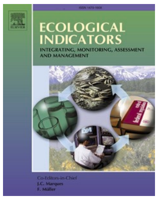
Ecological Indicators 146 (2023) 109762

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



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

Duy X. Tran [a,b,*], Diane Pearson [b], Alan Palmer [b], Estelle J. Dominati [a], David Gray [b], John Lowry [c]

[a] AgResearch, Grasslands, Palmerston North, New Zealand
[b] School of Agriculture and Environment, College of Sciences, Massey University, Palmerston North, New Zealand
[c] School of People, Environment and Planning, College of Humanities & Social Sciences, Massey University, Palmerston North, New Zealand

ARTICLE INFO

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

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, visualize 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.

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 resources” (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 decreasing 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 landscapes resilience to adapt to climate changes and environmental disturbances, maintaining food production, and improving human health and well-being (Naumann et al., 2013; Smith et al., 2013). Given that sufficient international responses to global environmental problems are still lacking, a local scale

---

* Corresponding author at: AgResearch, Grasslands, Palmerston North, New Zealand.
E-mail addresses: Duy.Tran@agresearch.co.nz (D.X. Tran), D.Pearson@massey.ac.nz (D. Pearson), A.S.Palmer@massey.ac.nz (A. Palmer), estelle.dominati@agresearch.co.nz (E.J. Dominati), D.I.Gray@massey.ac.nz (D. Gray), J.Lowry@massey.ac.nz (J. Lowry).

https://doi.org/10.1016/j.ecolind.2022.109762
Received 7 September 2022; Received in revised form 17 November 2022; Accepted 1 December 2022

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 and 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 and 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 and 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 and 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 a multifunctional landscape, where key ecosystem services are maintained and promoted, can offer an effective solution to decrease environmental footprints whilst ensuring economic outcomes and human well-being.

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.

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 New Zealand (Fig. 1a). This farm is a complex agricultural landscape (Fig. 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.

The farm consists of eight land management units (LMUs) (Fig. 1c). A LMU is defined as "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 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.

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 (Fig. 2) which integrates the concept of multifunctional landscapes following the geodesign process developed by Steinitz (2012).

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 (Supplementary S1). This is the *Description* stage of the conceptual framework. 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.

