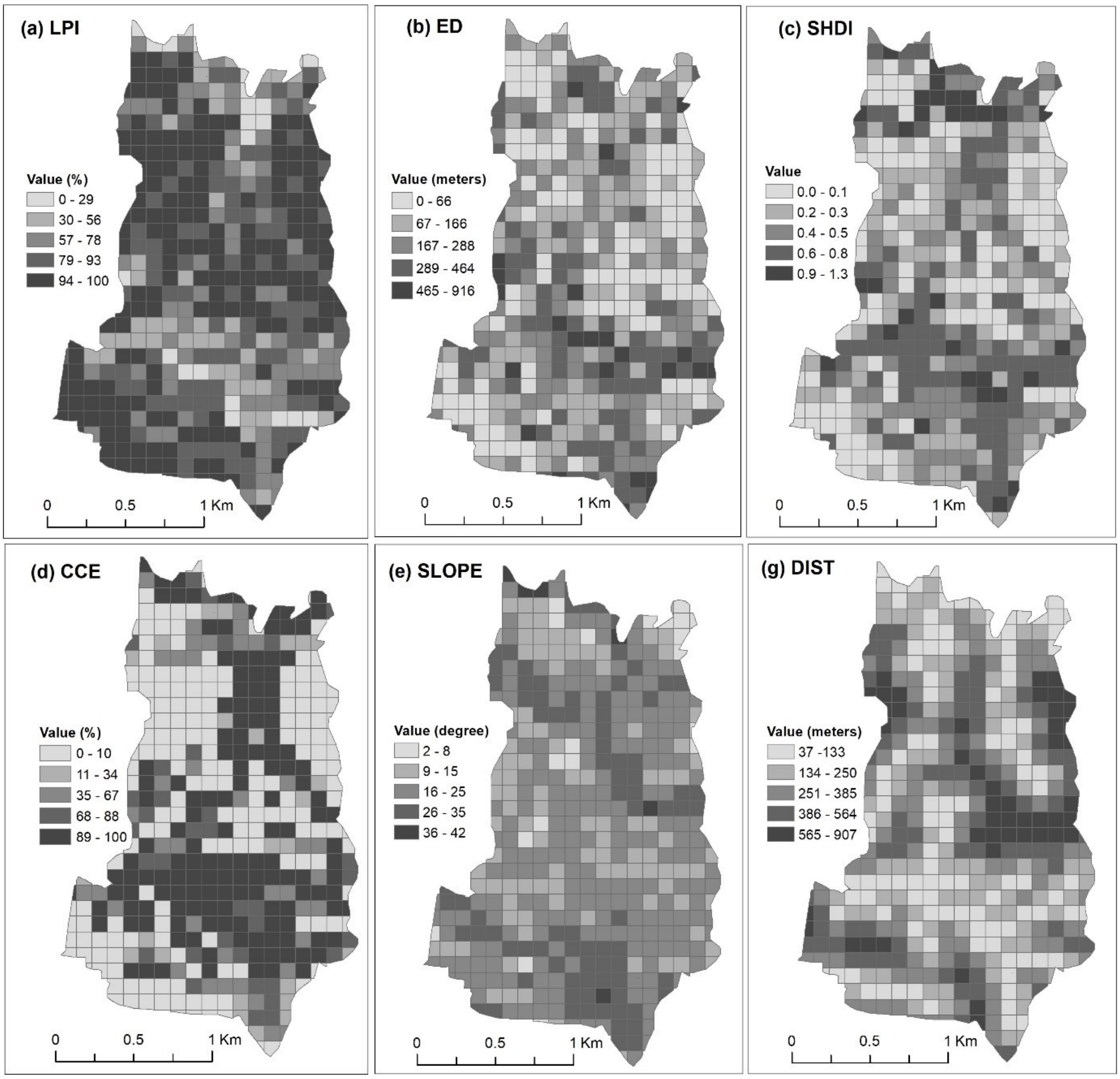

Figure 4.3. Landscape structure pattern indicators: (a) Largest Patch Index, (b) Edge density, (c) Landscape diversity (d) Contrast class edge, (e) Slope degree, and (g) Distance to stream.

4.2.5. Geographic unit of analysis and exploratory regression

One-hectare grid cells were used for the geographical unit of analysis (i.e., used as the zones for the zonal statistics and zonal metrics analysis). A 100 x 100 m cell was deemed appropriate because it is larger than the minimum land mapping unit in the LULC data (0.1 ha). Using a geographic unit larger than the land mapping unit assured heterogeneity within most geographic units. In other words, the size of geographic unit used in this study enabled capturing edges (landscape configuration) and having mixed LULC classes (landscape composition) within a unit. Moreover, a value of 100 m is a common resolution for environmental modelling and site characterisation as well as a common geographic unit used in local scale analysis (McCarthy et al., 2021; Powers et al., 2020). As with the ecosystem services variables (pasture productivity, sediment retention, and water supply), the absolute values for the explanatory variables were normalised to range between 0 and 1.

Exploratory regression was conducted in ArcGIS (version 10.8). This was to evaluate the suitability of the landscape structure indicators as potential explanatory variables for use in the regression analysis with each of the ecosystem services variables (productivity, sediment retention, and water supply). Exploratory regression identifies statistically significant explanatory variables, multicollinearity among explanatory variables, normally distributed residuals, and the spatial autocorrelation of model residuals. For instance, landscape structure variables that are statistically significant at the 95% confidence level ($p < 0.05$) and have variance inflation factors (VIF) below the threshold of 5 (Menard, 2001) were selected in our study. The exploratory regression applies this wide range of criteria to determine the most appropriate regression model. Using this technique is advantageous over other methods such as stepwise regression that normally use prediction performance (i.e., *Adjusted* R^2 values) to select the appropriate regression model (Nathans et al., 2012; Rosenshein et al., 2011). The six landscape structure variables were found suitable for regression analysis, although spatial autocorrelation in model residuals was present.

4.2.6. Multi-scale Geographically Weighted Regression

Geographically Weighted Regression (GWR) is described as (Fotheringham et al., 2017):

$$y_i = \sum_{j=0}^{m} \beta_j(u_i, v_i) x_{ij} + \varepsilon_i \qquad (1)$$

where (u_i, v_i) is “the spatial location of the ith observation”, y_i is “the response variable”, x_{ij} is “the jth explanatory variable", $\beta_j(u_i, v_i)$ is “the j coefficient”, m is “the number of predictor variable", and ε_i is "the random error term". By adding the location parameter to produce the local coefficients to account for spatial non-stationarity, GWR is seen as a significant improvement over traditional global regression (e.g., OLS) and spatial regression models (e.g., simultaneous autoregressive model and conditional autoregressive model) (Fotheringham & Oshan, 2016).

Multiscale Geographically Weighted Regression, an extension of GWR, is used to consider the conditional relationships between the response and predicted variables. Variation at different spatial scales across the study area is achieved by using several bandwidths instead of a single bandwidth (Yu et al., 2020). MGWR equation is presented as (Oshan et al., 2019):

$$y_i = \sum_{j=0}^{m} \beta_{bwj}(u_i, v_i)x_{ij} + \varepsilon_i \tag{2}$$

where bwj in β_{bwj} is "the bandwidth used for calibration of the jth conditional relationship", and the rest of the parameters are the same as Eq. (1). See Oshan et al. (2019) for further explanation on the bandwidth selection and model calibration processes.

Multiscale Geographically Weighted Regression was used to quantify the effects of landscape structure and pattern on the provision of ecosystem services (i.e., pasture yield, sediment retention, and water yield). Three MGWR models were created, one for each of the landscape provision services as the response variable, with the six landscape structure indicators as the explanatory variables. OLS regression and GWR were also performed with common statistical diagnostics such as adjusted R^2, corrected Akaike Information Criterion (AICc), and Global Moran's I, in order to compare their performance to the MGWR model. For instance, when comparing two types of regression model, corrected Akaike Information Criterion (AICc) measures the regression model's performance on the basis that the model with the lower AICc (e.g., more than 3) is considered as a better model (Lee & Ghosh, 2009). Global Moran's I quantifies spatial autocorrelation of the residuals. If spatial autocorrelation in the regression residuals is statistically significant, it indicates misspecification or a missing key explanatory variable in the model (Andy, 2005; Cavanaugh, 1997).

4.3. Results

4.3.1. Statistical diagnostics of the regression analysis

OLS regression provides information about the global relationship between landscape structure indicators and ecosystem services and therefore is useful baseline information from which to better understand the MGWR results. Table 4.3 provides summary statistical information about the relationship between landscape structure and the provision of ecosystem services obtained from OLS model. R^2 values are 0.800, 0.434, and 0.656, indicating the selected variables explain 80%, 43.4%, and 65.6% of the variation of pasture yield, sediment retention, and water yield across the study area, respectively.

Table 4.3: Summary statistics from the OLS model after modelling the relationship between landscape structure on (a) Pasture yield, (b) Sediment retention, and (c) Water yield

Pasture yield (a)			**Sediment retention (b)**			**Water yield (c)**		
Variables	β	VIF	Variables	β	VIF	Variables	β	VIF
Intercept	0.000	n/a	Intercept	0.000	n/a	Intercept	0.000	n/a
LPI**	0.878	1.65	LPI*	-0.104	1.65	LPI**	0.847	2.19
ED**	-0.107	1.25	ED**	-0.116	1.25	ED*	0.092	2.17
CCE**	0.148	1.52	CCE*	0.117	1.52	CCE**	-0.308	1.80
SLOPE**	-0.064	1.03	SLOPE**	0.535	1.03	SHDI**	0.450	4.17
DIST*	0.060	1.41	DIST**	-0.266	1.41	DIST**	0.115	1.40
$R^2 = 0.800$			$R^2 = 0.434$			$R^2 = 0.656$		

*Definitions: LPI is Largest Patch Index, ED is Edge Density, CCE is Edge Contrast Index, SHDI is Shannon Diversity Index, SLOPE is degree of terrain slope, DIST is Distance to stream, β is the regression coefficients, VIF is the variance inflation factor; Variable's significance (*p< 0.05; ** p < 0.01).*

Table 4.3a reveals that the most significant variable is the largest patch index (LPI) which shows a strong positive relationship with the pasture yield, followed by the contrast between agricultural land cover and tree cover (CCE), and distance to the stream (DIST). In contrast, the variables that have a negative relationship with the pasture yield are edge density (ED) of agricultural land and degree of terrain slope (SLOPE). The relationship between landscape pattern and overland sediment retention is demonstrated in Table 4.3b. The strongest positive and negative relationship is found in relation to the SLOPE variable, whereas the most significant inverse relationship is seen in the DIST factor. In contrast, the capacity of the landscape to retain sediment is less efficient in a landscape with more dominance of agricultural land cover. Regarding the role of landscape pattern on the water supply (Table 4.3c), all variables but the CCE are positively correlated to water yield.

Model diagnostics for OLS, GWR, and MGWR are presented in Table 4.4. Higher adjusted R^2 values in MGWR (0.912, 0.531, and 0.778) compared to OLS (0.798, 0.427, and 0.652) and GWR (0.899, 0.485, and 0.783) imply that MGWR can explain a greater proportion of the total variation in ecosystem services supply in the study area. MGWR also resulted in the lowest AICc/AIC scores and global Moran's I values among the regression models.

Table 4.4: A comparison of the model's performance between global and local regression models

	Pasture yield			**Sediment retention**			**Water yield**		
	OLS	***GWR***	***MGWR***	***OLS***	***GWR***	***MGWR***	***OLS***	***GWR***	***MGWR***
AIC	522.999	304.461	248.616	955.554	924.110	897.678	748.650	622.469	611.509
AICc	525.273	354.503	300.176	957.829	925.987	903.280	750.925	669.919	633.220
Adjusted R^2	0.798	0.899	0.912	0.427	0.485	0.531	0.652	0.783	0.778
Moran's I	0.238	0.010	-0.012	0.120	0.050	-0.018	0.157	-0.010	-0.026
p-value	0.000	0.825	0.5234	0.000	0.000	0.284	0.000	0.612	0.104

Definitions: AIC is Akaike Information Criterion, AICc is the corrected Akaike Information Criterion, Moran's I is the spatial autocorrelation of residual in regression models.

4.3.2. Spatial relationship between ecosystem services and landscape pattern

Figure 4.4 presents maps of MGWR beta coefficients for the landscape indicator variables. Figure 4.4a shows the relationship between landscape structure variables and productivity. LPI coefficients at the north end of the farm are high and gradually decline toward the south end of the farm. For ED, a negative relationship exists over most of the farm and the lowest negative coefficients are in the central part, whereas a small area showing a positive trend is seen in the north-central area of the farm. The spatial pattern of CCE is similar to that of LPI in which the coefficients tend to decrease toward the south of the farm. It is notable that the pattern of SLOPE and DIST coefficients is more heterogenous, and the relationship is more complicated than other factors, in the sense that both positive and negative relationships are found, and they are dispersed across the landscape.

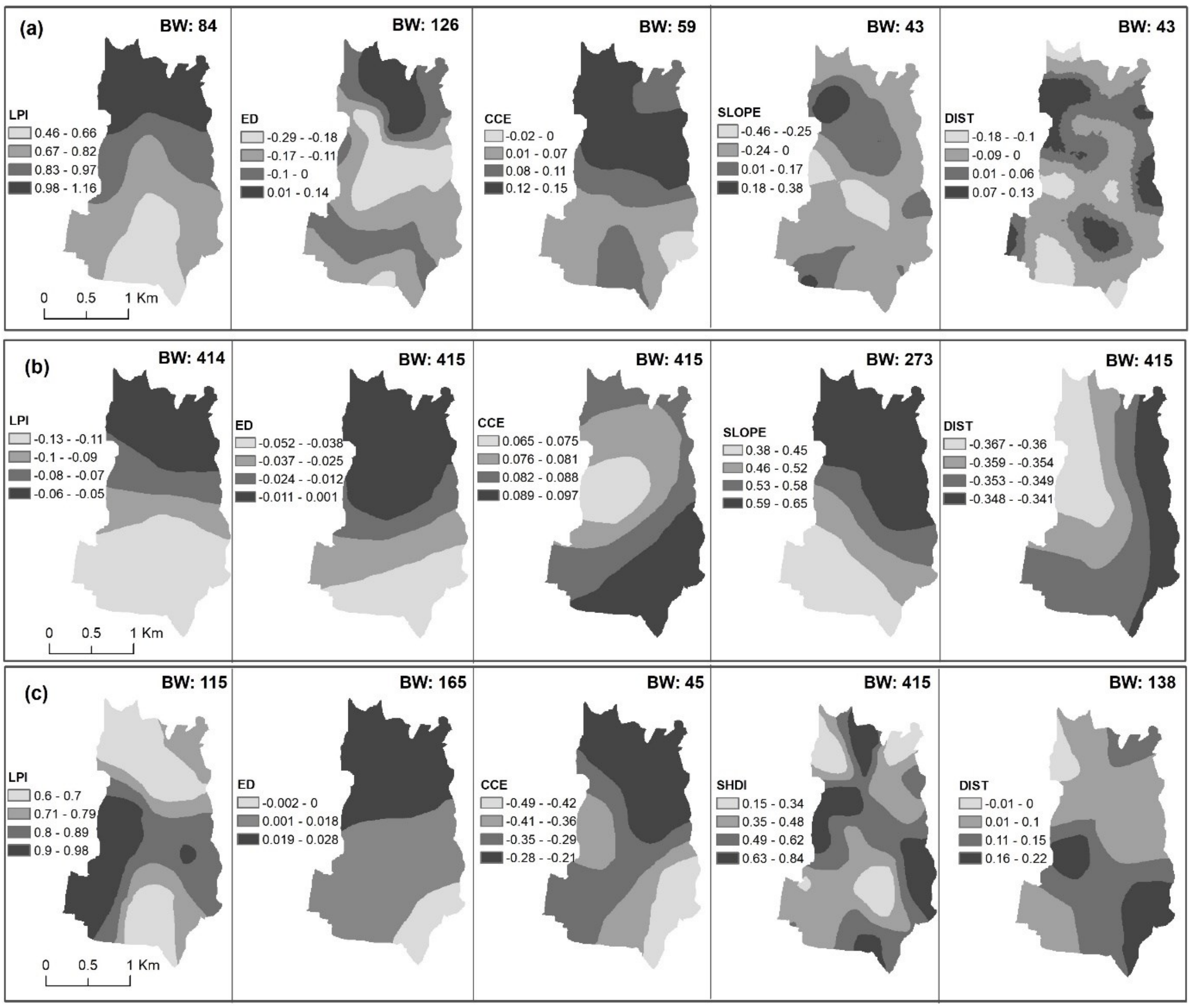

Figure 4.4. Spatial pattern of the relationship between landscape pattern and (a) pasture yield, (b) sediment retention, (c) water yield. The regression coefficients (β) were obtained from MGWR model. Landscape pattern indicators include LPI (Largest Patch Index), ED (Edge density), SHDI (Landscape diversity), CCE (Contrast class edge), SLOPE (Slope degree), DIST (Distance to stream). BW are optimal bandwidths that specify the spatial scale applied to model the relationship.

Spatial variation in the effect of landscape patterns on sediment retention is presented in Figure 4.4b. Both LPI and ED show a negative relationship with sediment retention, and the level of influence increases from the north to the south. However, the contribution of these variables is not as crucial as other variables in the sediment retention service. Significant variables that influence the overland sediment retention service are degree of slope (SLOPE) and proximity to the stream (DIST). The value of the coefficients gradually increases from the south to the north of the farm. The strong positive coefficient values of slope demonstrate the significance of topography on soil erosion control.

Figure 4.4c illustrates spatial variation in the relationship between landscape structure indicators and water yield. A positive correlation between LPI and water yield is highest in the southwest of the farm, whereas the lowest coefficients are in the northwest and south-central part. The SHDI also has a positive relationship with water yield, and the effect varies across the farm (e.g., lower in northeast and northwest and higher in the west, east, and north-central). The ED of agricultural land on the farm, in all but a small area in the southeast, has a weak and positive impact on the water yield, and the variation across space is relatively small. Except for an area in the northwest of the farm, DIST positively affects the water yield, and the strongest effect is observed in the west and southeast of the farm.

4.3.3. Insight into spatial non-stationarity between landscape patterns and ecosystem services

To illustrate the benefits of applying a geographically weighted model to explore spatial relationships at the farm scale, we present the MGWR results for pasture yield in two paddocks that are contrasting in terms of the pattern of landscape structure (Figure 4.5). Paddock A located in the north end of the farm, is a flat and homogenous landscape, which presents a single soil type. Its elevation ranges from 240m to 246 m and has slope values of less than 10 degrees throughout the paddock. Whereas, paddock B located in the south end of the farm, is a highly complex landscape with six different soil types, elevation varying between 280 to 402 m and slope fluctuating from 6 to 32 degrees.

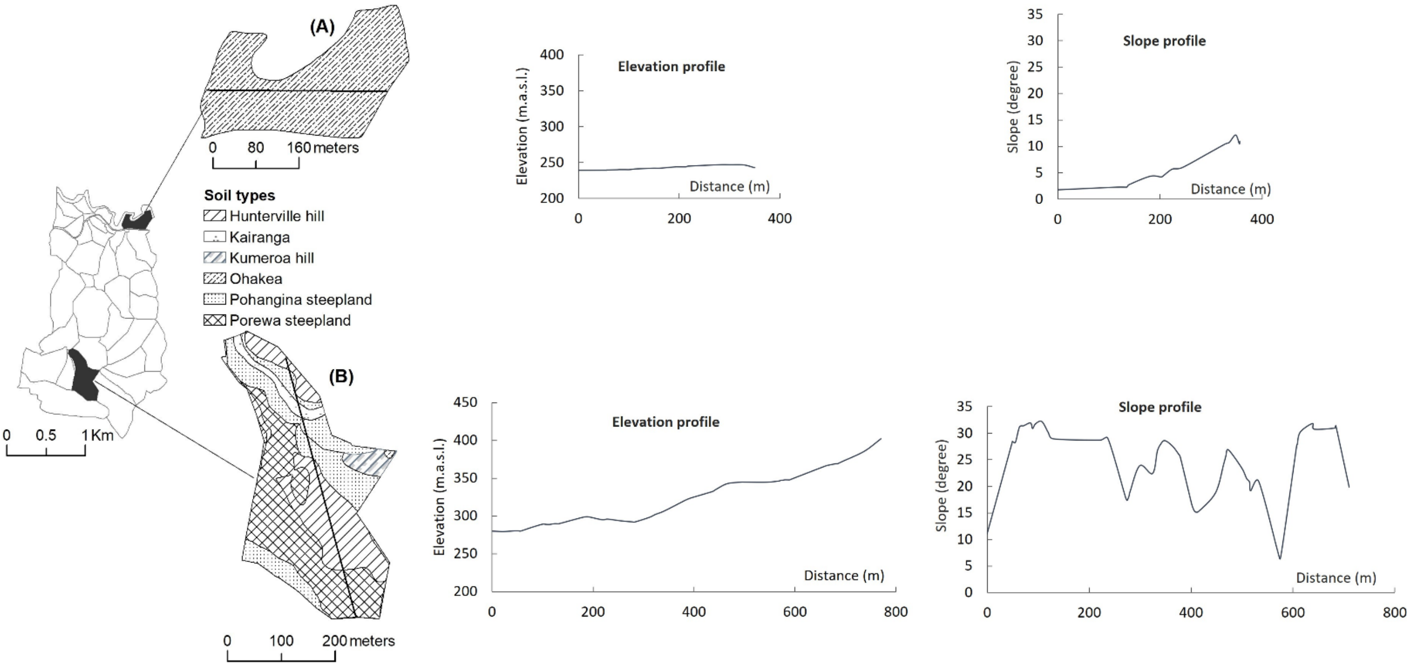

Figure 4.5. Soil types and topographical profile of (A) homogenous landscape paddock and (B) complex landscape paddock. Elevation and slope profile were derived using the Elevation Profile tool in ArcGIS (version 10.8) indicate that paddock A is flat to undulating land, whereas paddock B covers various landforms, including rolling land, hill country, and steep-land.

The difference in the spatial variation of the relationship between landscape pattern and pasture yield (i.e., non-stationarity) in the two paddocks is illustrated in Figure 4.6. It is notable that the range in correlation coefficients between landscape pattern and pasture yield is substantially higher in the complex landscape compared to the homogenous landscape. The MGWR maps also reveal a stronger positive relationship between LPI and pasture yield in the flat paddock (1.5-2 times higher in beta coefficient), whereas the negative relationship between pasture yield and other variables such as ED and DIST in this paddock is 2-3 times lower compared to the complex landscape paddock.

Local R^2 maps for the two paddocks show very high and consistent values in the flat landscape paddock ($R^2 \sim 0.89$-0.94) and lower and highly variable values in the complex landscape paddock ($R^2 \sim 0.67$-0.91). For example, the selected landscape structure variables explain 89-94% for the variation of pasture yield in a homogenous landscape.

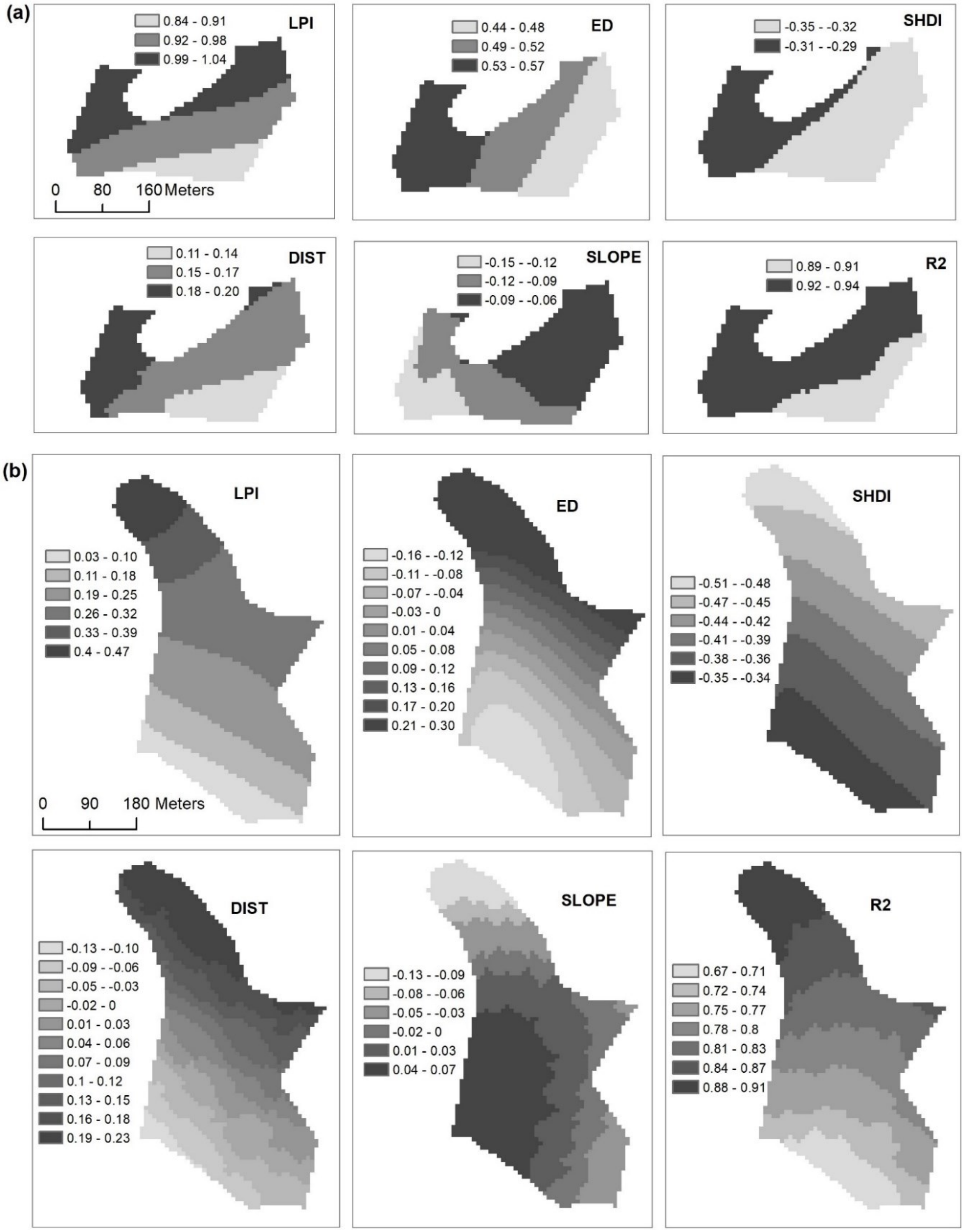

Figure 4.6. MGWR coefficient maps of the relationship between landscape pattern and pasture yield in the (a) homogenous landscape and (b) heterogeneous landscape. LPI (Largest Patch Index), ED (Edge density), SHDI (Landscape diversity), DIST (Distance to stream), SLOPE (Slope degree).

However, these variables account for only 67% of the difference in pasture yield in the southwest area of the complex landscape paddock. The relationship is more complex in the heterogeneous landscape, and hence, more variables may be needed to better understand the spatial variation in pasture yield. Mapping local R^2 is advantageous because this information can be used to determine which areas need more explanatory variables to better understand the underlying processes that affect ecosystem services provision.

For a comparison between a simple and a complex paddock, we present the distribution of beta coefficients from the MGWR model along with global coefficients from the OLS (Figure 4.7). While the OLS model shows a single coefficient (which can be thought of as "global average") for both paddocks (as well as for the entire farm), MGWR beta coefficients vary across the two paddocks and are significantly different for the two paddocks. MGWR reveals not only variation in the beta coefficients but also a trend in the correlation between landscape pattern and pasture yield.

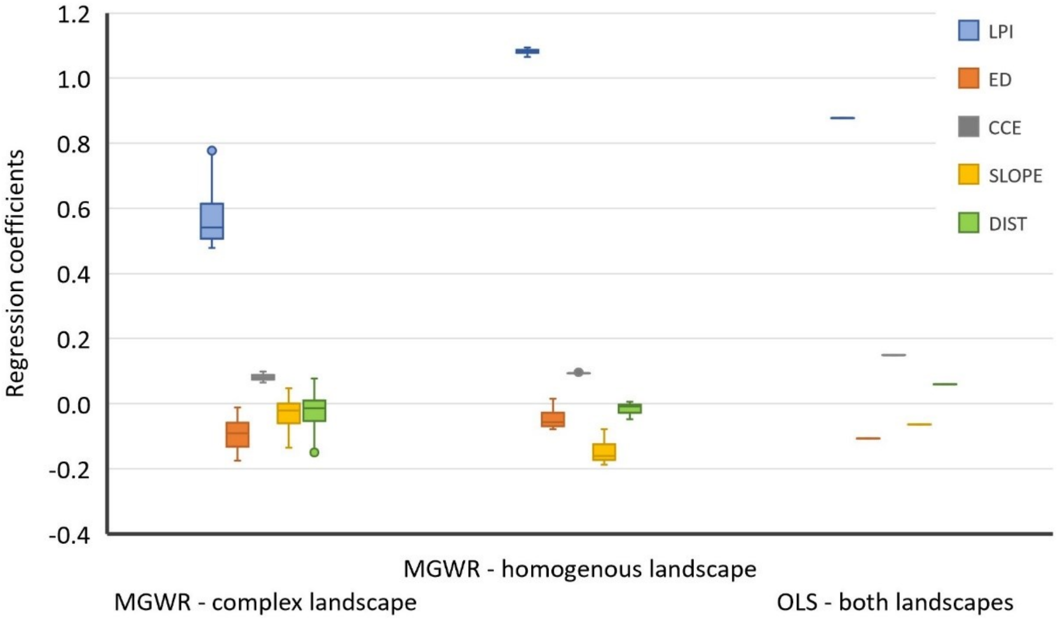

Figure 4.7. Regression coefficents between landscape structure pattern and pasture yield obtained from local and global models in a complex landscape paddock and a homogenous landscape paddock. The boxplots present maximum, median, minimum, and range of correlation coefficients. LPI (Largest Patch Index), ED (Edge density), CCE (Contrast class edge), SLOPE (Slope degree), DIST (Distance to stream).

4.4. Discussion

4.4.1. Spatial variation of ecosystem services response to landscape structure: the advantages of MGWR

This study demonstrates the benefits of using a multiscale spatial regression model (i.e., MGWR) to detect the heterogeneity effects of landscape structure on the provision of ecosystem services using a case study of a highly complex hill country farm landscape in NZ. Statistical information associated with model performance suggests that MGWR outperforms GWR and OLS by improving model fit and reducing spatial autocorrelation in model residuals. An important advantage of MGWR over GWR is its ability to produce individual optimal bandwidths to analyze the relationships between the landscape structure and ecosystem services. This is particularly important in spatially complex, heterogenous landscapes such as the hill country of NZ.

Our results show that the pattern of pasture yield, sediment retention, and water yield is strongly affected by the landscape composition and configuration, slope, and proximity to stream. This is consistent with previous studies that have shown the key role of landscape structure and topographical features in the provision of ecosystem services (Duarte et al., 2018; Eigenbrod, 2016; Mitchell et al., 2016; Schirpke et al., 2013). Our study suggests that pasture yield tends to be higher when the size of patches of agricultural land cover are larger or where there is greater contrast between agricultural land and tree cover. A landscape made up of larger patch sizes of agricultural land is strongly associated with higher water yield and lower sediment retention capacity, whereas a landscape with a mixture (i.e., configuration) of tree cover and grassland is better for sediment retention (Zuazo & Pleguezuelo, 2009), and a more fragmented landscape is related to a decrease in both pasture yield and sediment retention. These results enrich the findings from previous studies that demonstrate that landscape simplification due to agricultural intensification is often associated with an increase in agricultural production but results in negative environmental impacts such as decreasing soil and water quality and a reduction in biodiversity (Stoate et al., 2009).

Our study makes a unique and significant contribution to scholarly literature through a thorough investigation of the use of MGWR (compared to OLS and GWR) offering insight into spatial non-stationarity in the relationship between landscape structure and the supply of ecosystem services. In the study area, spatial non-stationarity is clearly seen in all three services. For pasture yield, the positive impact of LPI on pasture yield declines significantly from the north end to the south end of the farm. This suggests that a decrease in the dominance of the agricultural land cover (i.e., larger patches to smaller patches) in the north of the farm will lead to a more significant decline in pasture yield compared to the south end. This is due to the fact that the northern paddocks of the farm are flatter and more homogenous than the southern areas, rendering them more suitable for pasture production. The positive relationship between DIST and pasture yield, especially found in the central-south areas of the farm, can be explained by the fact that areas close to the stream on this part of the farm are mainly the steeper land classes with low pasture growth. For ED, the lowest negative coefficients are in the central part of the farm, indicating that increasing agricultural land fragmentation in this area will cause the least impact on pasture yield. While the negative relationship between ED and pasture yield is dominant across the farm, a positive trend seen in the north-central area of the farm is somewhat of an unexpected result as it indicates that pasture yield is likely to be higher due to an increase in edge density of agricultural land. In areas dominated by agricultural land cover, an increase of ED is often due to agricultural land being fragmented by other LULC types. However, it is not the case for an area mainly covered by non-agricultural LULCs. For instance, if an area is covered by woody vegetation, a conversion from forest to agricultural land is the possible option to increase ED. Consulting the LULC map (Figure 4.1c), we can see that there is a substantial amount of area of land in this part of the farm not covered by pasture, including a forest block and the farm residential area. The increase in edge density in these areas translates to the presence of agricultural land for pasture production, and consequently, this leads to increased pasture yield. The positive relationship between SLOPE and pasture yield presented in some areas may be due to these areas having received the positive influence of other conditions. For instance, previous studies have emphasised that pasture yield is significantly affected by factors such as soil, aspect of slope, and fertiliser distribution (Ledgard et al., 1982; Radcliffe, 1982; Sun et al., 2008). This suggests that these areas may need more explanatory variables to explain the variations in ecosystem services provision.

Given overland sediment retention values are “the difference between sediment export from bare soil and actual land cover class” (Hamel et al., 2015), the regression coefficients of SLOPE and DIST variables indicate that the capacity of the landscape to reduce overland sediment export to the stream, compared to that of bare soil, is reflected more strongly on steeper land and areas in closer proximity to the stream. In the study area, the strongest positive correlation between SLOPE and sediment retention that is found in the steep-land in the northeast paddocks can be explained by previous studies which demonstrated that a landscape with high slope length and steepness values often has a much higher erosion rate than a flatter landscape (Liu et al., 2000; Doetterl et al., 2012), and therefore, a change from bare soil to tree cover can significantly increase sediment retention capacity when steeper areas are targeted (Woznicki et al., 2020). Similarly, the study site's topographical and land cover characteristics could explain the strong negative relationship between proximity to water bodies and sediment retention. The steepest areas on the farm are generally located along the streams, and these are mainly covered by woody vegetation, so these areas will have a greater chance of retaining sediment than other parts of the farm compared to areas where there is bare soil.

For water yield service, increasing LPI and SHDI leads to more water reaching the stream because an increase in these indicators translates to a greater presence of agricultural land cover (e.g., pasture, short rotation cropland) and other non-vegetated land cover types (e.g., bare ground). Since these LULC types on the farm are covered by short vegetation such as grass, kale, and turnips that uptake and intercept a much lower amount of water than woody vegetation cover (Davie & Fahey, 2005; Brown et al., 2005), an increase in these LULC types result in more water being able to reach the stream. In addition, the strongest positive relationship between water yield and DIST is found in the south of the farm because areas along the stream in this part of the farm are mainly covered by indigenous forest and manuka/kanuka, whereas areas farther from the stream in this part of the farm are mostly pasture.

These results show that even in a small area such as a farm or a paddock, the relationship between landscape structure and ecosystem services can still be highly complex. This suggests that detecting non-stationarity in the relationship between them, especially in a heterogeneous landscape, is important to fully understand this complexity. For instance, previous studies report inconsistent findings associated with the impacts of landscape pattern on the provision of ecosystem services (Grab et al., 2018; Martin et al., 2019; Nelson & Burchfield., 2021). Whereas we found that a non-linear relationship exists and that various impacts of landscape structure can take place within the study area. This illustrates that a misunderstanding or inappropriate interpretation of the relationship between landscape structure and ecosystem services can result if relying solely on the information obtained from global regression models. Using multiple spatial scales (i.e., bandwidths) to capture the nature of the spatial relationship between different geographical process is an advantage of MGWR that normally cannot be obtained by using other spatial methods (Mollalo et al., 2020; Oshan et al., 2020). For instance, the bandwidth values of 115 and 415 used to model the spatial relationship between LPI and SHDI and water yield (Figure 4.4c) reveal that the impacts of LPI (i.e., the size of patches of agricultural land cover) on the provision of water yield is influential at a local scale, whereas the influences of SHDI (diversity of land cover pattern) on water yield are more effective at a broader scale.

The application of MGWR demonstrates that this model not only efficiently captures the non-stationary relationship between dependent and explanatory variables but allows us to visualise this on a map. Compared to global regression models, the ability to map the estimate surfaces that relate to the relationship between landscape structure and ecosystem services provides beneficial information that is not otherwise apparent. For example, OLS regression considers the relationship between all explanatory variables and pasture yield is stationary (either positive or negative), but MGWR demonstrates that there is a non-stationary relationship between the explanatory variables and the response variable (e.g., proximity to the stream and slope). Of value is being able to determine from the mapped data where and to what extent the pattern of landscape structure influences the provision of ecosystem services. We can then integrate the MGWR map with other types of information (e.g., LULC, topography, climate, geology, land management, stocking information) to understand and to help to explain the underlying process which can describe the ecosystem services variations for an exact location in the landscape. Given the highly complex nature of the NZ hill country, MGWR is an efficient and superior method to characterise the relationship between landscape structure and ecosystem services because within this landscape the impacts of landscape structure on ecosystem services differ from one location to another, which also makes it relevant for other regions in the world that exhibit heterogeneity. While being able to carry out field survey in larger geographical areas such as catchments or regional scales is challenging, using a farm-scale case study is advantageous as it allows us to fully explore and understand the landscape with the field experience of the study area and therefore, this helps us confirm the performance of the MGWR model outcomes. Whilst we demonstrate the significant contribution that MGWR makes, this does not suggest a complete elimination of the use of the global models in future research. An effective way to study the relationship between landscape structure and ecosystem services is applying an integration between both models, in which global regression provides the background for a broad understanding and for selecting appropriate explanatory variables, whilst MGWR can be used to examine the spatial variation in the relationship between the two.

4.4.2. Implications for landscape planning and management

Given that landscape structure and topographical features can negatively or positively affect patterns of ecosystem services (Duarte et al., 2018), understanding the spatial relationship between them is critical to guide decision making and to develop land and environmental planning and management strategies that lead to positive changes in the provision of ecosystem services. Given that the local regression determines a location-based relationship between landscape pattern and ecosystem services, it provides advantages over other methods that are not location specific. Although relevant information can be obtained based on the results from the global model, developing strategies based on MGWR is potentially more useful because it provides more detailed information than the global model and therefore is more powerful for prioritising more targeted management actions. For instance, the MGWR coefficient maps of the relationship between pasture growth and underlying landscape pattern factors can be used to determine fertiliser application at variable rates to different parts of the paddock. This type of information combined with advanced geospatial technologies such as a farm drone can be utilised to promote and support the applications of precision farming (i.e., precision agriculture). In the steep-land areas where pasture yield is higher than other parts of the paddock (which may be due to the positive influence of other conditions such as soil and aspect of slope), grazing might be maintained if environmental issues are not significant. If management changes need to be implemented in these areas to address erosion, for example, practices such as space planting of trees could be used so as not to significantly reduce pasture production (Guevara-Escobar et al., 2007). In contrast, on land areas that have a strong negative relationship between pasture yield and terrain slope, planting native vegetation (e.g., manuka and/or kanuka) or exotic forestry should be encouraged as doing so would not significantly affect overall pasture production (Dominati et al., 2019).

Similarly, the relationship between pasture yield, sediment retention, and water yield and landscape structure indicators such as ED or CEE can also be used to target sustainable environmental management practice. For instance, paddocks having high water yield concurrent with high soil erosion often creates a significant negative impact on the downstream water quality. In this case, environmental management practices such as space planting, planting of riparian margins or woodlots are used as solutions to reduce the erosion rate (e.g., 50-90%) (Basher., 2013) or installing sediment retention ponds can be used to prevent sediment travelling to the stream (Farjood, 2016). The use of the results from MGWR can form the basis of a mechanism to determine areas suitable for change (for example, areas closer to the stream where the change in ED or CCE creates the least impact on pasture yield) that enables a better balance between environmental and economic outcomes to be achieved. Being able to determine the priority or target areas and the specific land management practice that could be applied to enhance the sustainability of the farm is especially valuable on NZ hill country properties where the resources to implement LULC change are limited (Heath et al., 2016).

Applying a modelling approach such as MGWR at the farm scale can provide a good foundation for developing a land use or management change optimisation model that can assist with farm planning. As this approach generates maps of the local variations in the regression coefficients, it can help to better capture the underlying mechanisms of ecosystem services supply and, therefore, has the potential to increase the accuracy of land pattern change optimisation. It can also provide useful data inputs for a spatial decision support system that can be applied to design multifunctional landscapes of the future. Previous studies suggest that in a landscape that is highly simplified due to agricultural intensification, it is important to redesign the current landscape to achieve long-term sustainable development (Landis, 2017; Pretty et al., 2018). Whist current studies carried out at the farm scale often focus on how to improve current land systems rather than how to implement a fundamental change in the farmed landscape (Boeraeve et al., 2020; Bullock et al., 2021), our study provides justifications for the use of an alternative approach from which to carry out a redesign of the farmed landscapes. For instance, results obtained from quantifying the spatial relationship between landscape structure and ecosystem service provides important information that can be used in three out of six stages (e.g., landscape process, landscape design, and impact assessment) outlined in a farm scale multifunctional landscape geodesign process (Tran et al., 2020). Moreover, the study provides evidence that landscape structure indicators are relevant for decision making. Although the definition of four landscape metrics (LPI, ED, CCE, SHDI), as well as the concepts of composition and configuration that are used for the modelling process, sound complicated to non-technical users, these metrics are calculated directly from LULC data so they can easily be transferred back to the LULC structure and pattern to be applied in practice.

Understanding the spatial relationship between landscape structure and the provision of ecosystem services is useful because it can inform the stakeholder, farmer, or land manager about potential benefits from making change to landscape structure. However, all models are limited by their accuracy, and without calibration and validation of model outcomes, interpretation and application based on the model need to be considered with caution. For instance, in the present study, applications of the model results should be limited to decisions about the pattern and relative scale of landscape structure change in relation to ecosystem services provision (e.g., which part of the farm should be prioritised for erosion control?), and not how much ecosystem services provision is obtained from a particular landscape change (e.g., how many tonnes of soils are retained?). Decisions based on absolute values of ecosystem services provision and MGWR coefficients would require a more thorough field validation that is beyond the scope of this study.

4.4.3. Limitations and uncertainty

This study was limited by the unavailability of high resolution spatially explicit data (e.g., sub-metre LiDAR) to model the three ecosystem services at the farm scale. While the advantages of higher resolution data suggest greater detail in the model, they also result in introducing greater complexity and a requirement for more elaborate methods of field verification. With limited field verification of the ecosystem services provision data in this study, we must recognise the possibility of inaccuracies in the MGWR model due to data resolution. For practical landscape planning and management in a real-world project, integrating different sources of data, expert knowledge, and model calibration is suggested as a way to have more accurate values in relation to ecosystem services provision (Stritih et al., 2019). In this study six landscape structure indicators were used to map the explanatory variables, and in a complex landscape like the NZ hill country, more variables may be needed to better explain spatial variations in the provision of ecosystem services. For instance, adding topographical explanatory variables such as the aspect of terrain slope and soil nutrient variables such as soil carbon level may better explain sediment retention and pasture yield determinants. Also, different conditions in thickness of soil and moisture storage, and aspect of slope may be other factors that influence the pasture yield in the complex landscape. In addition, this study used a one-hectare grid as the basic geographic unit to create the landscape metrics and to model the relationship between the landscape pattern and ecosystem services. This generated geographic unit is suitable for the modelling process but, in practice, may not be convenient for the farm's land and environmental management. Other units such as Land Management units (LMUs) or paddocks that are often used could be considered in future studies to increase the practical application of model results.

4.5. Conclusions

In this research, MGWR was applied, and its performance was compared to other global or local regression models. This study confirmed and built upon previous research findings by demonstrating that MGWR gives the best model performance in terms of dealing with issues of spatial autocorrelation and spatial non-stationarity. Specifically, this model is efficient for quantifying the heterogeneity effects of landscape structure on the provision of ecosystem services in the NZ hill country because this landscape is highly complex. The high spatial variability of ecosystem services provision across a landscape, even as observed within a paddock, demonstrates that detailed spatial information is essential to better understand the landscape value and processes on a farm. The spatially heterogeneous effects of the pattern of landscape structure on the provision of ecosystem services suggest that even within a farm, it is necessary to consider place-based (i.e., location-based, site-specific) planning and management for the best utilisation of ecosystem services. To date, there appears to be a lack of research that examines the spatial relationship between landscape patterns and the supply of multiple landscapes services; therefore, this study has the potential to serve as a primary reference for future studies and can provide a good foundation for generating a land change optimisation model or for in the use of a spatial decision support system to help to design a multifunctional landscape. Although our research presents a case study in NZ, it provides valuable information for global applications.

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Supplementary materials

Table S4.1. Questionnaire format for the survey of stocking information

General Information

Farm name and type:

Total effective area (ha):

Survey date:

Contact: Name Email Tel

Sheep information

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1. Block/Paddock ID (Name, number):
2. Pasture types:
    a) Ryegrass/white clover
    b) Browntop
    c) Unimproved/tussock grasslands
    d) Kikuyu pastures
    e) Lucerne
    f) Grass only
    g) Others (specify):
3. Primary land use types
    a) Cut and curry – producing supplement
    b) Pastoral - Grazing animals
4. Stock numbers method (e.g., Stock reconciliation):
5. General information
    a) Capital breeding animals:
    b) Mean birth date: dd/mm
    c) Mean weaning date: dd/mm
    d) Breeding replacement rate: %/yr
    e) Birth rate: %
    f) Production: total weight of wool produce: kg/yr
6. Livestock

6.1. Livestock name:

6.2. Breed:

6.3. Stock class:
    a) Breeding ewes (mixed age)
    b) Breeding ewes
    c) Breeding replacements
    d) Breeding rams (mixed age)
    e) Lambs

f) Ewes and female hoggets
g) Wethers
h) Rams

6.4. Mature weight (weight of animals when fully grown): kg

6.5. Monthly stock counts: Describe the livestock and enter the events that brought animals on or removed animals from the farm.

Event type	Event date (when)	Number of animals
Starting/Bring on		
Sale/Take off		

Cattle information

1. Block/Paddock ID (Name, number):
2. Pasture types:
    a) Ryegrass/white clover
    b) Browntop
    c) Unimproved/tussock grasslands
    d) Summer C4 pastures
    e) Kikuyu pastures
    f) Lucerne
    g) Grass only
    h) Others: specify
3. Primary land use types
    a) Cut and curry – producing supplement
    b) Pastoral - Grazing animals
4. Stock numbers method (e.g., Stock reconciliation):
5. General information
    a) Capital breeding animals:
    b) Mean birth date: dd/mm
    c) Mean weaning date: dd/mm
    d) Breeding replacement rate: %/yr
    e) Birth rate: %
6. Livestock

6.1. Livestock name:

6.2. Breed (e.g., Angus, Ayshire):

6.3. Stock class:
  a) Breeding cows (mixed age)
  b) Breeding cows

c) Breeding replacements
d) Breeding bull (mixed age)
e) Weaners
f) Heifers and cows
g) Steers
h) Bulls

6.4. Mature weight (weight of animals when fully grown): kg

6.5. Monthly stock counts: Describe the livestock and enter the events that brought animals on or removed animals from the farm.