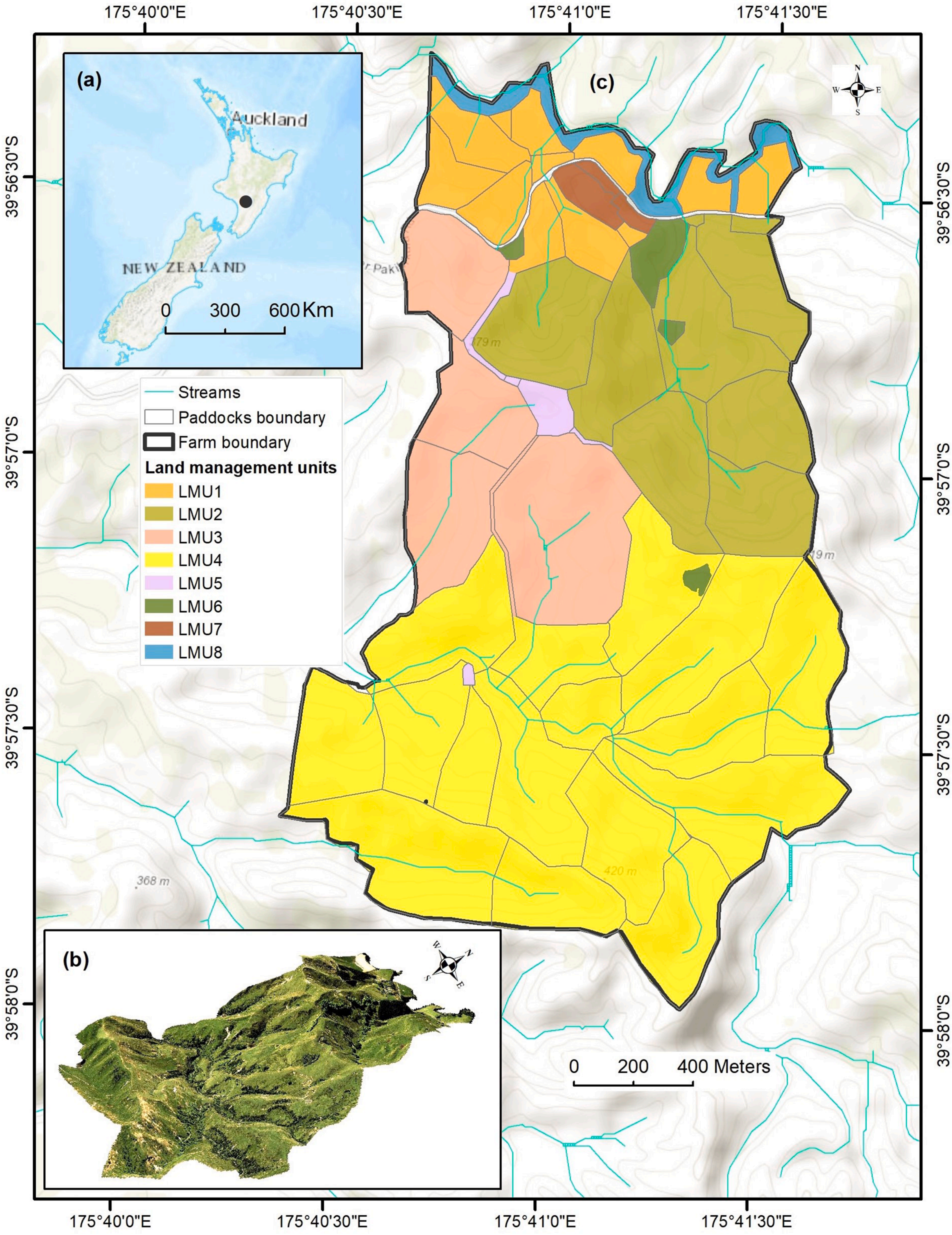


Fig. 1. Location of the farm in New Zealand (a); the farmed landscape in 3D visualisation (b); and land management units (LMUs) of the farm (c).

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 m 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 (10 m × 10 m). All data were organised in a geospatial database optimised for storing, querying, and sharing data in the landscape analysis and design applications.

The second stage of the conceptual framework was to spatially quantify major ecosystem functions and services and their interactions. This is the *Process* stage (Fig. 2). For example, types and pattern of ecosystem services are strongly affected by landscape simplification/

Table 1
Description of land management units (LMUs).

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

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 (Supplementary S2). 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 the 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. To map the overall quality of ecosystem services, a landscape quality index of multiple ecosystem services was created (Quinn 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 CO_2 equivalents.

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.

3.2.1. *Participatory mapping*

A geodesign workshop was organised at the farm and facilitated by a GIS expert. This is the first step of the *Design* stage. 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. 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 digitizing 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 ha), indigenous forest, the space planting of poplar trees for soil

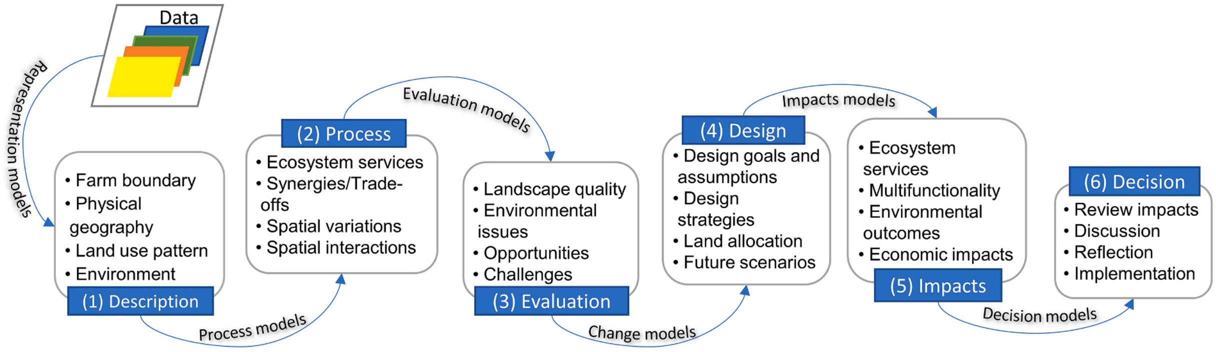


Fig. 2. Conceptual framework of the ecosystem services-based geodesign process for creating future landscape, adapted from Tran et al., 2020. The geodesign follows six stages: (1) Landscape description, (2) Landscape process; (3) Landscape evaluation; (4) Future landscape design; (5) Impact assessment 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.

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.

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 (Fig. 3). 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 S3.

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 (Fig. 3a) and a landscape conservation scenario which focuses more on overall landscape sustainability and restoration (Fig. 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.

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). 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 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) (Supplementary S4). 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 (10). For example, the area that is located on steepland (slope > 25°) with a high risk of soil erosion, low pasture yield, and close to the stream is considered as highly suitable for indigenous Manuka planting. 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 (Fig. 4).

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. 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. 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. The results from this step of the process are maps showing the pattern and types of land use for different scenarios (Fig. 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 (Fig. 2).

For each land use scenario, eleven ecosystem services (Supplementary S2) 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 was (NPV) used (with a discount rate of 2 % - see Supplementary S5 for clarification) to compare the profitability of different mixes of enterprises for the future scenarios. 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

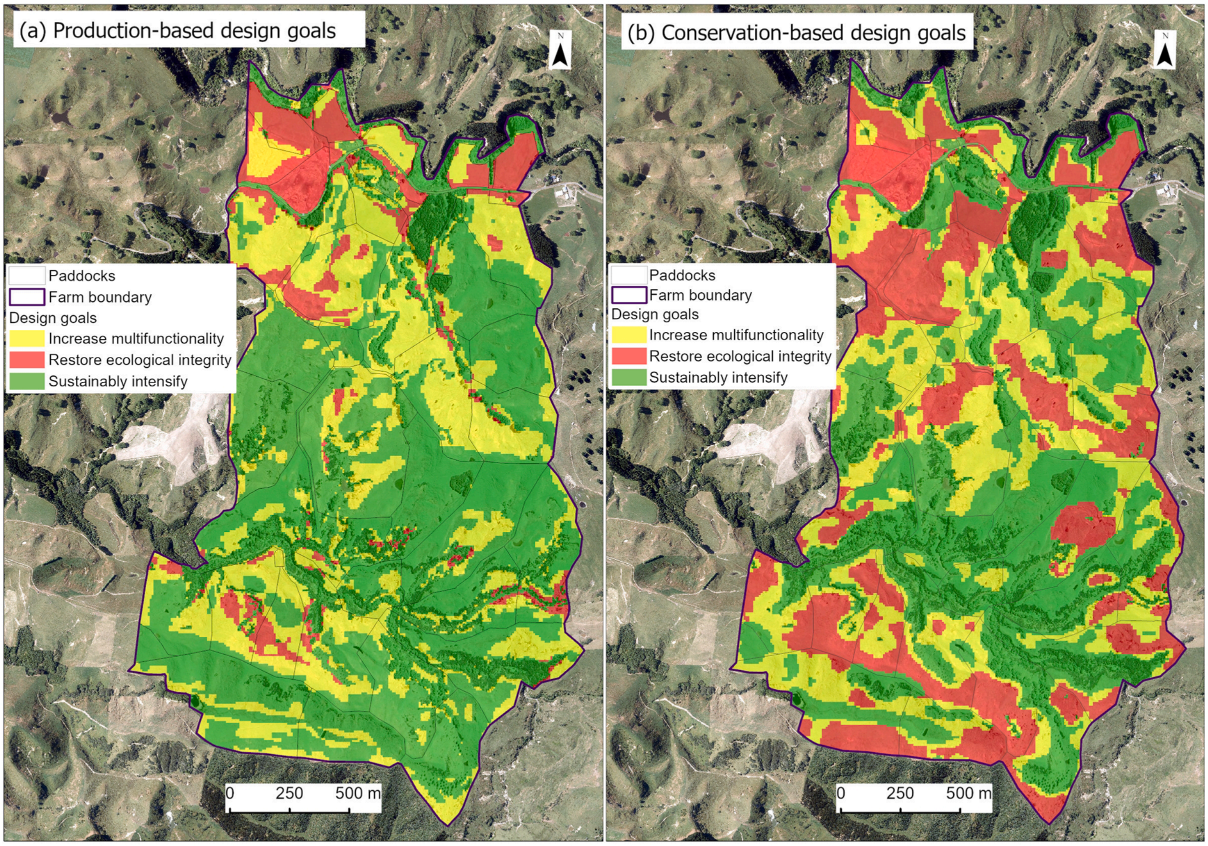


Fig. 3. Spatially explicit design and management goals for (a) the agricultural production scenario and (b) the landscape conservation scenario.

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 S6. 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 Supplementary S6 and S7.

3.4. Decision making (stage 6)

In the final stage (*Decision*) of the framework (Fig. 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.

4. Results

4.1. Scenarios of future land use for the case farm

Land use maps for the current and future scenarios for the case farm are presented in Fig. 5 and area of LULC types are showed in Table 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.

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.