Event type	Event date (when)	Number of animals
Starting/Bring on		
Sale/Take off		

5. Integrating ecosystem services with geodesign to create multifunctional agricultural landscapes: a case study of a New Zealand hill country farm

Abstract

An ecosystem-based management approach (EBM) is suggested as one solution to help to tackle environmental challenges facing worldwide farming systems whilst ensuring socio-economic demands are met. Despite its usefulness, the application of this approach at the farm-scale presents several implementation problems, including the difficulty of (a) incorporating the concept of ecosystem services (ES) into agricultural land use decision-making and (b) involving the farmer in the planning process. This study aims to propose a solution to overcome these challenges by utilising a geodesign framework and EBM approach to plan and design a sustainable multifunctional agricultural landscape at the farm scale. We demonstrate how the proposed approach can be applied to plan and design multifunctional agricultural landscapes that offer improved sustainability, using a New Zealand hill country farm as a case study. A geodesign framework is employed to generate future land use and management scenarios for the study area, visualise changes, and assess the impacts of future land use on landscape multifunctionality and the provision of associated ES and economic outcomes. In this framework, collaboration with the farmer was carried out to obtain farm information and co-design the farmed landscapes. The results from our study demonstrate that farmed landscapes where multiple land use/ land cover types co-exist can provide a wide range of ES and therefore, meet both economic and environmental demands. The assessment of impacts for different land use change scenarios demonstrates that land use change towards increasing landscape diversity and complexity is a key to achieving more sustainable multifunctional farmed landscapes. The integration of EBM and geodesign, is a transdisciplinary approach that can help farmers target land use and management decisions by considering the major ES that are, and could be, provided by the landscapes in which these farm systems are situated, therefore maximising the potential for beneficial outcomes.

Keywords: Land use planning; Sustainable farming; Environmental management; Collaborative planning; Farm scale analysis.

Based on:

Tran, D. X., Pearson, D., Palmer, A., Dominati, E. J., Gray, D., & Lowry, J. (2023). Integrating ecosystem services with geodesign to create multifunctional agricultural landscapes: A case study of a New Zealand hill country farm. *Ecological Indicators 146,* 109762. https://doi.org/10.1016/j.ecolind.2022.109762.

5.1. Introduction

Ecosystem services-based management (EBM) (i.e., ecosystem-based adaptation, ecosystem services-based approach) is "an integrated approach that incorporates biological, socio-cultural, and economic factors into a comprehensive strategy aimed at protecting and enhancing sustainability, diversity, and productivity of natural resource" (Delacámara et al., 2020). The EBM approach has emerged as an effective approach to address socio-economic and environmental concerns arising from human activities and climate change impacts (Naumann et al., 2011). This is because applying an EBM approach can help maintain and promote key ecosystem functions and services within agro-ecosystems, and therefore, ensure the provision of multiple benefits to society and the natural environment, as well as decrease environmental footprints of agricultural production activities (Doswald et al., 2014; MEA, 2005). Benefits from this include but are not limited to maintaining soil health, carbon stocks, regulating air and water flow, enhancing biodiversity, increasing landscape resilience to adapt to climate change and environmental disturbances, maintaining food production, and improving human health and well-being (Naumann et al., 2014; Smith et al., 2013). Given that sufficient international responses to global environmental problems are still lacking, a local scale and place-based response driven by local governments and societies can play a vital role in fostering sustainability transitions (Wamsler et al., 2014). In this context, the importance of ecosystem-based management is considered as a multi-benefit approach that provides the most promising paradigm for achieving sustainable development (MEA, 2005).

Among various strategies that have been proposed and implemented to accelerate a transition to sustainable farming systems such as leveraging technological innovations, changing agricultural practices, implementing nature-based farming, and providing training and education to farmers (Burns, 2021; Eyhorn et al., 2019; Keesstra et al., 2018; Lynde, 2020; Schlesinger, 2022), the EBM approach has been applied increasingly in recent years (Bretagnolle et al., 2018; Harvey et al., 2017; Tamburini et al., 2020; Vignola et al., 2015). This approach aims to recreate and strengthen key ecosystem functions and services to sustainably increase agricultural production (Abdourahamane Illiassou and Oeba, 2020). In practice, the central idea behind EBM is that one can redesign current landscapes to maintain and restore natural capital stocks, and at the same time create multifunctional landscapes that allow the joint production of both agricultural commodities and various ecological and cultural ecosystem services (Landis, 2017; Lovell & Johnston, 2009). As such, applying EBM enables the establishment of more diverse and complex landscapes where farming systems are tailored to ensure multiple human needs are met while sustaining the environment (McGranahan, 2014). In the context of the increasingly negative impacts of climate change and more environmental regulations/standards required from agricultural systems, this approach is a powerful tool to ensure the sustainability of farming systems.

Although the importance and benefits of utilising EBM for designing multifunctional agricultural landscapes has been widely highlighted and discussed internationally (e.g., Huang et al., 2015; Huang et al., 2019; Lavorel et al., 2022; O’Farrell & Anderson, 2010; Ssegane et al., 2015), the application of this approach has several challenges. A fundamental barrier to the implementation of EBM in practice is the difficulty of incorporating the concept of ecosystem services into agricultural land use decision-making (Bürgi et al., 2017; De Groot et al., 2010). More particularly, in order to use the concept of ecosystem services at the farm scale, a wide range of data and models are needed, which often requires assistance from experts to help farmers navigate through the process (Abdourahamane Illiassou & Oeba, 2020). Taking a design-driven perspective to land use planning, which integrates a knowledge of the range of ecosystem services provided by different parts of the farm, should also involve landowners as a key participant in all stages of the process (Tran et al., 2020). Being able to involve farmers in the design of multifunctional agricultural landscapes is likely to result in land use strategies that are practical or more likely to be adopted by the farmer (Haaland et al., 2011; Speelman et al., 2014).

It is important that the development of future landscapes follow an effective framework which integrates different types of models and processes (Chopin et al., 2017). Such a framework must also facilitate the collaboration between different stakeholders to develop a comprehensive land use plan (Karrasch et al., 2017; Natarajan, 2017). The concept of geodesign is recognised as an innovative approach that has been widely utilised in land and environmental management (Gottwald et al., 2021; Lee et al., 2014; Li & Milburn, 2016; Newman et al., 2020). In addition, frameworks that integrate ecosystem services into the geodesign process have been developed (Chopin et al., 2017; Huang et al., 2019; Tran et al. 2020). However, geodesign has been implemented mostly in urban and catchment scale projects. Studies that apply a geodesign framework following EBM at the farm scale are uncommon.

This study utilises a geodesign framework and EBM approach to plan and design a sustainable multifunctional agricultural landscape, using a New Zealand (NZ) hill country farm as a case study. Farming in NZ hill country faces considerable environmental challenges due to the historical clearance of natural and seminatural land cover for pastoral production (McGlone, 1983). Through these processes, the hill country landscape structure and pattern have been significantly modified, resulting in loss and degradation of ecosystem functions and services (Blaschke et al., 1992). This impacts on the long-term sustainability of hill country landscapes, and it is likely that the possible effects of climate change will exacerbate these problems (Macinnis-Ng et al., 2021). Through this study we demonstrate that farming systems designed around a multifunctional landscape, where key ecosystem services are maintained and promoted, can offer an effective solution to decrease environmental footprints whilst ensuring good economic outcomes and farmer's well-being are achieved.

Research that applies an ecosystem services-based geodesign approach in a complex farmed landscape has the potential to contribute to the provision of planning tools that can be used by farmers and their advisors to design better sustainable multi-functional agricultural landscapes. This would improve ecosystem services from hill country and help NZ hill country farmers better manage the tensions they currently face between minimising environmental impacts from farming and improving farm productivity and profitability (Scrimgeour, 2016). The proposed approach provides a valuable reference for sustainable farm system design and can make an important contribution to sustainable development of agriculture in NZ and other countries faced with similar land management issues.

5.2. Geodesign case study

The case study farm is situated in the hill country and steep-land of the Manawatū-Whanganui region, in the lower half of the North Island of NZ (Figure 5.1a). This farm is a complex agricultural landscape (Figure 5.1b) formed by various topographical features (e.g., slope, elevation, landform) and comprises a range of soil types. The landscape has been deforested and significantly modified for agricultural production. Many environmental issues must be considered when thinking about the design of modern farm systems in this landscape, including increased soil erosion and GHGs emissions, loss of biodiversity and reduction in water quality. This highlights the importance of redesigning the farmed landscape to achieve long-term sustainability of agricultural businesses. Although the landscape is covered by various categories of land use land cover (LULC), pasture is the dominant land cover, with the main land use being sheep and cattle grazing.

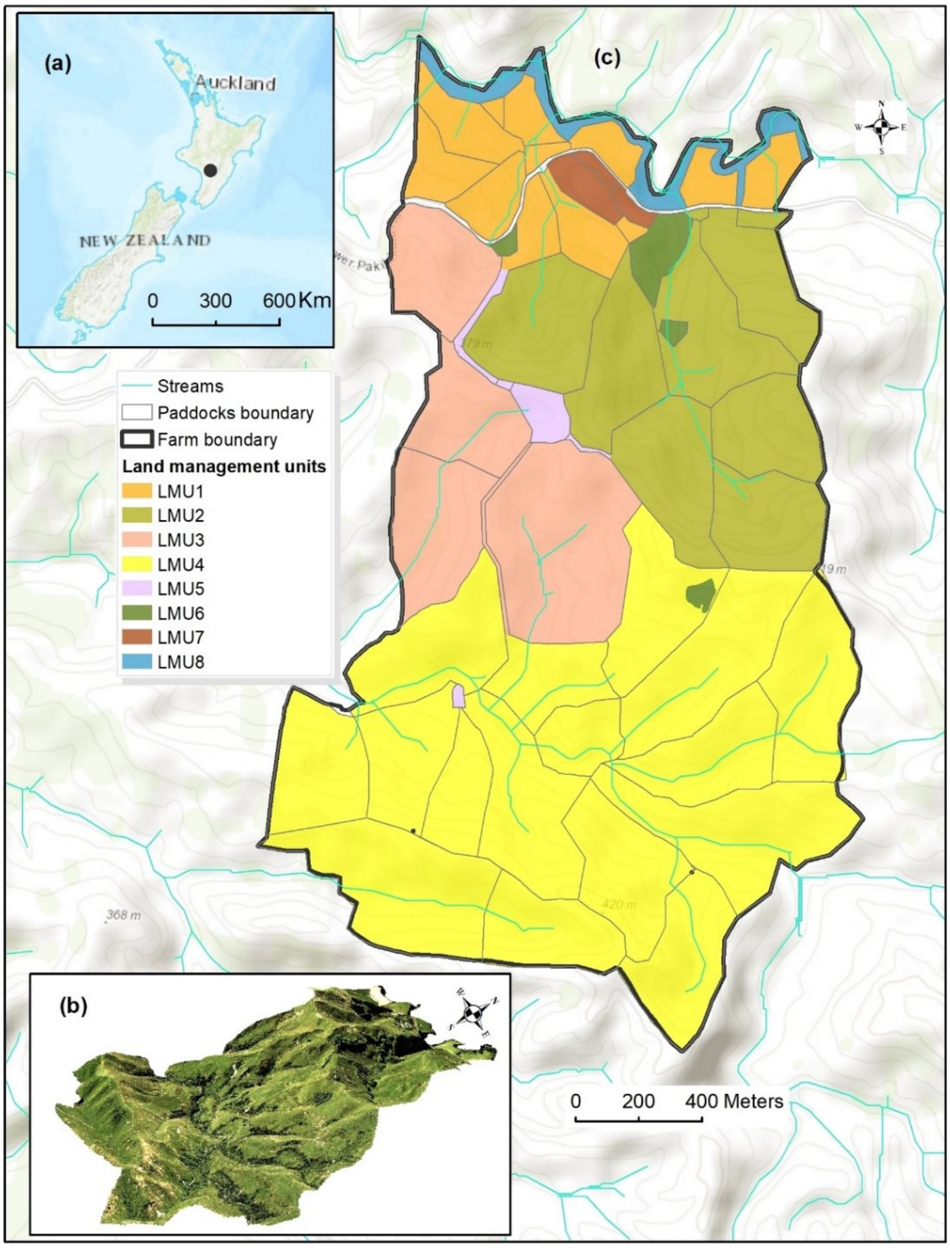

Figure 5.1. Location of the farm in New Zealand (a); the farmed landscape in 3D visualisation (b); and land management units (LMUs) of the farm (c).

The farm consists of eight land management units (LMUs) (Figure 5.1c). A LMU is defined as an "area of land that can be farmed or managed in a similar way because of underlying physical similarities" (Beef and Lamb, 2022). A description of LMUs in the case study farm is presented in Table 5.1. Most of the LMUs were available in the property's whole farm plan produced by the local regional council (https://www.horizons.govt.nz/). However, some changes to the boundaries were identified and updated due to recent change in land use and management in some parts of the farm. As such, the final LMUs and associated boundaries and descriptions were obtained by working with the farmers.

Table 5.1: Land management units on the case-study farm

LMUs	Area (ha)	Land use and management practices
LMU1	31.9	Pasture grazed by sheep
LMU2	79.4	Pasture grazed by sheep, lambing, and cattle
LMU3	57.9	Pasture grazed by sheep and cattle, calving
LMU4	188.7	Pasture grazed by sheep, cattle, and manuka honey production
LMU5	4.0	Holding paddocks for livestock
LMU6	4.9	Exotic forest blocks
LMU7	3.9	Residential area
LMU8	8.2	Riparian zone with indigenous vegetation cover

5.3. Materials and methods

This study utilised an ecosystem-based geodesign approach to design different land use scenarios for the future farmed landscape. The conceptual framework for agricultural landscape design proposed by Tran et al. (2020) was adapted to this case study (Figure 5.2) which integrates the concept of multifunctional landscapes following the geodesign process developed by Steinitz (2012).

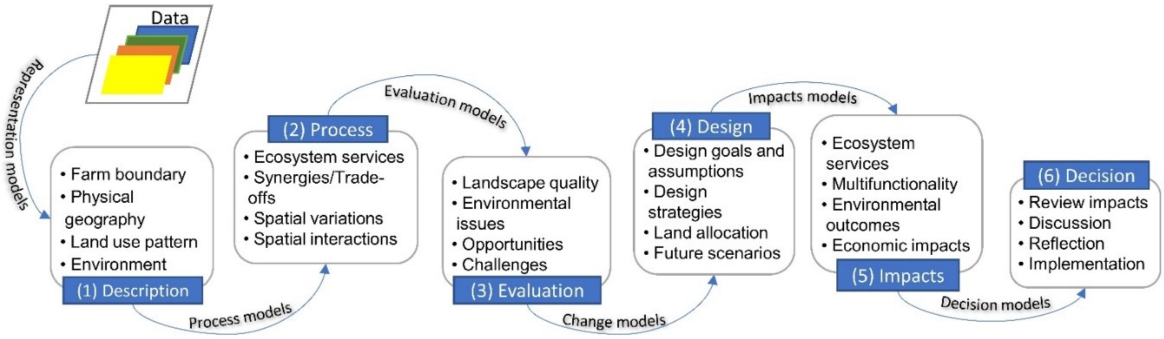

Figure 5.2. Conceptual framework of the ecosystem services-based geodesign process for creating future landscape, adapted from Tran et al., 2020. The geodesign follows six stages: (1) Landscape

description, (2) Landscape process; (3) Landscape evaluation; (4) Future landscape design; (5) Impact assessment of alternative land use scenarios; and (6) Decision-making. Stages 4-6 tend to be iterative in response to the feedback/reflections of the decision makers.

Although major steps and processes were inherited and followed, the conceptual framework proposed by Tran et al. (2020) (described in Chapter 2 of this thesis and visualised in figure 5.2) has been slightly modified for this chapter. The framework implemented here involved a reduction of some ecosystem services, a limited number of stakeholders collaborating towards the landscape design, and climate change scenarios not being considered in the development and implementation of future land use plans. The original conceptual framework outlined in chapter 2 is an ideal. The reality of available study resources and covid restrictions meant that the study needed to be simplified whilst still demonstrating proof of concept. This also demonstrates that the reality of implementing a conceptual framework to a specific case study often requires some adaptation to meet the farm context and farmer perspectives (Tran et al., 2020).

5.3.1. Description, process, and evaluation models (stages 1-3)

To describe and visualise the landscape of the case study farm, various types of spatial data were used (Figure 5.3). This is the Description stage of the conceptual framework (Figure 5.2). These data were obtained from different sources, including NZ government agencies and government-funded projects, research institutions, and include remote sensing-based data, data from a survey questionnaire, and field surveys (See Tran et al., 2022b). Because spatial data for the study area were of different spatial resolution and data types (i.e., vector shape files and raster images), these data were standardised to a raster data format with a resolution of 10 meters using ArcGIS software. Doing this resulted in dividing the farm into a grid of pixels where the area for each grid cell is 0.01 ha or 100 square meters (10m x 10m). All data were organised in a geospatial database optimised for storing, querying, and sharing data in the landscape analysis and design applications.

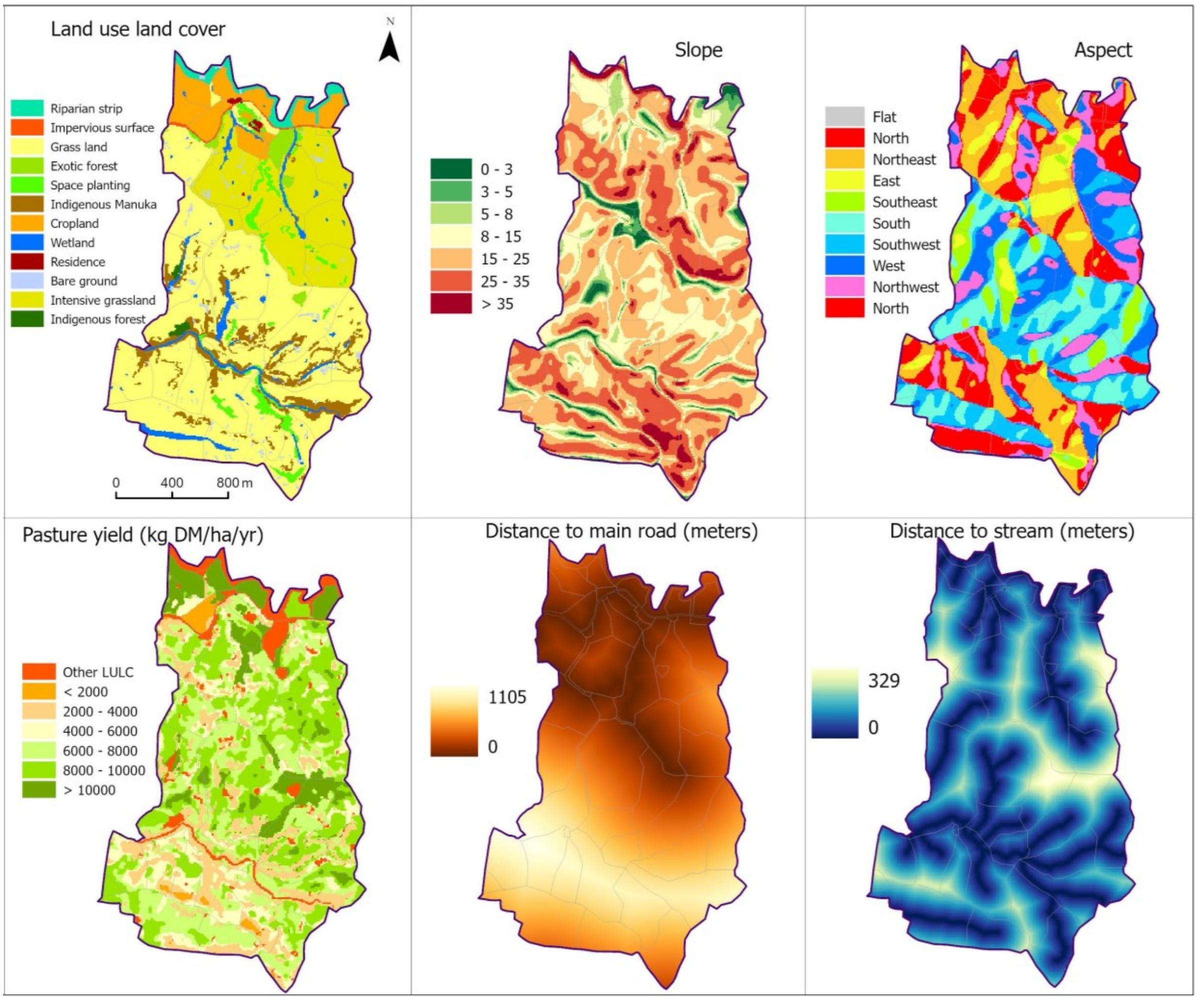

Figure 5.3. Major data used for land suitability evaluation in the case study

The second stage of the conceptual framework was to spatially quantify major ecosystem functions and services and their interactions. This is the Process stage (Figure 5.2). For example, types and pattern of ecosystem services are strongly affected by landscape simplification/modification for pastoral production. Also, topographical features (e.g., slope and aspect) play an important role in shaping ecosystem functioning and processes such as soil erosion, water flow, and vegetation growth in the study area. Because hill country landscapes may supply various type of ecosystem services, a range of models and methods were used to derive spatial data of ecosystem services, including biophysical approaches and LULC-based approaches (Tran et al., 2022b). Specifically, InVEST and ArcGIS were the primary tools used to quantify and map the spatial pattern of provisioning, supporting/regulating, and cultural ecosystem services based on the methods described in Tran et al. (2022a, 2022b). Because the ecosystem services were measured in different units, all ecosystem services values were normalised to a 0–1 scale to allow these ecosystem services to be comparable and aggregated for quantifying landscape multifunctionality (MFC).

The third stage of the framework, Evaluation, employed a model that utilises the assessment indicators to evaluate the quality of the farmed landscape (Figure 5.2). To map the overall quality of ecosystem services, a landscape quality index of multiple ecosystem services was created (Quin et al., 2013; Hermes et al., 2018). The Analytic Hierarchy Process (AHP) pairwise comparison method (Saaty, 1988) was used to weight the relative importance (i.e., preference) of the different ecosystem services and the weighted ecosystem services layers summed to create a MFC index layer. Finally, hotspot analysis using the Getis Ord tool in ArcGIS (ESRI, 2022) was used to identify hot spots and cold spots within the MFC index layer. This enabled the identification of areas with low and high levels of ecosystem services supply, which provides important information for landscape planning and management. Soil erosion, nutrient loss, and GHGs emissions, were used as the main indicators for evaluating environmental challenges in the study area. This was carried out using InVEST Sediment Delivery Ratio (Hamel et al., 2015), InVEST Nutrient Delivery Ratio (Sharp et al., 2014), and the Agricultural Emissions Calculator tool from the Ministry for the Environment (MfE, 2022a). This calculator provides a basic estimation of the GHGs emitted and absorbed by a farm based on stocking and land use information. GHGs include carbon dioxide, methane and nitrous oxide, all converted to CO2 equivalents.

5.3.2. Change models for future land use scenarios design (stage 4)

Designing future land use scenarios is a complex process requiring a mixed approach that combines different models and methods. Participatory mapping, GIS-based multi-criteria decision-making using the suitability model in ArcGIS Pro, and an integration of these methods were used to develop future land use scenarios for the case-study farm. Stage 4 of the conceptual framework, ***Design,*** is described in the following sections (Figure 5.2).

5.3.2.1. Participatory mapping

A geodesign workshop was organised at the farm and facilitated by a GIS expert. He is a spatial scientist who is familiar with the case study and carried out data collection and processing, and ecosystem services modelling and assessment. This is the first step of the ***Design*** stage (Figure 5.2). The workshop started with a broad overview of the current landscape characteristics (e.g., LULC pattern, topography), environmental issues (e.g., soil erosion and nutrient loss), and drivers of land use changes (regulations in GHGs emissions and the recent release of the government's freshwater management policy (Larned et al., 2022; Leining et al., 2020). Afterwards, a set of printed maps with information on the farm boundary, paddocks/fence lines visualised on an aerial photo (i.e., base maps) were provided to the farmers. The maps displayed the current LULCs, and the environmental issues identified on the farm.

The workshop facilitator introduced a set of land use mapping tasks to the farmers (i.e., farming couple who own and operate the farm). In the case study farm, future land use options were based on two different land management goals—an agricultural production-oriented scenario and landscape conservation scenario. The first scenario focused on promoting pastoral production, while the second scenario focused on reducing negative environmental impacts from agricultural production such as soil erosion and degraded water quality. For the latter scenario, a defensive design strategy was applied by which the creation of future landscapes is based on avoiding vulnerability or risks.

The farmers were asked to sketch their preferred land use on the base maps (e.g., such as identifying new areas for planting manuka trees and drawing it on the map). This could be done by using the digitising tool in GIS software or a drawing tool in web-mapping applications. However, in our case study, the farmers preferred using paper maps so an additional step was required to transfer the mapping results to a digital form (i.e., shapefile) for use in GIS.

In addition to the land use scenarios mapped by the farmers, a similar geodesign process was done by an external expert. For this scenario, the expert is a soil scientist with expertise in sustainable use of land, particularly hill country and steep-land in NZ. While the mapping tasks for the farmers to map the production- focused scenario are rather simple, the conservation-focused scenarios involved more complicated land allocation tasks. For instance, in the latter scenario the landscape designer was required to define suitable areas for exotic forest blocks (e.g., 40 hectares) (i.e., planted forest), indigenous forest, the space planting of poplar trees for soil conservation, and draw and mark the boundary of these areas on the paper map. Given the complexity of this landscape design, a combination of both defensive (i.e., proactive) and offensive (i.e., reactive) strategies was used to create future land use changes. In the defensive strategy, the development of a future landscape is based on one that avoids vulnerability or risks. Whereas the development of a future landscape using offensive strategy is based on utilising the advantageous or attractive landscape characteristics (see Steinitz, 2012 for detailed description of these design strategies). The results from this step are maps showing the future landscape with the anticipated distribution and pattern of different LULC types based on production-focused goals and conservation-focused goals developed by the farmers and the expert.

5.3.2.2. Design optimisation using a hybrid approach

Land use design optimisation begins by determining the targeted areas to undergo future land use changes. In other words, this required defining the spatial-based design and management goals for future landscapes in which a specific level of land use change intervention is quantified and visualised on the map. This was done by applying the concept developed by Landis (2017) who proposed three design goals for multifunctional agricultural landscapes based on the degree of ecosystem services supplied: “restore ecological integrity”, “increase landscape multifunctionality”, and “sustainably intensify”. High and low levels of ecosystem services supplied by provisioning, supporting, and aesthetic services were obtained from the hotspot analysis carried out in the second or process stage. These maps were then integrated using the spatial analysis tool in ArcGIS to determine design goals for the study area (Figure 5.4). For instance, using this approach, a high level of land use change intervention is required in an area with a high level of provisioning services (i.e., hot spot), but low in supporting/regulating and landscape aesthetics (i.e., cold spot). Details associated with the process of quantifying the design goals map from ecosystem services are described in the Supplementary S5.1.

Because the relative priorities of the different ecosystem services are strongly dependent on the specific land use management goal, we applied a pairwise comparison to create two weighted scenarios: an equal weighting and a farmer-based scenario. This resulted in two major land use change scenarios: a production-oriented scenario which promotes agricultural production with limited environmental sustainability (Figure 5.3a) and a landscape conservation scenario which focuses more on overall landscape sustainability and restoration (Figure 5.3b). The design and management goals obtained from this step enable the landscape designer to quickly define areas that require changes to future land use or management.

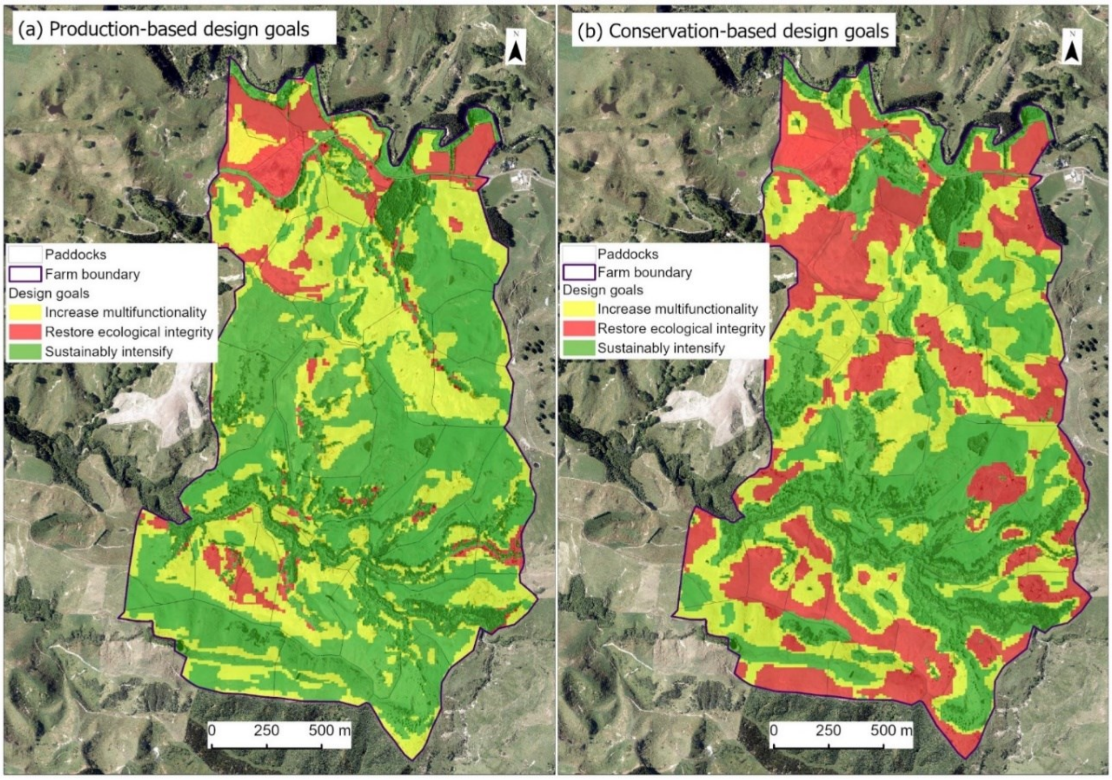

Figure 5.4. Spatially explicit design and management goals for (a) the agricultural production scenario and (b) the landscape conservation scenario

The second step of the ***Design*** stage involves land suitability evaluation to determine suitable areas for a specific land use purpose (i.e., specific land use changes) (Figure 5.2). The assessment was done using a GIS-based multicriteria decision making (MCDA) method, which was integrated in a land suitability model in ArcGIS Pro. In this study, the land suitability assessment for exotic forest, indigenous forest, indigenous manuka, and space planting were carried out because modifying the landscape to increase these land use types leads to a significant improvement in MFC and the provision of multiple ecosystem services (Dominati et al., 2021).

Based on published literature (Harris et al., 2021; Lynn et al., 2009; Thomas et al., 2021) and advice from a local expert, relevant land evaluation criteria for such land uses were defined (e.g., current LULC, topographic features such as slope and aspect, pasture production, and accessibility to transport and water bodies). For exotic forest, suitable areas are low in pasture yield, steep-land, and close to the main road or farm track which can be accessed by a logging truck. For indigenous forest, suitable areas are those covered by indigenous manuka, near the water bodies, far from the farm tracks, and avoid the sunny sides (i.e., the more northerly-facing slopes). The areas that are located on steep-land with a high risk of soil erosion, low pasture yield, and close to the stream are considered as highly suitable for indigenous manuka planting. Space planting is more suitable in pasture areas with high risk of erosion and steep-land. These criteria were then prepared in the form of raster GIS layers, reclassified into different levels of suitability, and standardised using ranked scores, for example, ranking from the lowest (1) to the highest suitability (9). The land suitability evaluation was carried out using the Suitability Analysis toolset in ArcGIS Pro (version 2.9). Step by step instructions for the land suitability evaluation were described in ESRI user guide documentation (see ESRI, 2023 for more details). Climate data (i.e., temperature and rainfall) is not included as evaluation criteria here, given that climate condition is relatively homogenous across the farm.. See Supplementary S5.2 for more details on the evaluation criteria and associated suitability score for specific land use in the case study. A land suitability map for each land use modification was determined by combining all the suitability criteria.

The result from this step are maps which determine suitable areas for the distribution of exotic forest, indigenous forest, indigenous manuka, and space planting (Figure 5.5).

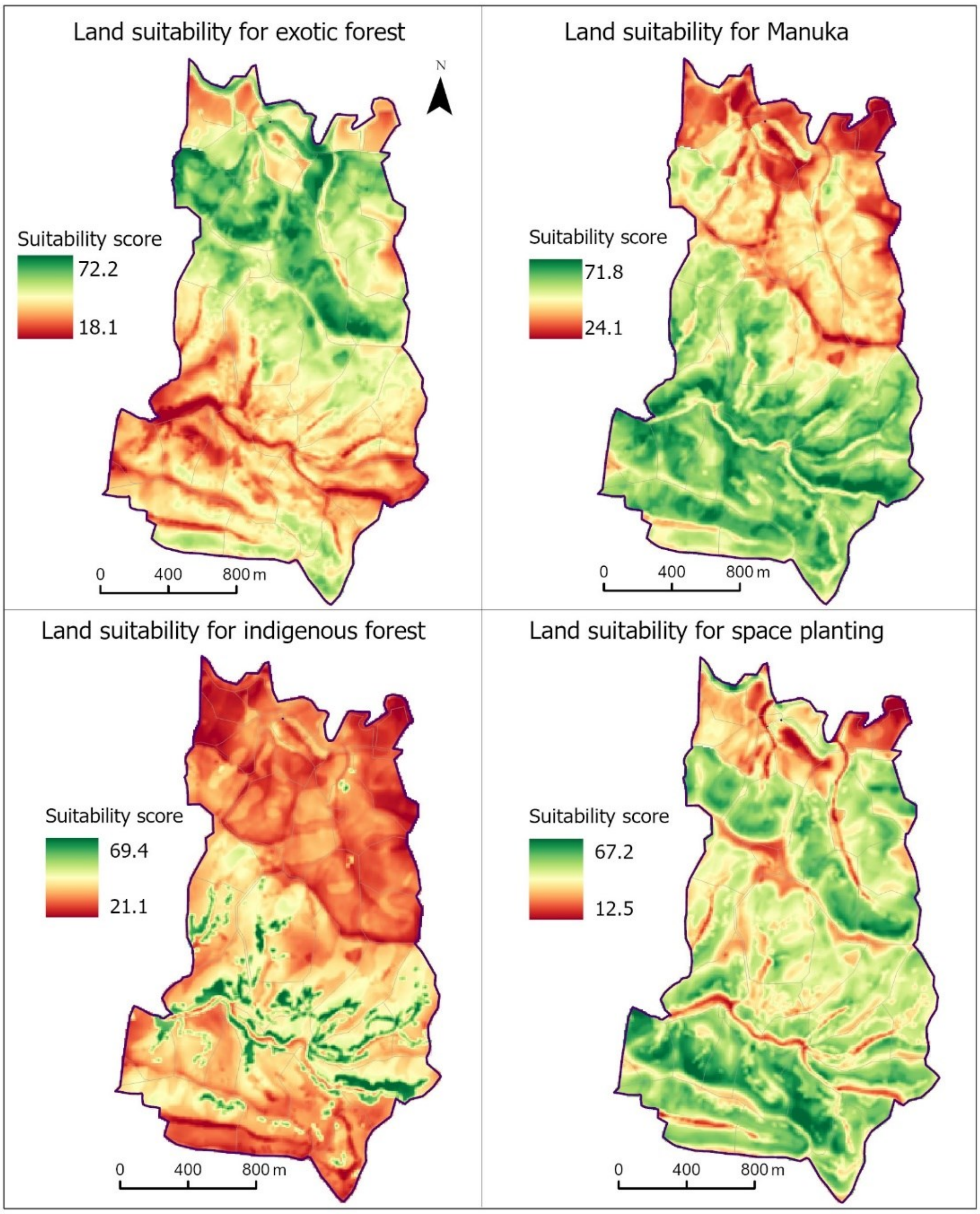

Figure 5.5. Land suitability for a specific land use purpose for the case study using the land suitability model. The highest suitability score presents the most suitable area for land use change through the proposed framework.

The third step of the Design stage involves integrating land suitability maps, design goals, landowner preferences, and expert knowledge to modify the landscape by allocating future land uses (Figure 5.2). In this step, the design goal maps from step 1 and the land suitability maps from step 2 are used as reference information to quickly find targeted areas for allocating specific land use types. Information from the landowner and the expert was utilised to refine the land use plan. For instance, the design goal map for the landscape conservation scenario reveals a high and medium level of land use change intervention on steep land areas in the south of the farm, indicating a need to increase MFC or restore ecological integrity. The land suitability maps show that these areas are suitable for both indigenous manuka and poplar planting, suggesting changes towards these land uses offers a solution to achieve the design goal. However, the paddocks in this location are easy to farm and the planting of manuka in these areas is not favoured by the landowner. This is because the farm is already covered by a good amount of manuka (~30 ha) and converting land that is suitable for grazing stock would substantially impact the productivity and profitability on farm, especially significant in a marginal hill country sheep and beef farm like this case study. As such, it is unlikely that the landowner will convert these paddocks to manuka. Therefore, spaced-poplar planting in these paddocks is determined as the priority for future land use change in these areas as it could help farmer achieve the environmental outcomes whilst maintaining the pasture production. The results from this step of the process are maps showing the pattern and types of land use for different scenarios (Figure 5.6).

5.3.3. Impact assessment of future land use changes (stage 5)

To evaluate the impacts of future land use scenarios on landscape sustainability, a MFC index with associated ecosystem services provision and environmental issues, and economic indicators, were applied to measure how changes to future land use will impact on the ecological/environmental and economic aspects of the landscape. To explore the long-term impacts of future land use change, the assessment for current (base in 2020) and future land use (in 2050) was carried out. This is the ***Impact*** assessment of the conceptual framework (Figure 5.2).

For each land use scenario, eleven ecosystem services (See Chapter 3, Table 3.1.) were quantified and an integration of these services using the Analytic Hierarchy Process AHP was applied to map the overall multifunctionality of the farm. Because the primary goal of designing future landscapes for the farm is to achieve long-term sustainability, we assume that all types of ecosystem services play the same role and contribute equally to MFC. Results from this assessment enabled comparison between future and current land use so that the impacts of land use changes on MFC and ecosystem services can be evaluated. Changes in the supply of ecosystem services were examined using the spatial statistics tool in ArcGIS software. The environmental impact indicators that were selected for the case study were soil erosion, nutrient loss, and GHGs emission. Reducing these environmental issues is the current focus of the NZ government.

To evaluate the effects of future land use changes on the mix of revenue streams and the financial performance of the farm business as a whole, a financial analysis of each of the resulting scenarios was undertaken and compared to the current situation of the business. For each of the potential commercial activities on the farm, including wood production, carbon farming, manuka honey production and sheep and beef grazing, net cash flows over 30 years were modelled, and the net present value (NPV) was used with a discount rate of 2% (see Supplementary S5.3 for clarification) to compare the profitability of different mixes of enterprises for the future scenarios.

Net Present Value is the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. The NPV method converts payments in the future to present values so that it enables a comparison between them to be undertaken. The calculation of NPV can be carried out using the following equation (Thakur, 2019):

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t}$$

where NPV is net present value; NCFt is net cash flow generated by an investment in year t; and r is the discount rate. If the NPV is greater than zero, the project is worthwhile from an economic perspective. Also, when comparing the economic profit between two or more investment scenarios, the project with the greatest NPV should be selected.

To model the pastoral enterprise over time, the farm system model AgInform (Version 6.8.2.6) was used. AgInform utilises linear programming to optimise economic profit for the pastoral enterprise, over a set time period, from changes made to specific LMUs (area, pasture quantity or quality) (Rendel et al., 2017). This model uses a wide range of input information such as pasture yield overtime, the seasonal pattern of pasture growth rates on different LMUs, livestock performance levels, the monetary costs associated with the production of forage and those incurred for running the whole farm business. These data were primarily obtained directly from the farmers. Missing information was collected from regional databases. For each land use scenario, capital investments such as fencing, planting, hive purchase were considered along with on-going costs and revenues over 30 years. The 9 steps for the financial analysis for each land use was demonstrated in the Supplementary S5.4. Outputs from the model include, stock classes and numbers, investment costs in tree planting and fencing, and NPV of the initial investment in capital livestock and the annual earnings before interest, tax, depreciation, and amortisation (EBITDA) over the set period. See Dominati et al. (2019, 2021) for more detailed explanation of the AgInform model. Given that AgInform models the pastoral systems only, other revenues including manuka honey and carbon farming were calculated manually using the assumption provided in Table S5.5.

5.3.4. Decision making (stage 6)

In the final stage (***Decision***) of the framework (Figure 5.2), the results of the future land use scenarios and impacts of land use change were utilised as the basis for a discussion with the landowners. The focus of this step is to discuss in detail the trade-offs between scenarios and getting farmer’s reflection/opinions on the feasibility of proposed land use options.

5.4. Results

5.4.1. Scenarios of future land use for the case study

Land use maps for the current and future scenarios for the case study are presented in Figure 5.6 and area of LULC types are showed in Table 5.2. For the current farm system (S0), grassland is the dominant land use which occupies 74.3% of the total land (282.4 ha). This is followed by indigenous manuka that is mainly distributed in gullies within LMU 4 (the south-central area of the farm) and it accounts for 7.36% (~30 ha). Cropland is located in LMU1 (the north of the farm), covering an area of 27.7 ha (7.28%). Space plantings and wetlands are scattered across the farm and each land use occupies 3.4% of the total farm's land area (13 ha). Other LULC types including exotic forest, indigenous forest, riparian strips, and residences account for only a small proportion of the farm's land cover.

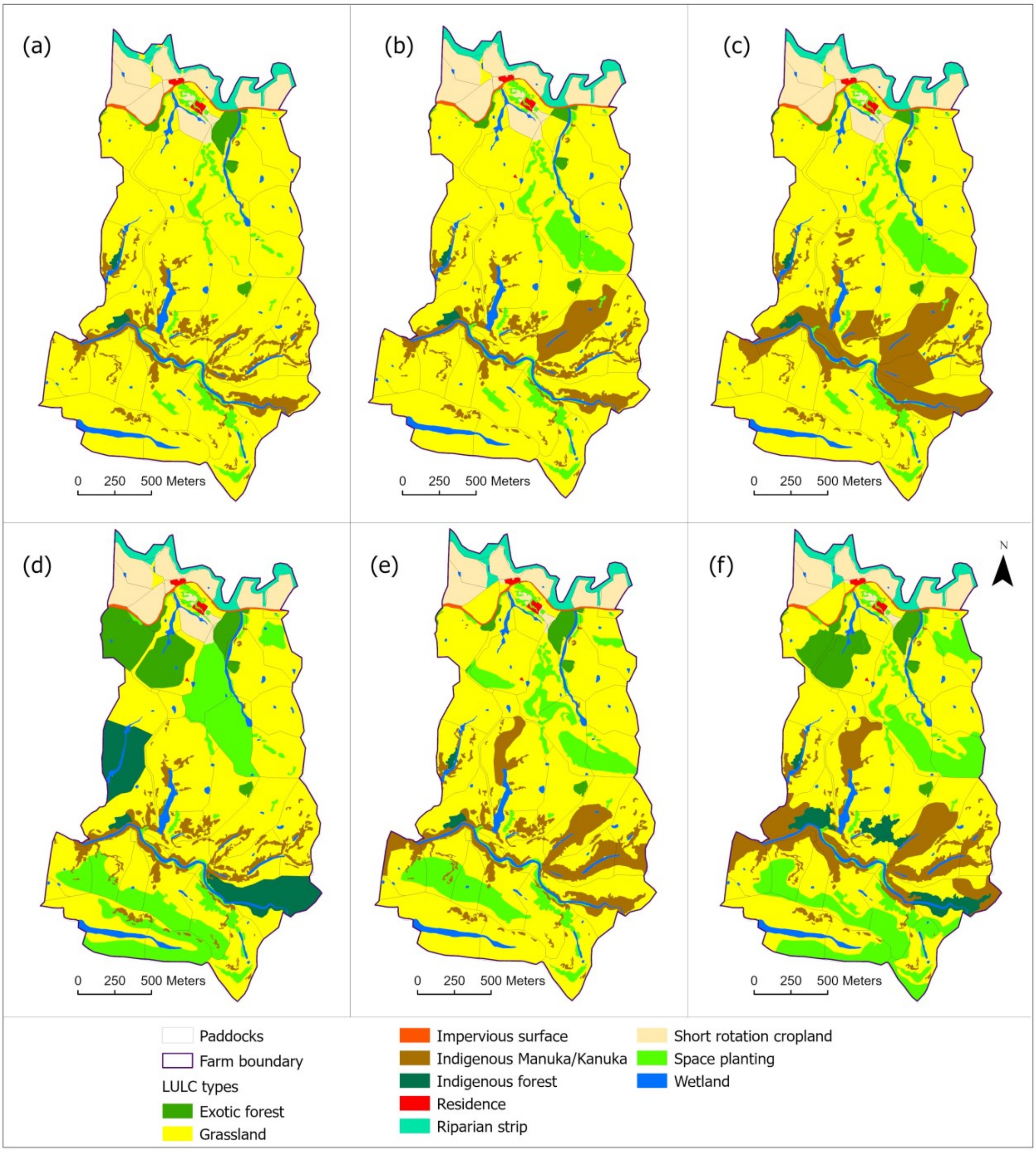

Figure 5.6. Land use and land cover (LULC) in 2020 – S0 (a) and future LULC scenarios for the case study in 2050: (b) agricultural production-based farmers design (S1), (c) landscape conservation-based farmers design (S2), (d) landscape conservation-base expert design (S3), (e) agricultural production-based model optimisation (S4), and (f) landscape conservation scenario using a hybrid approach (S5).

The agricultural production-oriented land use scenario proposed by the farmers (S1) shows the least LULC change. Major changes include an expansion in space planting (9.6 ha), in the northwest of LMU2, a new block of indigenous manuka (9.3 ha), in the north of LMU4, and a reduction in exotic forest (2.4 ha). This scenario features the least reduction in pasture, with only 6.9 ha removed from production. The landscape conservation-based scenario mapped by the farmers (S2) presents a similar trend to the S1 scenario. However, there is a significant difference in the amount and pattern of indigenous manuka plantings, with a 3-fold increase in the area. In this scenario, the area under pasture is reduced by 25 ha, and this is replaced by indigenous manuka.