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

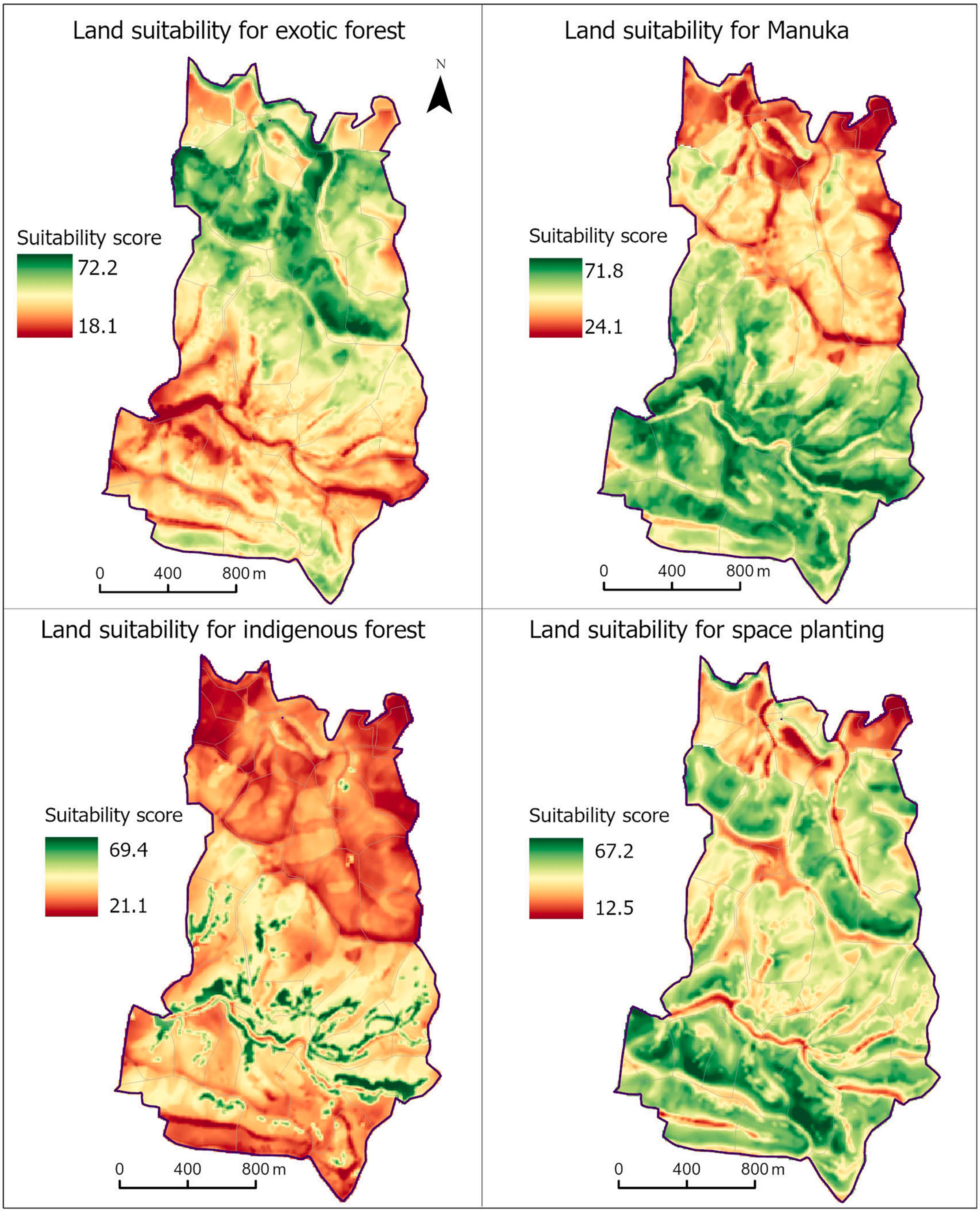


Fig. 4. Land suitability for a specific land use purpose for the case farm using the land suitability model. The highest suitability score presents the most suitable area for land use change and vice versa.