Table 5.2: Land use land cover area for the current and future land use scenarios (ha)

LULC types	**S0**	**S1**	**S2**	**S3**	**S4**	**S5**
Exotic forest	5.6	3.1	3.1	25.9	5.6	17.9
Grassland*	282.4	275.5	257.4	243.6	275.0	238.3
Indigenous forest	1.4	1.4	1.4	25.9	1.4	11.1
Indigenous manuka	28.0	37.2	55.3	21.9	42.9	49.1
Residence	0.9	0.9	0.9	0.9	0.9	0.9
Riparian strip	8.1	8.1	8.1	8.1	9.0	9.0
Short rotation cropland	27.7	27.7	27.7	27.7	20.2	20.0
Space planting	13.1	22.7	22.7	62.8	39.2	57.5
Wetland	13.0	13.0	13.1	13.0	13.0	13.1

* *This includes pasture areas with space-planted poplar trees*

The land use scenario designed by the expert (S3) demonstrates a significant LULC change from S0, including two additional exotic forest blocks (20.4 ha) in the west of LMU2 and the north of LMU3, and two indigenous forest blocks (24.5 ha) in the west of LMU3 and in the east of LMU4. In addition, S3 has a large area under space plantings (49.8 ha), which is mostly concentrated in the west and northwest of LMU2 and the south of LMU4. The newly added area of exotic forest and indigenous forest is mainly converted from pasture (38.8 ha) and indigenous manuka (6.1 ha).

In the agricultural production-based model optimisation scenario (S4), the main land use change is an expansion in the area of indigenous manuka (14.9 ha) and space plantings (26.1), and a small reduction in the area under pasture (7.4 ha) and cropland (7.5 ha). The expanded indigenous manuka areas are in the south of LMU3, and in the west, along with several locations in the east of LMU4. Space plantings are distributed across several areas in the west and southwest of LMU2 and a big block in the upper south of LMU4.

The landscape conservation scenario using a hybrid approach (S5) demonstrates a change in most of LULC classes. This scenario presents an increase in exotic forest in the north of LMU3 (12.4 ha), indigenous forests in the central areas of LMU4 (9.7 ha), and a small riparian strip (0.91 ha) in LMU1. Also, a large amount of space planting (44.4 ha) is added in the south and southwest of LMU2 and the south of LMU4. The expansion of indigenous manuka (21.1 ha) is relatively similar to the pattern seen in the S3 and in addition to this is a large strip extended along the stream in the south-central of the farm. The decreasing land uses are pasture (44.1 ha) and cropland (7.5 ha). Among six land use options, the agricultural production-oriented scenarios proposed by the farmers (S1) and optimised by the model (S4) demonstrate a similar trend of land use change and are close to the current land use (i.e., the least decrease in pasture area). Whereas scenarios 2 and 5 have relatively similar area of pasture.

5.4.2. Impacts of future land use changes

The impact assessment associated with a comprehensive analysis of ecosystem services and environmental and economic evaluation for all land use scenarios is time-consuming and involves processing and presenting a large amount of information. Therefore, we selected three contrasting scenarios that reflect the largest difference in LULC pattern to demonstrate how land use changes influence the provision of ecosystem services, environmental performance, and economic output. These scenarios are the base (current) land use, the landscape conservation-based scenario designed by the farmers, and the landscape conservation-based scenario developed using a hybrid approach.

5.4.2.1. Changes in ecosystem services

The mean value of ecosystem services provision for 11 quantified services for the case study is presented in Figure 5.7. In relation to the current LULC, S5 shows an increase in a wide range of ecosystem services that include landscape naturalness (0.14), landscape diversity (0.02), provision of natural habitat (0.09), freshwater purification (0.03), carbon sequestration (0.16), erosion control (0.03), provision of manuka honey (0.05), and provision of timber production (0.03). The S2 demonstrates an increase in landscape naturalness (0.08), provision of natural habitat (0.04), freshwater purification (0.01), carbon sequestration (0.06), erosion control (0.02), and provision of manuka honey (0.07). Both S2 and S5 exhibit a reduction in the provision of stockfeed production (-0.03 and -0.08), ease of farming (-0.01 and -0.1), and water yield (-0.02 and -0.03).

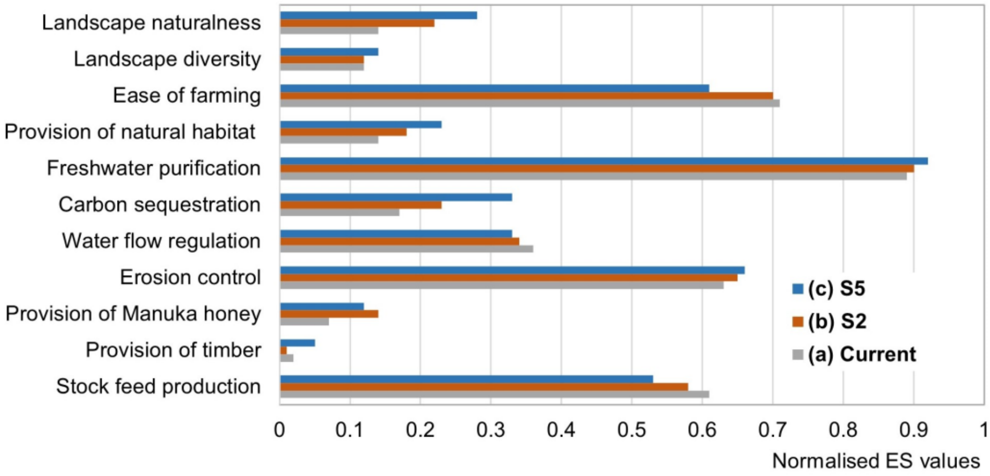

Figure 5.7. Provision of ecosystem services (ES) under different land use scenarios: (a) current land use, (b) land use scenario 2 (S2), and (c) land use scenario 5 (S5).

It can be seen that the differences in ecosystem services change values between land use scenarios are not high when the comparison is considered at a whole farm unit (Figure 5.7). This is because the LULC areas that remain unchanged occupy a large amount of the total farmland. This suggests a further analysis in the areas where LULC changes occurring is needed to better understand the impact of land use change on ecosystem services. Figure 5.8 shows the spatial pattern of the changes in MFC and associated ecosystem services categories between current and future land uses. Overall MFC and MFC by ecosystem services categories are found to have increased in both land use scenarios. For example, an increment of 0.02 and 0.03 in overall MFC are seen in the S2 and S5 scenarios, respectively. In the S2 scenario (Figure 5.8a-d), the increase in overall MFC and three ecosystem services categories occurs mainly in the south-central part of the farm (LMU4) which would be changed from pasture to indigenous manuka. In the south and southwest of LMU2 where there has been a new area of space planting, there is an increase in supporting services and landscape aesthetics, but a reduction in provisioning services. The reduction in MFC, provisioning, and supporting services can be seen in the north of LMU2 where the exotic forest was replaced with pasture. The S5 scenario demonstrates an increase in overall MFC in different parts of the farm, including the south and southwest of LMU2, the north of LMU3, and the north and the south of LMU4 (Figure 5.8e). This pattern is strongly aligned with the changes in supporting/regulating services (Figure 5.8g) and landscape aesthetics (Figure 5.8h). A decrease in provisioning services is found to be strongest in some areas in the south-central area of the farm (LMU4) where indigenous manuka has been replaced with indigenous forest cover (Figure 5.8f). A reduction in provisioning services is also seen in areas that have been space-planted with poplars, although the reduction is relatively low as these areas can still be grazed by livestock.

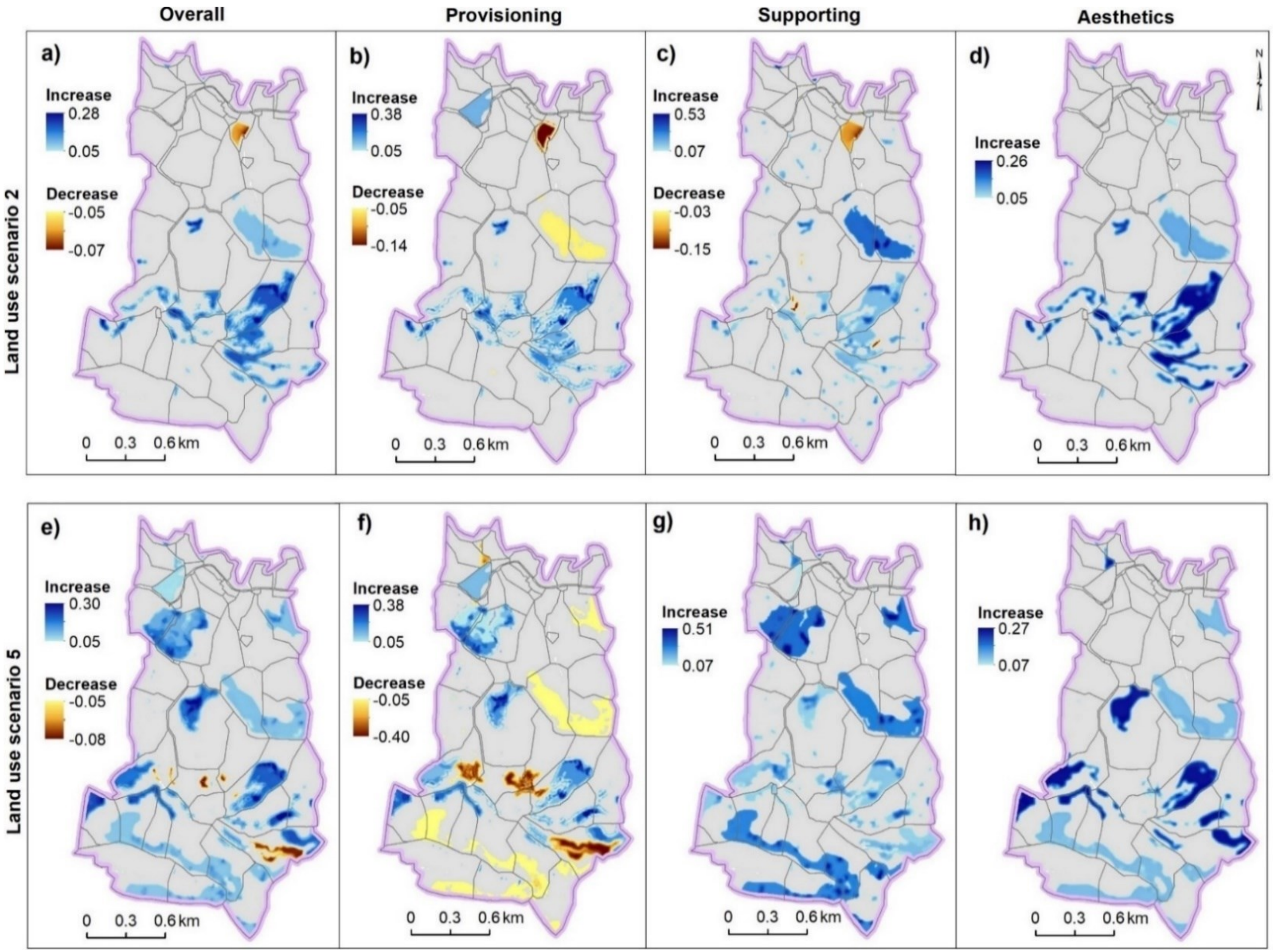

Figure 5.8. Changes in landscape multifunctionality (MFC) and ecosystem services (ES) provision in the case study under land use scenario 2 (Figures 5.8a-d) and land use scenario 5 (Figures 5.8e-h). The grey colour denotes areas that have experienced very little or no change in MFC and ES.

As land use change can lead to a significant change in MFC and ecosystem services provision (Figure 5.8), insight into this process was examined by looking at the variation between different types of land use transformation (Table 5.3). The results show that a shift from pasture to indigenous manuka will provide the greatest improvement in MFC and the provision of all ecosystem services categories.

Table 5.3: Change in landscape multifunctionality (MFC) and associated ecosystem services categories by different types of land use conversion

Types of LULC change	**Changes in landscape multifunctionality**			
	MFC	PS	SS	AES
Scenario 2				
Grassland → indigenous manuka	0.13	0.10	0.10	0.18
Grassland → space planting	0.08	-0.05	0.20	0.10
Exotic forest → grassland	-0.05	-0.08	-0.08	0.02
Scenario 5				
Grassland → exotic forest	0.12	0.11	0.23	0.03
Grassland → indigenous manuka	0.15	0.13	0.11	0.22
Grassland → riparian strip	0.09	-0.11	0.21	0.16
Grassland → space planting	0.08	-0.05	0.20	0.11
Indigenous manuka → indigenous forest	-0.05	-0.28	0.12	0.03

Definitions: MFC - overall landscape multifunctionality, PS - provisioning services, SS – supporting/regulating services, AES – landscape aesthetics.

Despite a minor change in landscape aesthetics, a conversion from pasture to exotic forest results in a significant improvement in MFC concurrent with a substantial increase in the provision of supporting services. In comparison to indigenous manuka, space planting of poplar trees on grassland or the conversion of pasture to riparian plantings will not obtain a high rate of MFC increment (e.g., 1.5 - 2 times lower) due to a reduction in provisioning services. However, these land use changes enhance the supporting services and landscape aesthetics of the farm. In addition, a transformation from indigenous manuka to indigenous forest may reduce the MFC due to a significant loss of provisioning services, but in turn, indigenous forest is seen to be a better land use in terms of providing supporting services and landscape aesthetics.

5.4.2.2. Environmental impacts of LULC changes

Table 5.4 provides information about the environmental impacts of the current and future land use scenarios. Results from the InVEST SDR model demonstrate that the mean values of annual soil loss (i.e., the amount of annual soil loss on a pixel is given by the revised universal soil loss equation (RUSLE) for the case study change from 4.1 (current land use) to 3.59 (S2) and 2.78 tonnes/ha/yr (S5). The average soil loss via surface erosion for the current land use in the case study is in line with values reported in previous studies in hill country and upland areas which range from 1.1 to 5.7 tonnes/ha/year (Lambert et al., 1985; Page et al., 2004). The sediment export that is the amount of sediment eroded from a pixel that reaches the stream (i.e., RUSLE Sediment delivery ratio) (See Hamel et al., 2015) values decrease from 0.26 tonnes/ha/yr (current land use) to 0.23 tonnes/ha/yr (S2), and 0.16 tonnes/ha/yr (S5), respectively. As such, the changes in land use reduce sediment export to the stream for the farm by 11.5% (S2) and 38.5% (S5) compared to the current land use. The InvEST NDR model showed that the land use changes reduce nitrogen (N) leaching on the farm. For instance, mean values of N loss are reduced from 7.62 kg/ha/yr to 7.06 kg/ha/yr for S2, and to 6.22 kg/ha/yr for scenario 5. It means that the average N loss for the whole farm is reduced by 7.4% (S2) and 18.4% (S5).

Table 5.4: Mean value of environmental indicators by different land use scenarios

Environmental indicators	**Current**	**Scenario 2**	**Scenario 5**
Annual soil loss (tonnes/ha/yr)	4.10	3.59	2.78
Sediment export (tonnes/ha/yr)	0.26	0.23	0.16
Nutrient loss (kg N/ha/yr)	7.62	7.06	6.22
Net GHGs emission (tonnes/ha/yr)	1.42	0.03	-4.90

The spatial variation in these environmental changes (Figure 5.9) is an inversive pattern of the supporting services maps presented in Figures 5.8c and 5.8g, as an increase in the provision of these ecosystem services will result a reduction in associated environmental issues. The most significant reduction in sediment export occurs in the steep-lands where pasture is: (a) replaced with exotic forest (the south of LMU3) or (b) replaced with indigenous manuka (the north of LMU4), or (c) spaced planted with poplars (southwest LMU2). In contrast, the greatest reduction in nutrient loss is seen in the south of LMU1 where cropland has been replaced with permanent pasture. In S2, an increase in sediment export and nutrient loss occurs in the north of LMU2 due to a change from exotic forest to pasture.

For the current farm system, the GHGs emitted from grazing livestock and agricultural practices such as fertiliser use is 3.03 tonnes CO_2 eq/ha/yr, which is close to the average value of sheep and beef farm in the North Island of NZ (Vibart et al., 2021). However, net emissions from this farm are 1.42 tonnes/ha/yr because more than half of the GHGs are absorbed by the current indigenous trees and exotic forests. With a significant increase in indigenous manuka in the scenario 2, GHGs emitted by livestock are mostly absorbed. The farm comes very close to being a carbon neutral farm with GHGs emission sitting around 0.03 tonnes CO_2 eq/ha/yr. In S5, a reduction in stock numbers in combination with the planting of a large amount of woody vegetation including indigenous forest, indigenous manuka, and space planted poplars would enable the farm to achieve negative GHGs emissions with an average value of -4.9 tonnes CO_2 eq/ha. More detailed information about the GHGs emission values for each land use scenario are provided in Table 5.5.

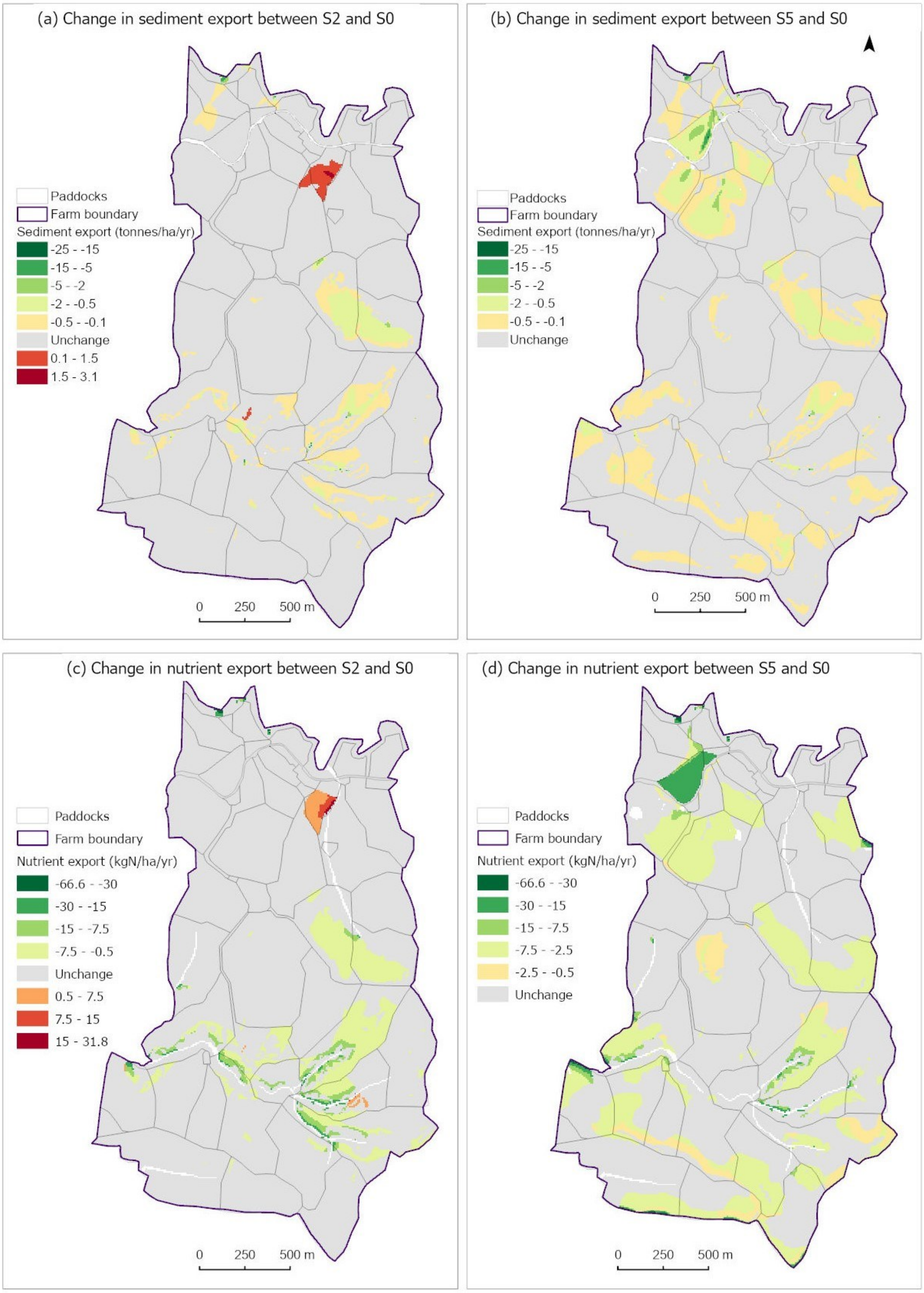

Figure 5.9. Spatial pattern of changes in soil erosion and N loss

Table 5.5: GHGs sources by different land use scenarios (tonnes CO_2-e)

Current land use (S0)				
Source	**Methane**	**Nitrous oxide**	**Carbon dioxide**	**Total**
Digestion (emitted)	991	None	None	**991**
Manure management (emitted)	11	None	None	**11**
Agri soils (emitted)	None	113	None	**113**
Fertiliser use (emitted)	None	None	38.3	**38.3**
Forests (absorbed)	None	None	-614	**614**
Totals	**1002**	**113**	**575**	**540**
Land use scenario 2 (S2)				
Source	**Methane**	**Nitrous oxide**	**Carbon dioxide**	**Total**
Digestion (emitted)	975	None	None	**975**
Manure management (emitted)	10.8	None	None	**10.8**
Agri soils (emitted)	None	111	None	**111**
Fertiliser use (emitted)	None	None	38.3	**38.3**
Forests (absorbed)	None	None	-1123	**-1123**
Totals	**986**	**111**	**1085**	**12.8**
Land use scenario 5 (S5)				
Source	**Methane**	**Nitrous oxide**	**Carbon dioxide**	**Total**
Digestion (emitted)	910	None	None	**910**
Manure management (emitted)	10.1	None	None	**10.1**
Agri soils (emitted)	None	104	None	**104**
Fertiliser use (emitted)	None	None	38.3	**38.3**
Forests (absorbed)	None	None	-2913	**-2913**
Totals	**920**	**104**	**2875**	**-1885**

5.4.2.3. Economic impacts

The results of the financial analysis for the mix of revenue streams for the 3 scenarios are presented in Tables 5.6 and 5.7. For the pastoral area, to maximise the NPV over the 30 years timeframe, the AgInform model recommended a sheep only breeding operation, with replacements, selling some lambs, prime, and some store (i.e., these lambs are sold to farmers on better land who finish them and sell them to the slaughterhouse). The farm currently runs a mix of sheep and cattle. The stocking rates per hectare from the model are on par with regional averages (see https://beeflambnz.com/data-tools/benchmarking-tool) and did not vary much between scenarios. These livestock numbers are greater than that of the current base farm operation, showing that the model has capability to maximise pasture resource use for economic returns.

Table 5.6: AgInform production outputs for the base (current) and future land use scenarios over 30 years for the case study

	Current	**Scenario 2**	**Scenario 5**
Stock unit at opening (1st April)	3116	3067	2861
Stocking rate (SU/ha)	9.5	10.1	9.9
Average EBITDA* from pasture (NZ$/yr)	102,466	113,207	101,726
Average EBITDA (NZ$/ha/yr)	313	374	353

**EBITDA: earnings before interest, taxes, depreciation, and amortization*

In S2 and S5, some of the more challenging pastoral areas of the farm (e.g., steep and eroding lands) have been converted to either manuka or planted with spaced trees. To reflect the positive effect of increased vegetation on animal performance (shade, shelter, easier terrain) (Parminter et al., 2001), animal performance indicators have been modified when running AgInform, hence the increase in stock unit and profit/ha. Average profit/ha increases by 19% and 13% respectively for scenarios 2 and 5, compared to the base farm, the model making the most of the better-quality pasture on the farm and better conditions for the animals.

Table 5.7: Results of the financial analysis, combining all land uses, for the current and future land use scenarios.

	Current	**Scenario 2**	**Scenario 5**
Capital investment for the whole farm (NZ$)	NA	158,188	306,201
Annuity of NPV* / land use (NZ$/yr) for the whole farm			
Pasture	105,612	116,147	104,327
Exotic forest (Pine)		5,188	29,234
Indigenous manuka	9,217	13,813	14,305
Poplars		6,083	41,659
Indigenous forest			2,980
NPV for all economic activities combined (NZ$)	2,571,781	3,120,702	3,634,614
Annuity of NPV for all economic activities (NZ$/yr)	114,830	139,339	162,285
Annuity of NPV /ha (total farm area) (NZ$/ha/yr)	302	367	427

**NPV: Net Present Value*

For the current scenario, the financial analysis including all revenue streams over 30 years, returned a NPV of $2,571,781 for the base farm (Table 5.7). Revenues for the base farm only included grazing and manuka honey. For S2 and S5, other revenue streams were added, including plantation forestry and carbon credits for new plantings (including pine, manuka and poplars for scenario 2 and also indigenous vegetation for S5). Therefore, the NPV and Annuity/ha increased by 12% and 35% respectively for scenarios 2 and 5, compared to the base farm system (Table 5.7).

5.4.3. Decision making on future land use

The results obtained from stages 5 and 6 (sections 5.4.1 and 5.4.2) were utilised for a discussion with the landowner. Among the developed land use scenarios, the landowners mentioned that S5 is the most interesting plan because it had the greatest positive impacts on the farm's environment. If they must change the current farmed landscapes to meet the regulations and constrains from the government such as the National Policy Statement for Freshwater Management (MfE, 2022b), S5 is the most suitable land use scenario. In contrast, the S1 and S4 are more feasible as these scenarios require the least investment. In relation to the types of land use change, the farmers viewed a change to indigenous manuka or space planted poplars as more favourable than a conversion to other land uses. This is because the farming family is open to diversifying into manuka honey production and the implementation of poplars planting does not significantly affect the grazing area. Increasing these LULC types also help them deal with a potential environmental tariff as this change improves shade and shelter for stock and therefore could attract a premium for the produce.

After considering the trade-offs between scenarios and the costs for the land use conversion (e.g., fencing, planting) (Table 5.7), the landowners suggested some modifications to S5 in order to make it both an interesting and feasible option for his farm. For instance, the farmers recommended the use of space-planted poplars instead of converting pasture to exotic forestry in the north of LMU3. Also, the farmers agreed that the expansion of indigenous manuka along the stream in the south-central of the farm was a good idea. However, they believed that this should be achieved through natural plant succession rather than planting the area in commercially propagated manuka seedlings.

5.5. Discussion

5.5.1. Land use changes and sustainability of farmed landscapes

The results from this study demonstrate that in a highly simplified landscape dominated by pasture, LULC change towards increasing land use diversity and complexity is important for increasing MFC and improving the provision of multiple ecosystem services. Consequently, this information enables the managers of farmed landscapes to reduce the negative impacts of farming practices on the environment. This finding is strongly aligned with the conclusion reported in previous studies which highlight that a multifunctional landscape with multiple LULC types co-existing can provide more ecosystem services than a simple landscape which has a dominant land use type (Gómez-Creutzberg et al., 2021; Mander et al., 2007; Pitman, 2022). In the case study farm, all land use scenarios present an increase in overall multifunctionality and ecosystem services provision as well as a decrease in environmental issues in comparison to the current land use (Figures 5.6 – 5.9). This positive impact is due to a conversion from pasture to other land uses which include the presence of woody vegetation. For instance, S5 is the future landscape that has the least pasture and the highest proportion of woody vegetation such as indigenous forest, indigenous manuka, space-planted poplars, and exotic forest. As a result, this landscape shows the highest level of MFC and ecosystem services provision and lowest level of soil erosion, nutrient loss, and GHGs emissions.

Although the importance of having multifunctional landscapes in an agricultural system is well-studied and discussed (Frei et al., 2018; Frei et al., 2020; Jordan & Warner, 2013; Ouin et al., 2022; Rallings et al., 2019; Slámová & Belčáková, 2019), a focus on the comprehensive assessment of the land use change impacts on ecosystem services, economic, and environmental issues at the farm-scale is limited. Recently, the economic assessment associated with changes in a farm's land was analysed in some studies, however, these present a limited measurement of ecosystem services and show a lack of the spatial-explicit assessment of ecosystem services change (Dominati et al., 2019; Dominati et al., 2021). Our study is one of the first farm-scale studies in NZ which covers a wide range of ecosystem services and considers both environmental and economic assessment of land use change. This gives insight into the benefits of alternative land use options and provides more comprehensive information to measure the sustainability of future land use planning. For instance, the financial analysis demonstrated that overall profit per hectare for S2 and S5, could be higher than the current mixed system run by the farmers. Overall profit for the farm is highest in land use scenario 5 due to having various sources of income, including timber, carbon farming, manuka honey production, and stocks grazing. Our study demonstrates that making appropriate land use changes can create a sustainable multifunctional landscape on a farm. As such, this landscape provides numerous benefits to meet multiple needs of the land users. Having such a landscape creates an opportunity to enhance a farm’s economic resilience due to having diverse sources of income. Also, land use diversification achieved by changing LULC enables an agricultural landscape to better adapt to environmental disturbances and climate change.

5.5.2. Advantages of ecosystem services-based geodesign approach

Whilst the fundamental challenge to applying EBM in practice is the difficulty of incorporating the concept of ecosystem services into agricultural land use decision-making (Abdourahamane Illiassou & Oeba, 2020; Bürgi et al., 2017; De Groot et al., 2010), the ecosystem services-based geodesign approach carried out in our study provides an effective solution to overcome this limitation due to its capability to fully integrate the ecosystem services concepts into the design of a sustainable multifunctional agricultural landscape. In the landscape design framework presented in Figure 5.2, ecosystem services concepts are central to almost all stages of designing the future landscape. It is also important that in a geodesign framework such as this, that the farmers actively participated in the process of mapping ecosystem services by providing necessary farm information and evaluating the mapping results (i.e., ground proofing the modelling results). Having farmers involved in the ecosystem services mapping and evaluation processes is also useful to enable non-technical people to understand ecosystem services concepts as they pertain to landscape planning and design.

While many land use planning studies are solely based on a modelling approach which lack collaboration with decision-makers and local people (Xie et al., 2017), our study provides the benefit of a hybrid approach that utilises the advantage of both modelling and non-modelling for land use allocation and modification at the farm-scale. In the modelling methods, different types of LULC can be allocated effectively by utilising optimisation algorithms to process a large amount of quantitative data (Yao et al., 2018). Whereas the non-model approach enables an integration of qualitative data that decision makers or landowners use for making land use changes, including cultural values and social and personal preferences (Knook & Turner, 2020). In this study, the hybrid approach meant that the modelling was utilised for land suitability evaluation which involves the integration and analysis of multiple layers of spatial data, and the non-model approach was used to adjust and modify the land use changes based on the preferences/recommendations from the farmers and local expert. Another advantage of the hybrid approach demonstrated in this study is its capability to reduce the uncertainties and inaccuracies in the modelling results which may occur due to the unavailability of experimental data at the farm scale to validate the models (Dominati et al., 2019; Tran et al., 2022a, 2022b;). With participation and collaboration of the farmers and local expert, the model's results can be qualitatively evaluated and adjusted. For instance, the farmers assessed the pasture production service map and identified the areas where pasture yield pattern was inaccurate and suggested the appropriate change to improve this information (Tran et al., 2022b). Among the five scenarios that were developed using both approaches, the land use scenario that applied the hybrid approach (S5) achieves the highest overall performance. It suggests that a hybrid framework applied for land allocation and modification in our study is advantageous as it utilises the benefits and minimises the limitations of modelling and non-model approaches. This is aligned with recommendations from recent studies that suggest a combination of both approaches is needed to ensure all information and criteria be included and utilised for land allocation in a landscape design project (Brooks et al., 2020; Rajakal et al., 2021; Xie et al., 2017).

In addition, an advantage of using geodesign is that results from each geodesign stage, such as landscape structure and pattern, environmental issues, pattern of future land uses, and the costs and benefits of making land use changes are presented and discussed with decision-makers (Slotterback et al., 2016). Being able to provide meaningful and comprehensive information to the farmers in an intuitive visualization such as in map, or graph format is an effective way to promote the application of ecosystem services approach. The practical relevance of our study is important. In our study, the farmers noted that if the farm landscape must change to meet a range of environmental regulations, the results from this analysis will be considered as an important reference from which to make decisions. Additionally, this approach can also be useful for regional council staff who work with farmers to help them better meet environmental regulations (Todd, 2018) and farm management consultants who work with farmers to help them design farming systems that better meet their goals (Eastwood et al., 2016). Given the capability of integrating comprehensive ecosystem services and associated environmental impacts in designing the future landscapes, integrating EBM with geodesign is a pathway to achieve environmental priorities identified by NZ government such as freshwater management and climate change mitigation (Larned et al., 2022; Leining et al., 2020).

5.5.3. Pathway to implementation

Given the variability within farmed landscapes, it is important that the development of multifunctional agricultural landscapes at the farm scale considers individual farm settings (e.g., LULC pattern, environmental issues, farm's economic situation) and farmer's preferences and experiences. This is similar to the concept of bottom–up and place-based assessment approaches which consider an incorporation of local context and involvement of local people as a key process in the local scale assessment of biodiversity and ecosystem services (Johansson et al., 2019; Kok et al., 2017; Raudsepp-Hearne et al., 2019). It is suggested that including human well-being into the ecosystem services assessment framework is central to the planning of sustainable and resilient agricultural landscapes (Fagerholm et al., 2020). Creating landscapes that are environmentally friendly enables meeting the demands of society and ensuring animal welfare (Romera et al., 2020). However, it is important that the planned farmed landscapes align with the needs and expectations of the farmers. As such, we suggest that having farmers involvement and contribution in the creation of farm-scale land and environmental plans is an important requirement. This is key to understanding the challenges that farmers face and to help with the creation of more feasible and applicable environmental policies and regulations (Crofoot, 2016).

Based on the findings associated with the land use scenarios and impact assessment, and decision making and feedback from the farmers, we propose two-phases of land use change implementation to achieve a sustainable multifunctional farmed landscape. In the first phase, the focus would be to optimise agricultural production and make LULC change to priority areas which exhibit the lowest provision of ecosystem services and which are most vulnerable to environmental issues on the farm. The land use scenarios associated with this goal will be ones involving the least change to area under pasture area such as S1 and S3. As such, MFC and associated ecosystem services improved significantly in some parts of the farm, and this helps to reduce the negative environmental impacts in these areas whilst having minimal impacts on the operation of the farm due to minimum LULC changes. The second phase would require significant changes to the farmed landscapes to achieve an improvement of overall multifunctionality and a wide range of ecosystem services. The aim being that landscapes with a high level of multifunctionality (e.g., the S5) in which LULC is significantly diversified to support the long-term sustainability and resilience of the farming business. Because this stage needs a significant investment in land conversion and a large amount of grassland would be converted to other LULC types, it should be staged over time, depending on the financial support available to farmers from different sources. Being able to do this is important to achieve long-term sustainable development of hill country farm landscapes, given that financial resources for land use change in this area are limited (Heath et al., 2016). To promote a wider implementation of land use diversification, several changes to policy and practice would be needed. The ability of farmers to access financial support in order to implement a sustainable land use diversification plan is critical. However, a barrier to the implementation of the designed land use changes developed from an EBM approach can be the lack of adequate long-term support to enable the farmers to be able to afford the cost of land use conversion and modification and to follow the suggested land and environmental practices. This is especially important for hill country farmers where economic returns are often considerably lower than other areas. Currently, the NZ government has allocated $37 million over 4 years to accelerate the delivery of the national farm planning framework, which aims to help farmers design more sustainable farm systems, following a process similar, but not as sophisticated, as the one presented in this paper. The budget primarily focused on making it easier for farmers to meet business and regulatory requirements (MPI, 2022). However, this funding is aimed at training and development of farm advisers to provide advice to farmers, for industry, regional council, community, and catchment initiatives, to keep farmers aware of regulations and processes, provide advice and ensure consistent farm planning standards. There is very little financial aid available for funding the actual implementation of plans for each farm. At present, farmers in NZ can receive funding for carbon sequestration services and in some regions, biodiversity restoration and protection of waterways (MfE, 2022b). Policy changes towards payments for a range of environmental services (i.e., ecological ecosystem services) such as "biodiversity protection, watershed protection, and landscape beautification", in addition to a long-term investment, may provide incentives to encourage farmers to voluntarily implement LULC changes that can enhance and promote multiple ecosystem services on their farm (Capodaglio & Callegari, 2018).

A lesson from a case study in Vittel, North-Eastern France shows that from 1992 to 2004, all 26 farms in the area had successfully shifted to a new farming system in which agricultural intensification practices such as the excessive use of fertilisers and pesticides, overstocking, and poor management of animal waste were eliminated (Perrot-Maître, 2006). Interestingly, this case study demonstrates that "the same goal could not have been achieved under applicable legislation" (Capodaglio & Callegari, 2018). This suggests that a bottom-up approach in land and environmental planning and management may be a more effective approach than the current policies practices in NZ, in which the central and local governments tends to address the environmental challenges by relying heavily on regulations and environmental legislation.

As well as having a focus on supporting the development of farm plans, it is important that local government (e.g., Horizon Regional Council in the case study area) consider the issues associated with available financial resources to support the farmers to overcome their economic concerns associated with changes in land use. Discussion with land managers to identify key factors and barriers that are preventing or facilitating land-use change on farm is suggested as a way to enable local government to find better solutions and identify means of support for the farmers (Renwick et al., 2022). In addition, the social-cultural aspects of land use change incentives should also be considered, given that a change to the future landscape is not only driven by economic purpose. It is also important that farm-scale land use change intervention towards a sustainable system is context-specific (i.e., dependant on specific type of farm system, farmer incentives, and farm business) (Stringer et al., 2020). As such, policies need to be more flexibles and take this variation into account, given that one policy cannot fit all systems.

5.5.4. Challenges with the designs of future farm systems and future directions

This study focused on LULC change solutions to create multifunctional agricultural landscapes in a NZ hill country farm, trying to optimise LULC based on the mix of natural resources and variability of the farm landscape. The impact of different management practices within land use was not fully considered here and is the next level of discussion needed with the landowners. Considering change in land management practices such as soil and nutrient management can significantly increase soil carbon stock and decrease nutrient leaching (Monaghan et al., 2020; Whitehead et al., 2018), it is important that future studies consider this in the landscape design and impacts assessment processes.

Given the significant impacts of climate change on farming systems (Nelson et al., 2009), measuring the how changes in climate variability can affect the ecological process and agricultural production within the farmed landscape is critical. This provides key information to demonstrate the benefit of developing multifunctional agricultural landscapes, which has been suggested as a climate-smart solution to adapt to changes and disturbances arisen from a changing climate (Lavorel et al., 2022; Scherr et al., 2012). For instance, the future farmed landscape should be designed to cope with an increase in extreme weather events such as storm and drought as this can severely affect the erosion risk and pasture production. Therefore, future studies should consider that the climate change scenarios are being integrated in the design of multifunctional agricultural landscapes.

The AgInform modelling performed for the pastoral area of the farm predicted a sheep-only breeding system would be the most profitable. However, landowners in NZ usually mix sheep and cattle to help with internal parasite management and the management of pasture quality and woody weeds. This behaviour reflects a practical consideration of holistic farm management that models cannot easily integrate. Therefore, working with the landowner to design farm systems is crucial. The financial analysis realised here is a rough first estimation. In practise, the investment in natural (plantings) and built (fencing) capital would be staged over the years as the business's finances allow. Moreover, the discount rate used here for the financial analysis, 2%, might seem low. It was chosen to reflect the lower risk profile associated with multifunctional farms, and investments in natural capital (see Supplementary S5.3). For land use changes, full business cases should be developed to try to predict impacts on cashflow and profit overtime. Integrating the impacts of changing policy and market concurrent with climate change into the economic modelling processes is also valuable to increase the feasibility of the proposed land use scenarios.

Although a wide range of ecosystem services were quantified in this study, the refinement of existing models for each ecosystem services layer as well as including more ecosystem services is needed to better reflect the socio-cultural aspect and well-being of farmers and their family in land use decision making. Given that the EBM approach requires the use of a wide range of ecosystem services assessment tools and models, conducting a sensitivity analysis to evaluate the level of confidence in model output would be ideal. However, if this cannot be carried out due to the lack of empirical/experimental farm-scale data as reported by Tran et al. (2022a), it is important that users recognise and be aware of the possibility of uncertainties and inaccuracies in the modelling results. The use of normalised values and a focus on the pattern of ecosystem services (e.g., hot spot and cold spot of ecosystem services) rather than the absolute values is recommended as a solution to minimise this limitation (Powers et al., 2020; Tran et al., 2022[a,b]). With limited assessment of the ecosystem services mapping models, it is suggested that the ecosystem services mapping involves "people of the place" such as the farmers, field experts, and subject specialists (e.g., farm consultants, land managers in regional council). These people who have knowledge and experiences in the local environment can provide different types of farm-scale information and help to verify and refine the models results.

To fully exploit the potential of geodesign, it is suggested that future studies utilise an application which integrates all landscape design processes and models into one system. Having this will enable the landscape design to occur in real-time and more stakeholders can be involved. Additionally, collaboration between farmers to co-design landscapes for multiple farms within a catchment may be more beneficial than doing an individual farm, given that the provision of many ecosystem services such as pollination, water regulation, animal biodiversity, do not just occur within a farm boundary (McKenzie et al., 2013). At present, a major implementation challenge of our proposed approach is that it requires numerous analyses and the assessment of a large amount of information. As such, it is time-consuming and expensive when utilising this approach in real-world applications. To overcome this limitation, an integration of relevant tools and models that are used to apply this approach into a decision support system (e.g., geodesign hub) is needed so the approach can be applied widely in practice.

5.6. Conclusions

Our study demonstrates a useful solution to promote and advance the application of an EBM approach to farmed landscape planning. Whilst the EBM approach enables the development of multifunctional agricultural landscapes at the farm-scale, the geodesign framework provides a promising tool for incorporating the ecosystem services concepts into agricultural land decision-making and promoting the participation and contribution of landowners in landscape design projects. Results from our study highlight the importance of having multifunctional landscapes in farming systems and applying a comprehensive approach utilising EBM and geodesign. Land use diversification to have farmed landscapes that have multiple LULCs co-existing is key to enhancing the provision of multiple ecosystem services and changing the farm's environmental footprint whilst improving a farm's economic viability. Our study provides a valuable reference for landscape planning and management at the farm-scale. The approach demonstrated here provides farmers with a planning tool that can explore the trade-offs between agricultural production and other ecosystem services. It allows farmers to design farming systems that best meet their production goals while ensuring the farm landscape provides improved ecosystem services. This can help them to work towards and the long-term sustainability of their agricultural businesses. Therefore, we believe that the approach and process presented in this study can be applied widely to help farmers worldwide develop sustainable multifunctional landscapes for their own farms.

Ethics Statement: The study involving human participants was reviewed and approved by Massey University Ethics Committee (Ethics Approval Number 4000021508). The participants (farmers) provided their written informed consent to participate in this study.

Author Contributions: Duy X. Tran: Conceptualization, Methodology, Data collection, Formal analysis, Writing - original draft, Visualization. Diane Pearson: Conceptualization, Writing - review & editing. Alan Palmer: Data collection, Writing - review & editing. Estelle J. Dominati: Conceptualization, Writing - review & editing. David Gray: Writing - review & editing. John Lowry: Writing - review & editing. All authors contributed to a portion of the research. The overall percentage contributed by Duy X. Tran is approximately 80% (see Appendix 1).

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Supplementary materials

Supplementary S5.1: Process of mapping the design goals/managements

In order to quantify the design and management goals for the case study, we based on an assumption that "the goals and methods for the design of particular agricultural landscapes will vary with their degree of intensification and the mix of desired ecosystem services" (Ekroos et al., 2014; Landis, 2017). Landis (2017) reported that three levels of design goals for landscapes that are developed on the basis of the current ecosystem services (ES) supply can be to "restore ecological integrity", "increase landscape multifunctionality", and "sustainably intensify" for high, moderate, and low simplification landscapes, respectively. We adapted this to determine three levels of land use change intervention, associated with three levels of ES supply. This process is described as the following:

(1) In the first step, the provision of multiple ES in the case study was quantified and mapped. A wide range of tools and models were applied to quantify 11 ES. Results from this step are 11 raster layers of ES. For the soil retention service, we used sediment export as a proxy, as suggested by a soil scientist who has experience in erosion assessment in the hill country landscapes. These services were then combined into three main categories (provisioning, supporting/regulating, and landscape aesthetics). The integration of these ES was based on two weighting scenarios: (i) equal weighting (long-term sustainable development scenario) and (ii) landowner weighting (agricultural production-oriented scenario). The raster calculator function in ArcGIS was used to integrate these layers.

(2) The second step involves the hot spot analysis for three ES categories. The ES categories achieved from step 1 was converted to the vector data (GIS shapefile). The Hotspot Analysis (Getis-Ord Gi*) tool in ArcGIS was then utilised for the analysis. Results from this step are the maps presenting the ES provision patterns which are hot spot (high ES provision), cold spot (low ES provision), and not significant.

(3) The third step is aggregating hot spot and cold spot maps of three ES (obtained from the second step) categories and assigning design and management goals for the case study. The spatial analysis tool in ArcGIS was used. This step produced a spatial layer that aggregates all the hots spot/cold spot polygons and an attribute table that incorporates all attributes in the ES hot spot maps. After that, the design and management goals for the study area were assigned using the Field calculator function in ArcGIS. The basis to define relevant goals is showed in Table S1. For example, if the level of ES provision is high in provisioning services, supporting services, and landscape aesthetics, the management goal is S1.

Table S5.1: Priority for landscape design goals

Level of ES provision		***Supporting services***								
		High	NS	Low	High	NS	Low	High	NS	Low
Provisioning services	High	S1	S1	S2	S1	S1	S2	S2	S2	S3
	NS	S1	S1	S2	S1	S2	S2	S2	S3	S3
	Low	S1	S1	S2	S1	S2	S3	S2	S3	S3
Landscape aesthetics		High			NS			Low		

Definitions: S1: Sustainably intensify – low level of land use intervention; S2: Increase landscape multifunctionality – medium level of land use intervention; S3: Restore ecological integrity – high level of land use intervention; NS: Not significant.

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Supplementary S5.2: Major land suitability evaluation criteria for exotic forest (i.e., Radiata Pine), indigenous forest, indigenous manuka, and space planting (i.e., poplar)

Slope can be a limiting factor for production forestry due to the health and safety and environmental reasons. With increasing focus on safety of planting operations, some very steep slopes may not be planted due to high risk for workers. Slope also affects the cost and complexity of harvest operations, and the susceptibility to erosion. It means that land that is too steep is not suitable for exotic forest. In addition, low slope areas are not considered to be high suitable for exotic forest because these lands are prioritised for pasture production (i.e., economic purpose). The very steep slope class (i.e., slope greater than 35°) is recommended for conservation land so this area is highly suitable for indigenous forest, manuka, and space planting.

Table S5.2.1. Land suitability scores for specific land use based on slope classes

Code	Slope classes	Exotic forest	Indigenous forest	Indigenous manuka	Space planting
1	0 – 3°	1	1	1	1
2	4 – 7°	1	3	3	1
3	8 – 15°	3	5	5	3
4	16 – 20°	5	6	6	5
5	21 – 25°	7	7	7	7
6	26 – 35°	9	8	8	8
7	> 35°	0	9	9	9

Aspect has a reasonable impact on productivity and tree growth, as it alters the pattern of radiation and therefore impacts the soil moisture condition. North-facing slopes are warmer than south-facing slopes. In addition, north-westerly aspects are often more exposed to high winds in the Waituna West region. A southern and cooler aspect is more suitable for exotic forest, indigenous forest and manuka, and space planting than a northern and hotter aspect.

Table S5.2.2: Land suitability scores for specific land use based on aspect classes

Code	Aspect	Degree	Indigenous forest	Exotic forest	Indigenous manuka	Space planting
1	North	0 – 22.5	1	1	1	1
2	Northeast	22.5 – 67.5	4	4	4	4
3	East	67.5 – 112.5	7	7	7	7
4	Southeast	112.5 – 157.5	8	8	8	8
5	South	157.5 – 202.5	9	9	9	9
6	Southwest	202.5 – 247.5	6	6	6	6
7	West	247.5 – 292.5	5	5	5	5
8	Northwest	292.5 – 227.5	3	3	3	3
9	North	337.5 – 360	1	1	1	1

Accessibility is an important factor for the establishment of a production forest. Access to main road impacts the planting and ongoing management cost, as well as the cost to harvest and get produce off the farm. A site closer to the road allows the logging truck and necessary equipment access the forest and harvest timber at a low cost. In contrast, the forest that is highly inaccessible can significantly reduce the profitability of timber production, as this requires more expenses related to road construction and infrastructure development. For indigenous forest, a site that is further from the farm track is considered more suitable because indigenous trees can regenerate and growth with minimal disturbances from human and animal activities. Farm tracks are frequently used for agricultural activities such as the transportation of machinery and farm inputs, as well as the regular presence of livestock. These activities can disrupt the establishment and growth of indigenous tree species, and introduce non-native plant species, seeds, pests, to the forest site.

Table S5.2.3: Land suitability scores for specific land use based on the level of accessibility

Code	Distance to main road (m)	Indigenous forest	Exotic forest	Indigenous manuka	Space planting
1	0 – 50	N/A	9	N/A	N/A
2	50 – 100	N/A	8	N/A	N/A
3	100 – 200	N/A	7	N/A	N/A
4	200 – 300	N/A	6	N/A	N/A
5	300 – 400	N/A	5	N/A	N/A
6	400 – 500	N/A	4	N/A	N/A
7	500 – 1000	N/A	3	N/A	N/A
8	> 1000	N/A	1	N/A	N/A
Code	Distance to farm tracks (m)	Indigenous forest	Exotic forest	Indigenous manuka	Space planting
1	0 – 10	1	N/A	N/A	N/A
2	10 – 20	1	N/A	N/A	N/A
3	20 – 50	3	N/A	N/A	N/A
4	50 – 100	5	N/A	N/A	N/A
5	100 – 200	7	N/A	N/A	N/A
6	> 200	9	N/A	N/A	N/A

Pasture yield and LULC determine the availability of land area for land use change in the study site. Changes to exotic forest, manuka, and space planting mostly occur in pasture. Generally, areas with low and very low pasture yield are more suitable for a change to other land uses and vice versa, areas with high pasture productivity are preferred to be reserve for pasture production. This will minimise the impacts of land use change on pasture production. For indigenous forest, manuka and kanuka set the stage for native forests to regrow (i.e., pioneering species in the regeneration of native NZ forests) so the land cover by manuka/kanuka is defined as the most suitable area.

Table S5.2.4: Land suitability scores specific land use based on pasture yield

Code	Pasture yield	Class definition	Indigenous forest	Exotic forest	Indigenous manuka	Space planting
1	< 2000	Very low	9	9	9	9
2	2000 - 4000	Low	8	8	8	8
3	4000 – 6000	Medium low	7	7	7	7
4	6000 – 8000	Medium	5	5	5	5
5	8000 – 10000	Medium high	3	3	3	3
6	> 10000	High	1	1	1	1

Table S5.2.5: Land suitability scores for specific land use based on land use land cover types

Code	LULC types	Indigenous forest	Exotic forest	Indigenous manuka	Space planting
1	Residence	0	0	0	0
2	Exotic forest	1	1	1	1
3	Space planting	1	1	1	1
4	Riparian strip	1	1	1	1
5	Indigenous forest	1	1	1	1
6	Indigenous manuka	9	1	1	1
7	Low intensive pasture	1	9	9	9
8	High intensive pasture	1	9	9	9
9	Short rotation cropland	1	1	1	1
10	Water bodies	0	0	0	0
11	Bare ground	1	3	9	9
12	Impervious surface	0	0	0	0

For indigenous forest and indigenous manuka, distance to the stream is also an important factor influencing the suitability evaluation, given that these LULC types play an important role in minimising the negative impacts of agricultural production on water quality. As such, a site that is closer to the stream is considered more suitable for indigenous forest and manuka planting. The suitability score is assigned as an inverse function to the "distance to farm track".

Table S5.2.6: Land suitability scores for specific land use based on the distance to stream

Code	Distance to stream (m)	Indigenous forest	Exotic forest	Indigenous manuka	Space planting
1	0 – 10	9	N/A	9	N/A
2	10 – 20	9	N/A	9	N/A
3	20 – 50	7	N/A	7	N/A
4	50 – 100	5	N/A	5	N/A
5	100 – 200	3	N/A	3	N/A
6	> 200	1	N/A	1	N/A

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Supplementary S5.3: Justification for the use of discount rate 2% in the AgInform modelling

We chose to use a low discount rate for a number of reasons:

- For multifunctional farms, income would be diversified so it makes sense to use a low discount rate, since risk is lower.
- we have assumed all scenarios have the same level of risk, so we are using the same discount rate for all scenarios.
- For 2019, the New Zealand risk-free rate was 2.0% (previously 5.0%). It has gone up again since but stays low. https://www.treasury.govt.nz/information-and-services/state-sector-leadership/guidance/reporting-financial/discount-rates/discount-rates-and-cpi-assumptions-accounting-valuation-purposes
- Investments in ecological infrastructure, such as biodiversity, should include the idea of intragenerational equity, and therefore not be discounted. Some studies use discount rate of 0% (e.g., Costanza et al., 2021), so using a low discount rate of 2% is aiming to accommodate paradigm.

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Supplementary S5.4: Details of the financial analysis for each land use

For each land use type, we followed the same methodology to determine cashflows over 30 years:

1. Estimate set-up/planting costs NZD/ha, including fencing,
2. Estimate on-going/maintenance costs over the years,
3. Include insurance costs when appropriate,
4. Estimate C sequestration over the years,
5. Estimate revenue from C sequestration when appropriate, using a C price of $65/tonnes,
6. Estimate changes in revenue from the different land uses over the years,
7. Calculate net cash flow combining land uses for each scenario,
8. Calculate net present value of the cashflow for each scenario using a 2% discount rate,
9. Calculate the annuity associated with the NPV.

Table S5.5: The main values used for each land use and references

Land use	**Planting costs $/ha**	**Ongoing or one-off costs, depending on land use**	**Revenue**	**References**
Pine	1,410 – planting	Tracking between $0/ha, $110/ha and $700/ha depending on years	$22,500/ha at logging	Afforestation Economic Modelling, Final Report, MPI Technical Paper No: 2022/02 ISBN- Prepared for Ministry for Primary Industries by Professor Bruce Manley School of Forestry University of Canterbury November 2021. http://www.mpi.govt.nz/news-and-resources/publications/
Manuka for honey	2,200 – planting 700 – hives	Apiculture care/harvest costs $450/ha	Honey price $45/kg	Angus J McPherson, A. 2016, Manuka, a viable alternative land use for New Zealand's hill country? NZ Journal of Forestry, Vol. 61, No. 3
Indigenous forest	4,500 - planting	$50/ha some years – pest/weeds management	Only carbon sequestration	Review of Actual Forest Restoration Costs, 2021 Contract Report prepared for Te Uru Rākau – New Zealand Forest Service, by Forbes Ecology, March 2022, http://www.mpi.govt.nz/news-and-resources/publications/
Space planted Poplars	2,000 - planting	$50/ha some years – pruning and pollarding	Only carbon sequestration	Parminter I., Dodd M., Mackay A. (2001). "Economic analysis of poplar planting on steep hill country." Proceedings of the New Zealand Grassland Association 63: 127–130.

6. Synthesis, discussion, and conclusions

The research explored in this thesis develops an approach that assists in the adaptive planning of farmed landscapes that can support the creation of long-term sustainable agricultural landscapes. The findings demonstrate the effectiveness of this approach using a case study farm in the NZ hill country. Three research questions guided the research. These are: 1) *Why is it necessary to design sustainable agricultural landscapes in New Zealand (NZ) hill country farms*, 2) *How can EBM (and the concept behind multifunctional landscapes) and geodesign be integrated to develop an approach that can assist with sustainable agricultural landscapes planning for hill country farms in NZ*, and 3) *How can the proposed approach and framework integrating EBM with geodesign generate useful spatially explicit land use scenarios for sustainable multifunctional landscapes on hill country farms in NZ*? The following provides a summary of the main results collected in Chapters 2, 3, 4, and 5 which address the defined research questions. The findings are then evaluated in terms of the contribution they make to the field of applied landscape ecology and environmental management studies, and farm environmental planning and management in particular. An evaluation of the advantages and limitations of the proposed approach are discussed, recommendations for future research are presented and some final conclusions made.

6.1. The necessity of designing multifunctional farm landscapes in NZ hill country

To answer the first research question – "*Why is it necessary to design sustainable agricultural landscapes in NZ hill country?*" I first examined the major environmental issues that are confronting the sustainable development of NZ hill country farming systems by exploring relevant literature to provide the background outlined in Chapter

2. Intensification of the hill country for agriculture since European settlement has resulted in significant modification and simplification of the hill country landscape's structure and pattern (McGlone, 1983). Changes to hill country landscapes have increased agricultural production (e.g., pasture production), but substantially reduced, and degraded other non-agricultural landscape functions and ecosystem services and created various negative environmental impacts (e.g., increased soil erosion and GHGs emissions, loss of biodiversity and a reduction in water quality) (Betterige et al., 2017; McIvor et al., 2011; Moller et al., 2008; Parfitt et al., 2009; Parliamentary Commissioner for the Environment, 2016). This means that the major environmental challenges facing hill country farming identified in my study were land use change and deforestation, soil erosion, climate change, and agricultural intensification (Tran et al., 2020). In addition, it is noted that the NZ government has orchestrated a significant increase in environmental regulations and constraints to agricultural production to respond to society's concerns about the environmental impacts of farming and to contribute to the global effort to tackle climate change (Larned et al., 2022; Leining et al., 2020). In this context, NZ farmers are faced with a tension between increasing farm productivity and profitability and reducing their environmental footprint whilst also feeling that they are losing autonomy associated with their farm management. As such, I highlighted that a fundamental change towards recreating and promoting important landscape functions and ecosystem services is an effective solution for hill country farmers (Tran et al., 2020). To provide justification for this conclusion, I analysed the benefits of having a sustainable multifunctional agricultural landscape with emphasis on the NZ hill country context (Chapter 2). The ideal landscapes that are created through redesigning the current agricultural landscapes are those demonstrating a balance between ecological, social-cultural, and economic functions (Landis, 2017). If all the landscape functions and the provision of related ecosystem services are promoted and improved, farming in the hill country can maintain agricultural production to meet economic demand and increase the landscape resilience to adapt to climate change and other disturbances. The landscapes that are redesigned in NZ hill country can be farmed landscapes made up of a mosaic of both natural habitat areas and agricultural production areas where multiple

LULC types co-exist (Tran et al., 2020, 2022c). Whilst the important factors associated with having multifunctional hill country farm landscapes discussed in Chapter 2 are mainly identified based upon a review of literature, empirical results from Chapter 3 and Chapter 5 provide good examples and evidence to confirm this. The results in Chapter 3 show that multifunctional agricultural landscapes can provide multiple ecosystem services, and more importantly, that higher multifunctionality enables the landscape to supply a higher value of ecosystem services. In Chapter 2, I concluded that the creation of multifunctional agricultural landscapes is expected to be an effective solution to solve problems related to landscape simplification on NZ hill country farms. This argument is demonstrated and justified in Chapter 5, given that the future land use scenarios that have more complexity and diversity in their LULC pattern lead to a higher multifunctionality and result in an improvement in multiple ecosystem services, environmental, and economic outcomes. Therefore, these findings provide the rationale for developing a landscape design approach for hill country farms in NZ.

6.2. A conceptual framework for sustainable landscape design

In Chapter 2, I developed a conceptual framework for designing sustainable farmed landscapes in NZ hill country (Figure 2.3). This framework presents a landscape design approach which integrates a landscape ecological approach (EBM in particular) and a geodesign process that was established by Stenitz (2012). Compared to the existing conceptual framework for sustainable landscape design (Abbott et al., 2019; Eastwood et al., 2022; Moore et al. 2018; Romera et al., 2020), this is one of the first studies that provides a detailed framework that demonstrates how ecosystem services concepts can be incorporated into a geodesign process to create multifunctional landscapes at a farm scale in NZ. The creation of farmed landscapes utilising this framework is divided into six stages that are *(1) Landscape description (i.e., Description), (2) Landscape process (i.e., Process), (3) Landscape evaluation (i.e., Evaluation), (4) Future landscape scenarios development (i.e., Design), (5) Impact assessment of alternative landscape* *scenarios (i.e., Impact) and (6) Decision-making.* Relevant information that describes each stage of the framework outlined in Chapter 2 helps to explain how the EBM (and the concept behind multifunctional landscapes) and geodesign can be integrated to develop an approach that can assist with sustainable agricultural landscape planning relevant for hill country farming in NZ. Given the integration of landscape ecological concepts (e.g., ES provision, landscape multifunctionality, spatial interactions) with a geodesign process that promote the participation and collaboration of the farmers, this framework provides an effective solution to address the implementation challenges of applying EBM to the practice of landscape planning and management in NZ and other countries. This work addresses research question 2 of my PhD project: "*How can EBM (and the concept behind multifunctional landscapes) and geodesign be integrated to develop an approach that can assist with sustainable agricultural landscape planning for hill country farming in NZ?".* The proposed approach and associated framework illustrated in Chapter 2 provide a scientific basis for carrying out a comprehensive land and environmental planning process in practice (i.e., to create an integrated farm plan). Using a hill country farm in NZ as a case study, Chapters 3, 4, and 5 demonstrate how the conceptual framework developed in Chapter 2 is implemented to design multifunctional landscapes. For instance, the *Description* stage is reflected in the description of the study area (Chapter 3-5), Chapters 3 and 4 involve the *Process* and *Evaluation* stages, and Chapter 5 emphasizes the *Design, Impact*, and *Decision-making* stages. Also, this framework can be utilised as a starting point to develop a commercial land and environmental planning tool, so farmers and rural professionals have more options to conduct land use planning for the farm.

6.3. Ecosystem services provided by the farmed landscapes

Comprehensive information on the pattern of landscape multifunctionality, provision of ecosystem services and their interactions were presented in Chapter 3. The result from this chapter is useful to answer the first part of research question 3. As discussed in the framework in Chapter 2, quantifying the provision of major ecosystem services is essential to provide insights into the landscape operation in which important landscape characteristics are examined. Whereas, analysing the spatial pattern and interaction between the provision of ecosystem services helps to determine how these processes are linked to each other. In addition, the pattern of ecosystem services supply and overall landscape multifunctionality provide information to understand the overall quality of the landscape and determine areas in the farmed landscape which are at risk and vulnerable in the environment. To obtain these results, I applied a wide range of spatial analysis tools and methods and incorporated the farmer preferences into the process of mapping landscape multifunctionality.

It has been shown that a hill country farm can provide a wide range of ecosystem services, including not only supporting services associated with agricultural production but also the important ecological and cultural services (Tran et al., 2022b). This demonstrates the multiple roles and values that farmed hill country landscapes play in the NZ environment. This also enables farmers to identify and understand the multiple values of their farms which is difficult to recognise using LULC cover information. The pattern of landscape multifunctionality is highly variable across the farmed landscapes, and the interaction between ecosystem services is complex, showing both synergy and trade-off relationships (Tran et al., 2022b). The results also reveal the importance of woody vegetation and wetlands for the hill country farm as these LULC types provide more diverse ecosystem services than the LULC types that produce forage for stock feed (e.g., pasture and cropland). In contrast, the main trade-off was found to be between ecosystem services associated with pasture production (stockfeed production, ease of farming, water supply) and all other services.

Although there are several studies conducted at the farm-scale in NZ, most of the current work lack spatial context and often involve a limited number of ecosystem services (Dominati et al., 2014; Dominati et al., 2019; Dominati et al., 2021). The research presented in Chapter 3 presents one of the first attempts to quantify the spatially explicit nature of landscape multifunctionality at a farm scale in NZ to provide information to understand multiple values associated with the farmed landscapes and to support the decision making of farmers. The capability to quantify the spatial pattern of ecosystem services and associated environmental issues is advantageous compared to non-spatial methods (i.e., the tools and methods that only report the overall value of ecosystem services). This is because information associated with the spatial pattern of ecosystem services provision enables an understanding of the variation in the pattern of ecosystem services across the farm and therefore, allows the land manager to tailor decision making to the strengths and weaknesses of the landscapes. This information provides an important basis to develop effective land use options which can enhance multiple ecosystem services across the farmed landscape. My research also demonstrates that the value and quality of a farmed landscape is significantly dependent on the landscape management goals and preferences of the farmers (Tran et al., 2022b). This finding is in line with the conclusion from previous studies that highlight the importance of having farmers involved in the process of ecosystem services and landscape multifunctionality assessment (Fry, 2001; Solecka et al., 2022). Incorporating the views and preferences of farmers into the evaluation of landscape multifunctionality enables one to obtain more comprehensive results which are not able to be achieved by applying straightforward indices or indicators as demonstrated in several papers (Powers et al., 2020; Rodríguez-Loinaz et al., 2015; Stürck & Verburg, 2017). In addition, the spatial pattern of ecosystem services reflected by the hot spots and cold spots across the farm shown in Chapter 3 is fundamental information to determine the design and management goals for the farm which is utilised for the landscape design process outlined in Chapter 5.

6.4. Impacts of landscape structure on the provision of ecosystem services

Chapter 4 of my PhD thesis focuses on examining the variation in the relationship between landscape structure (i.e., LULC and topographical pattern) and the provision of ecosystem services using pasture production, sediment retention, and water yield as an example. Quantifying this relationship is central to understanding the landscape processes (i.e., the Process stage in the conceptual framework) and provides essential information to determine the effective landscape configuration where different LULC types co-exist (i.e., the LULC pattern is appropriately arranged to support multiple ecosystem services (Kirchner et al., 2015; Lamy et al., 2016). To spatially quantify this relationship, I applied the Multiscale Geographically Weighted Regression (MGWR) model to a range of landscape structure indicators such as Largest Patch Index (LPI), Contrast Class Edge (CCE), Edge Density (ED), and Terrain slope (SLOPE) and three ecosystem services that are stockfeed production, erosion control, and water regulation. To date, studies associated with the assessment of the relationship between landscape structure and the provision of ecosystem services have often been conducted at catchment or regional scales, whilst farm-scale studies have been limited (Redhead et al., 2020; Xia et al., 2021; Sannigrahi et al., 2020; Dahal et al., 2021; Jarvis et al., 2017; Sun et al., 2020). Although a few farm-scale studies associated with ecosystem services assessment have been conducted recently, most current studies often reported the aggregated average values for the whole farm, whereas spatial heterogeneity in the impacts of landscape structure on the provision of ecosystem services across the farm are not well presented (Boeraeve et al., 2020; Bullock et al., 2021; Campos et al., 2019; Dominati et al., 2021). My study is a good example to demonstrate the value of quantifying the relationship between landscape structure and ecosystem services provision, showing that such analysis can provide useful information to adequately develop farm management plans that inform localised practices that reflect the spatial variation across the farm.

Results obtained from this model reveal that the provision of ecosystem services in the case study hill country farm is significantly affected by the patterns of landscape composition and configuration and topographical features, and this varies across the farmed landscape. For instance, a landscape made up of larger patch sizes of agricultural land is strongly associated with higher water yield and lower sediment retention capacity, whereas a landscape with a mixture (i.e., configuration) of tree cover and grassland is better for sediment retention. The impact assessment of the change in ecosystem services due to LULC change in Chapter 5 confirms this finding, as showing that: (1) the farmed landscapes where multiple LULC types co-exist can provide a wide range of ecosystem services and therefore, meet both economic and environmental demands; and (2) land use change towards increasing landscape diversity and complexity is key to achieving more sustainable multifunctional farmed landscapes (see 5.5.1). This knowledge helps inform options for the potential modification of the LULC to optimise land use and management in the most suitable places to attain desired ecosystem services.

Results and information provided by Chapter 4 enable the second part of research question 3 to be answered. It has the potential to serve as a primary reference for future studies and can provide a good foundation for the development of an automated land change optimisation model or a spatial decision support system to help to design a multifunctional landscape. Although this application is not demonstrated in my PhD, the finding derived from this Chapter that associates with the high spatial variability of ecosystem services provision across the hill country farmed landscape, even within a paddock, demonstrates that detailed spatial information is essential to better understand the landscape value and processes on a farm. This suggests that it is necessary to consider place-based (i.e., location-based, site-specific) planning and management for the best utilisation of ecosystem services. Some key findings in this Chapter were demonstrated in the design of future landscapes in Chapter 5. For instance, results from Chapter 4 indicate that changing from pasture or cropland to other LULC in the north-end of the farm will create the most negative impact on stockfeed production and the least impact occurs if this happens in the central part of the farm. As such, in the creation of future land use scenarios for the case study, there is no LULC change suggested in the northern paddocks. Whereas the most complicated LULC change pattern is presented in areas around the centre of the farm where there exists the most complicated relationship between LULC pattern and ecosystem services supply.

6.5. Advantages of integrating ecosystem-based management with geodesign

The results from Chapter 5 of this PhD demonstrate the benefits of multifunctional landscapes design within agricultural systems and the process that was used to integrate the ecosystem services approach with geodesign to create multifunctional landscapes for a case study in NZ hill country. This provide key information to answer the research question 3: "*How the proposed approach and framework integrating EBM with geodesign generate useful spatially explicit land use scenarios for sustainable multifunctional landscapes on hill country farms in NZ?"*.

As described above, the second (Process) and the third stages (Evaluation) of the landscape design process are well presented in Chapters 3 and 4 so the focus of Chapter 5 is the Design, Impact, and Decision-making stages. A range of tools and methods were applied in this Chapter to create future land use scenarios (Design) and assess the impacts of land use change on the provision of ecosystem services/landscape multifunctionality and the environmental and economic output (Impact) (see section 5.3). Based on this information, the farmers made decisions on the future land use plan for the farm (Decision-making). Compared to recent studies in NZ that applied geodesign to develop sustainable multifunctional agricultural landscapes (Abbott et al., 2019; Eastwood et al., 2022; Moore et al. 2018; Romera et al., 2020), my thesis comprehensively integrates EBM with geodesign to support farmers to create different land use options for their future farmed landscape. The conceptual framework in Chapter 2 and the illustrated case study in Chapter 5 demonstrate that in the ecosystem services-based geodesign approach, ecosystem services are central to almost all stages of designing the future landscape. Often, most studies use the provision of ecosystem services as an indicator to measure and assess the impacts and performance of land use change scenarios (i.e., the Impact stage in this thesis) (Bretagnolle et al., 2018; Ouin et al., 2022; Romera et al., 2020). However, utilising the spatially-explicit information on ecosystem services to determine the design and management goals for a farm has not been explored Based on the concept developed by Landis (2017), my PhD used spatial information associated with the degree of ecosystem services supply to develop design goals for the case study farm. Given that the design goals are important basis for the development of future land use scenarios (i.e., design multifunctional landscapes) (Landis, 2017), incorporating ecosystem services information into the process of landscape design is an essential step to enable the EBM approach to be fully implemented.

A fundamental aspect of the implementation of the farmed landscape design approach described in this PhD is that it requires the participation and contribution of farmers in the design of future landscapes, including in the process of mapping ecosystem services, developing land use scenarios, and evaluating these. The proposed land use scenarios for the farm can be changed or revised based on the discussion with landowners (i.e., iterative design) and this enables the future farmed landscapes and associated land use change to be aligned with the needs and expectations of the farm owners. This is an effective solution to empower the roles of famers in the development of land and environmental planning and management plans for their farm (Fagerholm et al., 2020; Johansson et al., 2019; Kok et al., 2017; Raudsepp-Hearne et al., 2019). Another advantage of using geodesign and relevant GIS tools and techniques to implement the EBM approach is that information associated with the pattern of ecosystem services, environmental issues, current and future land uses, and the costs and benefits of land use changes are presented and discussed with farmers in an intuitive visualization such as in a map, or graph format. This is an effective way to promote the application of an EBM approach. As such, these advantages allow this approach to provide an effective solution to the implementation challenges facing the EBM approach.

6.6. Contributions of the thesis

This PhD thesis develops an approach that can assist adaptive farm planning through generating a long-term sustainable agricultural landscape in the NZ hill country farming system. Several contributions are made by the research:

The original publications incorporated in this thesis provide new findings and insights to the knowledge base of applied landscape ecology and environmental management studies. Key findings that make a contribution to the current literature include: (a) advancing the knowledge associated with local differences between landscape structure and the provision of ecosystem services in complex farmed landscapes (e.g., hilly and mountainous landscapes) and (b) acknowledging the importance of incorporating the views and preferences of landowners/farmers in the values of farmed landscapes.

Although many studies have been carried out to measure landscape multifunctionality and associated ecosystem services (Hermes et al., 2018; Hölting et al., 2018; Kalinauskas et al., 2021; Rodríguez-Loinaz et al., 2015; Powers et al., 2020; Song et al., 2020), comprehensive mapping and assessments at the farm scale are limited. Through utilising advanced spatial analytics tools and methods such as a spatial regression model to examine the pattern and interaction between ecosystem services and LULC structure at the farm scale, this thesis provides insights into the spatial variation of landscape multifunctionality and ecosystem services provision and demonstrates how land use and land management goals affect the value and quality of landscape multifunctionality. Also, the research presented in this PhD is one of the first studies to examine the spatial relationship between multiple ecosystem services supply and land use patterns. This work quantifies the various impacts of LULC composition and configuration patterns on the quantity and distribution of multiple ecosystem services and suggests how this type of information can be utilised in a sustainable farm planning context. The findings obtained from this analysis help to determine how to develop a landscape where different LULC types co-exist, and the land use pattern is appropriate to maintain and promote multiple landscape functions and services (Kirchner et al., 2015). This constitutes added value that can provide a better foundation for understanding the spatial-explicit pattern of ecosystem services and their interactions in farmed landscapes. Therefore, this helps to promote the application of a spatial-based approach for farm environmental planning and management.

By demonstrating how the proposed methodology and research findings can be used in the development of sustainable agricultural landscapes on a NZ hill country farm, this PhD provides evidence to support the significance of applying a multi-disciplinary or transdisciplinary approach in environmental management (i.e., the integration between landscape ecology and landscape architecture in farm planning). Through this approach farm planning has shifted from a process based largely on land evaluation that often uses environmental data to assess the land use capability for agricultural production, to a broader assessment that considers the impacts on receiving environments and multiple ecosystem services provided by agricultural landscapes (Dominati et al., 2018).

Ecosystem services-based management integrated with the theoretical and applied principles from the field of landscape ecology provides the pathway to operationalise this transition. This approach is strongly aligned with the concept of regenerative agriculture, the agricultural practices that seek to optimise farm performance for multiple benefits (i.e., environmental and socio-economic outcomes) to achieve sustainable agricultural systems. However, major barriers to the implementation of an EBM approach are the difficulty of incorporating the ecosystem services concepts into agricultural land use decision-making and the lack of methods for involving the farmers in the planning process (Di Lucia et al., 2018; van den Belt & Blake, 2014; Dominati et al., 2019; Abdourahamane Illiassou & Oeba, 2020; Bürgi et al., 2017; De Groot et al., 2010). My thesis demonstrates that by embedding the EBM in geodesign, which provides a bridge between geo-information technology and landscape architecture, an effective solution to tackling this challenge can be achieved. By combining landscape ecological concepts such as ecosystem functions and services, ecosystem services supply and demand, the value of ecosystem services, spatial pattern and interactions, land use change, within a geodesign framework, landscape multifunctionality can be fully incorporated in a design-driven approach that has collaboration with the farmers as a central to designing the farmed landscapes. Also embedding the EBM concepts in the geodesign framework is important for ensuring that this land and environmental planning tool is grounded by scientific theory. Therefore, this helps to promote the practical application of an EBM approach in sustainable planning and management of agricultural landscapes.

The approach demonstrated in this PhD thesis can provide an important basis for the development of a farm plan which utilises the landscape resources to achieve multiple goals such as agricultural production, environmental impacts mitigation, and cultural/social aspirations. This is strongly aligned with the objective of regenerative farming (i.e., transformative agriculture) in which a farm system is optimised to achieve multiple benefits (LaCanne and Lundgren, 2018; Pearson, 2020). Most environmental farm plans applied in NZ often target specific environmental management goals such as a “soil conservation plan” with a primary focus on erosion control, a “forestry-oriented environmental farm plan” with a goal of establishing production forestry, a “riparian plan" with a major focus on water quality, a "nutrient management plan" with a focus on the development of a nutrient budget to balance nutrient inputs with nutrient losses (Blaschke & Ngapo, 2003; Maseyk et al., 2019). As such, information that is used to develop options for land use and management using these methods is often limited. It means that applying these traditional methods to develop a comprehensive farm plan that covers various environmental and social-economic issues and requirements is challenging. In the context that NZ farming systems are transitioning to a more sustainable development focus, the ecosystem services-based planning and management approach developed in this study has the capacity to provide a comprehensive farm plan that will meet multiple management goals.

In its current form, the approach proposed in this PhD thesis can be seen as a conceptual solution for the challenges facing the NZ farming systems and environment. However, despite the conception nature of the work, the practical relevance and contribution of this PhD is important. The approach demonstrated in this thesis can be utilised as a structured platform to develop a farm-scale spatial decision support system to help NZ farmers and the farming sector overcome multiple socio-economic and environmental challenges. This planning tool considers the participation and contribution of farmers as central to the farm planning process. The tool can help farmers to explore the trade-offs between agricultural production and other ecosystem services. It can also support them to design farming systems that best meet their production goals while ensuring the farm landscape provides improved ecosystem services. This means that it helps to ensure the long-term sustainability of their agricultural businesses, and to visualise the land use changes that they might make. As such, if the farmed landscape must change to meet a range of environmental regulations, the results and information obtained from this tool will provide farmers with an important reference from which to make decisions. So far, farm environmental planning in NZ has tended to use geospatial data to generate maps to inform planning. However, it has not really embraced the idea of conducting important spatial analysis required for farm environment plans. This approach can provide the opportunity for alternative scenarios to be recommended and visualised within a geospatial framework that utilises ideas drawn from geodesign. A land use design system that incorporates the ecosystem services concept and allows farmers to be effectively involved in and contribute to the planning process via an easy-to-use system could be an effective solution for effective sustainable land use planning at the farm scale. Additionally, this tool can also be useful for regional council staff who work with farmers to help them better meet environmental regulations (Todd, 2018). It is also beneficial for farm management consultants who work with farmers to help them design farming systems that better meet their goals (Eastwood et al., 2016). Given the capability of integrating comprehensive ecosystems services and associated environmental impacts in designing the future landscapes, integrating EBM with geodesign is a pathway to achieve current environmental priorities identified by NZ government such as freshwater management and climate change mitigation (Larned et al., 2022; Leining et al., 2020).

6.7. Challenges and limitations

One of the major challenges of undertaking this farm-scale study that was evident through the three empirical studies conducted on the case study outlined in Chapter 3, 4, and 5, was the lack of relevant data and models for quantifying and validating a wide range of the farm-scale ecosystem services. In this PhD, the modelling of ecosystem services was limited by the unavailability of a wide range of farm-scale spatially explicit data. It is typical that in NZ the fundamental information required to understand the farmed landscape such as soils, topography, and climate data are not sufficient in terms of both spatial and temporal resolution. This is especially the case in the hill country and for steep-land farms as it is time-consuming and expensive to obtain high-resolution data such as soil carbon stock, nutrient concentration, and survey information of natural habitat due to the complexity of the landscapes. In most cases, long-term data at the farm-scale are often not available. Also, spatial-explicit models that can capture the variation of complex farmed landscapes like NZ hill country are still lacking. At present, most of the models used for ecosystem services mapping are designed and developed for catchment or regional scales. For instance, a comprehensive soil erosion model calibrated for farm scale analysis that can incorporate the complexity and detailed variations of the landscape into the erosion modelling process has not yet been developed. This is a significant barrier which prevents the application of an ecosystem services approach at the farm-scale. A typical example of this relates to the sediment retention (i.e., erosion control) service. The sediment retention values from the InVEST SDR model are approximated by estimating the difference between sediment export from the bare soil and the actual land cover class (Hamel et al., 2015). Under this model's assumption, the sediment retention capacity is often very low in flat areas like hill-tops and extremely high in steep-land areas (Tran et al., 2022a). This is somehow a counterintuitive sediment retention pattern as the areas like hill-tops have already retained a large amount of sediment as these landscapes have eroded the least, whereas it is the steep-lands where significant erosion often occurs. As such, when using the InVEST SDR model, this pattern needs to be interpreted as being one where changing land cover for the purpose of improving soil erosion will achieve the highest performance when steeper areas are targeted (Woznicki et al., 2020). However, this is a complicated explanation and it is difficult to use in practice when non-technical audiences are involved. Also, the current available DEM data that can be used for soil erosion modelling (8-15 meters resolution) is not detailed enough to capture the impact of micro-topographical features on the erosion process. With limited field verification of the ecosystem services mapping and appropriate farm-scale models, it is important that we must recognise and be aware of the possibility of uncertainties and inaccuracies in the modelling results.

In this study, only one farm was used as a case study and the assessment of socio-cultural aspects of the ecosystem services is limited. Only three landscape aesthetics indictors were used as representative examples of landscape aesthetics. The primary goal of this study is to propose an approach that integrates EBM with geodesign and to apply this to develop a sustainable multifunctional agricultural landscape that can meet environmental, economic, and socio-cultural demands. The conceptual framework that presents the approach has a relatively comprehensive number of ecosystem services and indicators covering these aspects so this can be used as a good reference when applying to a case study. It would be ideal if this comprehensiveness is reflected in the selected case study. However, including a large number of ecosystem services requires a significant increase in data collection and processing, modelling, and analysis and this is time-consuming and expensive meaning that a “proof of concept” only approach was taken in this study. In addition, the number of ecosystem services often differs between farms and the role each service plays in the planning process are dependent on farmer’s priorities and preferences. Given the limited number of socio-cultural ecosystem services quantified in the case study, it must be noted that it has a more environmental and economic focus.

Given that the collaboration between stakeholders is not fully demonstrated here, the approach demonstrated in this study is only one that reflects a farmer-centric approach. It would be ideal when attempting to design future landscape for the case study farm to involve a variety of participants (e.g., local people and iwi, farm consultant, regional council, and the Department of Conservation) so the collaboration process could be well-demonstrated, a wider range of perspectives on land management considered, and more land use scenarios could be developed for the study site. However, the absence of a variety of stakeholders does not mean that farm planning process proposed in this study neglects the regulations and public interests. It is important to note that farm plans developed for the case study take place within the boundary of environmental constraints/regulations (i.e., compliances) and some socio-economic dimensions. Public interest and preferences are strongly reflected in the planning goals, given that the development of future land use scenarios considers achieving a wide range of global and national interests (e.g., GHGs emission, water quality, biodiversity). Given that the geographic focus of this study is the hill country farm-scale land use planning in which the decision making takes place in private land use, public participants and collaborations are valuable but not mandatory. This is the main difference to public land use planning (e.g., public park, conservation areas, natural reserve) in which public participation is crucial.

Despite the effectiveness of integrating EBM with geodesign, the implementation in a real-world application is challenging. Due to the complexity of the ecosystem services and land use modelling, the current approach requires numerous data analysis and modelling. It also involves an assessment of a large amount of information. For example, the impact assessment associated with a comprehensive analysis of ecosystem services, environmental analysis, and economic evaluation for many land use scenarios is time-consuming and expensive. In addition, the participation and contribution of the farmers are central to the implementation of the geodesign approach. Active involvement in all the stages of geodesign to co-design the farmed landscapes requires the farmers to spend a large amount of time involved in the process. In reality, it is difficult and challenging for farmers to find the necessary time for this commitment. Besides, such an approach requires specific expertise in GIS to implement the processing, modelling, and presentation of spatial information. As a result, the approach in its current form may be not feasible for a wider application to commercial farms due to the challenges associated with the comprehensive modelling and assessment.

The implementation of the approach in the current study means that it is applied to an individual farm in a manner that considers the case study as an isolated island where all landscape processes are operating within the farm boundary. This helps to reduce the complexity and the cost of modelling and analysis. However, the provision of many ecosystem services and environmental impacts do not just occur within a farm boundary and each service may have different ecological, political, and cultural extents (McKenzie et al., 2013). For instance, some services and issues can be defined within a farmed landscape such as pasture and animal production. Whereas several ecosystem services such as pollination, water regulation, animal biodiversity, and environmental impacts (GHGs, erosion, water quality) that originate from a hill country farm may affect the neighbouring farms and lower catchment areas. Also, the regulations for the environmental standards under which farming operates may differ between farm systems (e.g., dairy vs sheep and beef) and vary across regions. As such, limiting the planning process within the farm boundary may result in a deficient farm planning outcome.

Another limitation is that this PhD demonstrates how the proposed approach can support the creation of sustainable future farmed landscapes, however, the implementation plan for the developed land use scenarios is neglected. It is recognised that the resources for land use change intervention, especially for the farms located in the hill country of NZ are very limited (Heath et al., 2016). Although the long-term benefit of a multifunctional landscapes is transparent and well demonstrated, having enough financial support to implement LULC change is always challenging. The capability of the proposed approach to create a multifunctional landscape for long-term sustainable development is advantageous. However, it is also important to ensure that the proposed farmed landscape has an associated implementation plan providing detailed guidance on the land use change and transition pathway. This is valuable to farmers as it helps them determine priority actions and how to utilise resources to carry out specific land use change actions. Without an implementation plan that specifies in detail the activities and associated costs and benefits of land use conversion within a time frame, the designed land use plan may be less practical or feasible.

6.8. Recommendations for future research and application

The objective of this PhD study was not to develop specific models to map ecosystem services or a new method, or algorithm to optimise land use, but rather to find an effective approach to utilise and integrate existing science for designing future farmed landscapes. However, future research needs to address the limitations associated with data and models used in a farm-scale analysis to improve the accuracy of the ecosystem services assessment and therefore enable the provision of better information for the planning process. The first step is to assess the capability of existing tools, models, and indicators to select the most appropriate/efficient ones that are suitable for the farm-scale analysis. This process should follow the frameworks and classification schemes that provide detailed guidance on a systematic selection of tools/models and indicators for quantifying ecosystem services provision and the interaction with land use management illustrated in the previous study by van Oudenhoven et al. (2012). The focus of this step should involve the confidence assessment for the models and input data. For instance, ecosystem services assessment tools/models developed and validated for use in the NZ context should have higher priority than ones developed elsewhere. Besides, integrating different sources of data and expert knowledge is recommended to provide more accurate value in relation to ecosystem services provision (Stritih et al., 2019). This PhD has utilised data and information from the farmers, scientists, and remote sensing. To obtain more farm-scale data, future work should engage more field experts and subject specialists (e.g., farm consultants, land managers in regional councils). Their knowledge and experiences in understanding a farm's land and environmental planning and management, especially the local environment allows different types of farm-scale information to be obtained. Using more advanced technologies and methods to derive farm-scale data is suggested to reduce the cost for data collection and processing. For instance, the application of hyperspectral remote sensing and machine learning methods can offer a solution to generate high-resolution data for ecosystem services modelling at the farm-scale, including soil carbon, biodiversity, and microclimate data. For a long-term solution, if the ecosystems services approach is to be used to advance land evaluation and planning as suggested by a number of studies (Boumaet al., 2021; FAO, 2007, Dominati et al. 2016, Wadoux et al., 2021) continuing investment in producing accurate spatial data at the farm scale and appropriate spatial models to capture the complexity of the farm landscape is critical. Calls have repeatedly been made for a national effort for providing farm-scale data (Manderson & Palmer, 2006; Carrick et al. 2014; Dominati et al., 2019; Burkitt & Bretherton, 2022). It requires more soil and land resources observations on the ground, and often more detailed information on the factors that control soil formation and land cover pattern. This is especially important in highly complex farm landscapes like NZ hill country where a higher level of soils and land and environmental information, such as detailed soil survey and site-specific observation of key land resource attributes may be required.

In addition, the inclusion of more services, especially the socio-cultural services, is needed to better reflect the well-being of farmers (and their family), and the wider community in land use decision making. For example, the services associated with animal welfare, or education value provided by farmed landscapes should be considered in the farm-scale assessment. Adaptation of the socio-cultural ecosystem services framework, tools, and methods to quantify them in an NZ context that were reported in several studies in NZ (Brown & Brabyn, 2012 [a,b]; Harmsworth & Awatere, 2013; Kerr & Swaffield, 2012; Swaffield & McWilliam, 2013;) would be useful to cover an appropriate number/indicator of socio-cultural services. Taking the Māori knowledge, values, and perspectives into account to develop the ecosystem services framework is suggested in future study as a way to increase the comprehensiveness of the EBM approach. Having a framework that integrates local cultural values and perspectives to western science will provide valuable guidance and a basis for the implementation of practical work in sustainable landscape planning and management in NZ.

Future studies should also consider defining the associated boundaries in which farm systems operate to select appropriate indicators and benchmarks for landscape assessment. Although the future landscape for a farm is designed and presented within the farm boundary, other boundaries need to be defined based on the extension of ecosystem services supply (e.g., catchment scale for biodiversity and water quality targets, or national scale for GHG emissions and animal welfare indicators). These boundaries need to be considered early to design complex multifunctional farm systems.

It is suggested that future research focuses on the collaboration between farmers and other stakeholders such as neighbouring farmers, iwi, farm consultant, regional council, and the Department of Conservation to co-design landscapes for multiple farms within a catchment and using multiple case study farms that represent different agricultural systems (e.g., sheep and beef, dairy, horticulture). Testing the approach for various farm systems is necessary to evaluate the performance and applicability of the EBM approach and geodesign framework. Inclusion of greater stakeholder and community participation in defining and setting boundaries within which resources have to be managed will ensure the preservation of natural capital stocks and the function of receiving environments, recognises that farms are not isolated, but part of wider landscapes. This is critical to ensure that farm planning aligns with needs and expectations of not only the farmers, but also wider society (i.e., citizens and consumers).

The development of an application which integrates all landscape design processes and models into one system such as a spatial decision support system (DSS) or a web-based application is suggested as a solution to overcome the implementation of the approach proposed in this PhD thesis in practice. This will enable the landscape design to occur in real-time, more stakeholders can be involved, and it could help to reduce the complexity of computation and the modelling process. To achieve this, a standardization of the process, tools, and data is required to make the approach more applicable in different farm systems. Although the DSS is a complex application as it integrates multiple tools and models, it is important that this application is easy to use (e.g., a friendly and smart user-interface). An upgrade from 2D to 3D visualisation of current and future farmed landscapes needs to be considered so that farmers and relevant users can have a greater understanding of the farm's data and modelling results. Also, this application should be able to provide long-term support to the farmers. For instance, if there are new regulations on nutrient use or GHGs emission level, the system will update and generate the adjusted land use plan. Thus, the development of DSS should incorporate into the geodesign framework a module for the development of an implementation plan to achieve the designed landscape and a protocol for the monitoring of the implementation of the land use change. This is needed to support adaptive farmed landscape planning and doing this will reduce the uncertainty of the developed farm plan. The DSS should be developed in a way that it is able to provide different levels of environmental analysis/modelling and is flexible to use for different purpose. This allows the application to be used by different types of users (farmers, consultants, regional council staffs) for different purposes. For instance, at its simplest level a farmer can obtain a report about the current level of soil erosion on his farm with just one click. In a more advance level, a farm consultant or environmental manager can enter the farm's information and use different tools to carry out the overall environmental assessment and develop future environmental management scenarios. Having this capability will promote the application of an EBM based-geodesign approach in land and environmental management practice.

6.9. Conclusions

The objective of this thesis was to develop and test a landscape design approach that integrates the ecosystem services method with a geodesign framework. Based on the analysis and results presented in this thesis it can be concluded that:

1. Designing multifunctional agricultural landscapes is a possible solution to tackle the challenges facing sustainable management of NZ hill country.
2. The development of multifunctional agricultural landscapes can contribute towards innovative future farming systems that can deal with emerging environmental issues, improve the landscapes' resilience to change and disturbance, and therefore achieve long-term sustainable farm management and development.
3. Integrating an ecosystem services approach within a geodesign framework enables the facilitation of a comprehensive implementation of the EBM approach to agricultural land use planning and management.
4. Spatially-explicit assessment of the provision of ecosystem services, the pattern of landscape multifunctionality, and the relationship between landscape structure and ecosystem services supply provide valuable information to design future multifunctional landscapes and inform decision making in relation to sustainable land use management.
5. Farmed landscapes where multiple LULC types co-exist can provide a wide range of ecosystem services and therefore, meet both economic and environmental needs. Land use change towards increasing landscape diversity and complexity is key to achieving more sustainable multifunctional farmed landscapes.
6. Engaging landowners/farmers into the process of farm planning is critical to design sustainable and more feasible land use scenarios at the farm scale. Incorporating preferences and expectations of the farmers into the development of future farmed landscapes is needed to ensure well-being of farmers and their families.
7. The integrated and comprehensive farm planning approach requires a range of farm-scale data and models that are time-consuming and expensive to acquire.

Investment in farm-scale data and models is an important requirement for a wider application of this approach.

8. The integration of landscape ecological science and digital technologies can make a valuable contribution towards accelerating the transition of the NZ agricultural systems to a sustainable future.

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Appendix 1

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STATEMENT OF CONTRIBUTION
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We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

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Tran, D. X., Pearson, D., Palmer, A., & Gray, D. (2020). Developing a landscape design approach for the sustainable land management of hill country farms in New Zealand. Land, 9(6), 185. https://doi.org/10.3390/land9060185.

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The candidate was responsible for research conceptualization, collecting, modeling, and analyzing data, and writing the manuscript.

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- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

The candidate was responsible for research conceptualization, methodology, formal analysis,writing-original draft, and visualization of research results.

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DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Duy Xuan Tran
Name/title of Primary Supervisor:	Diane Pearson

In which chapter is the manuscript /published work: Chapter 5

Please select one of the following three options:

● The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Tran, D. X., Pearson, D., Palmer, A., Dominati, E. J., Gray, D., & Lowry, J. (2023). Integrating ecosystem services with geodesign to create multifunctional agricultural landscapes: A case study of a New Zealand hill country farm. Ecological Indicators, 146, 109762. https://doi.org/10.1016/j.ecolind.2022.109762.

○ The manuscript is currently under review for publication – please indicate:

- The name of the journal:

Ecological Indicators

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

The candidate was responsible for research conceptualization, methodology development, data collection and modeling, and writing the majority of the manuscript.

○ It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Duy Xuan Tran Digitally signed by Duy Xuan Tran Date: 2022.10.27 11:12:50 +13'00'
Date:	07-Aug-2023
Primary Supervisor's Signature:	Diane Pearson Digitally signed by Diane Pearson Date: 2023.08.08 17:11:24 +12'00'
Date:	8-Aug-2023

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.