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

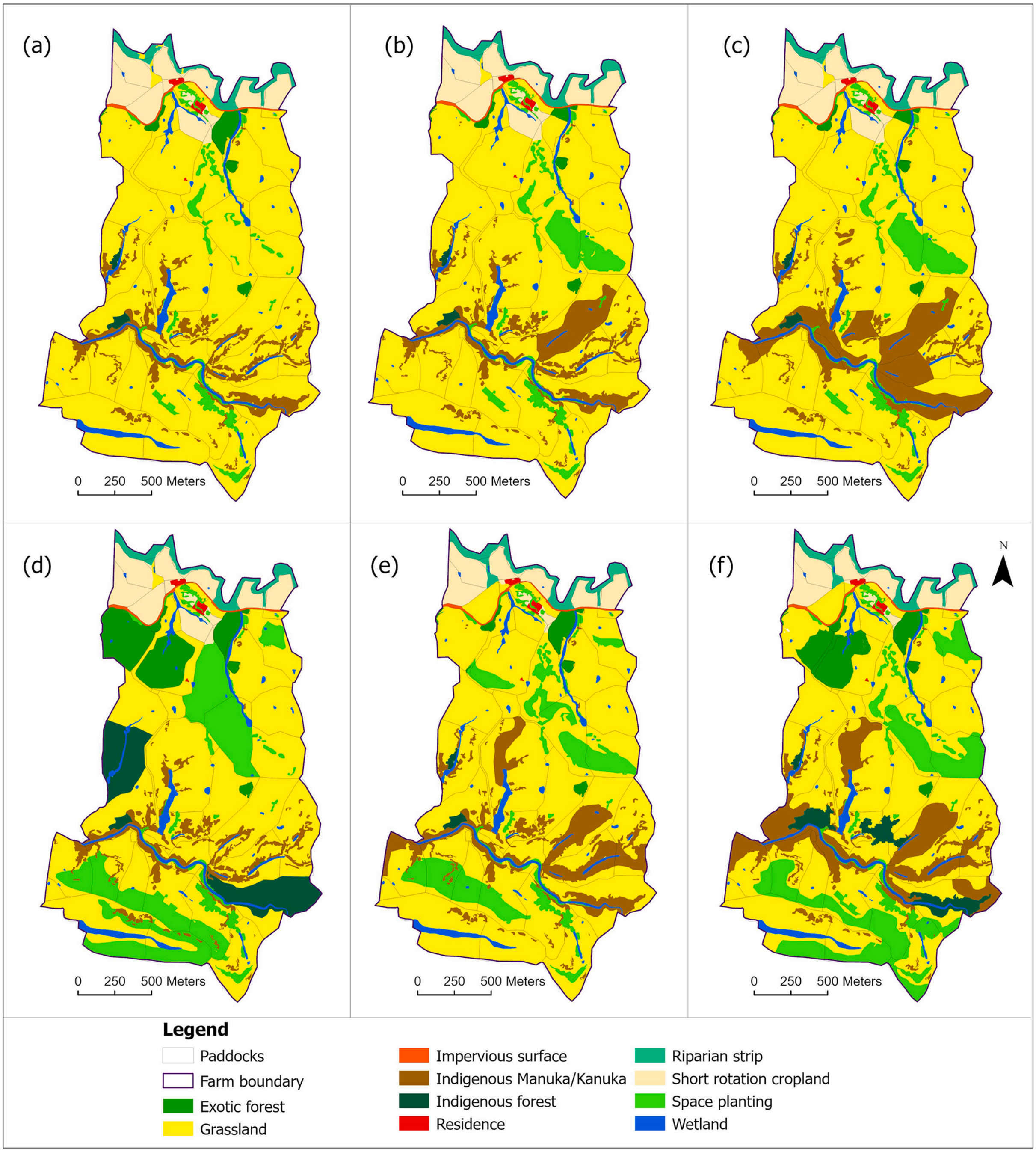


Fig. 5. Land use scenarios for the case farm: (a) current land use (S0), (b) agricultural production-based farmers design (S1), (c) landscape conservation-based farmers design (S2), (d) landscape conservation-base expert design (S3), (e) agricultural production-based model optimisation (S4), and (f) landscape conservation scenario using a hybrid approach (S5).

Table 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.

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.

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.

4.2.1. Changes in ecosystem services

The mean value of ecosystem services provision for 11 quantified services for the case farm is presented in Fig. 6. 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), provision of freshwater (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), provision of freshwater (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).

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 (Fig. 6). 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. Fig. 7 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 (Fig. 7a-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 (Fig. 7e). This pattern is strongly aligned with the changes in supporting/regulating services (Fig. 7g) and landscape aesthetics (Fig. 7h). 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 (Fig. 7f). 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.

As land use change can lead to a significant change in MFC and ecosystem services provision (Fig. 7), insight into this process was examined by looking at the variation between different types of land use transformation (Table 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.

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.

4.2.2. Environmental impacts of LULC changes

Table 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[1] for the case farm 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 farm is in line with values reported in previous studies in hill country and upland areas which ranges from 1.1 to 5.7 tonnes/ha/year (Lambert et al., 1985; Page et al., 2004). The sediment export[2] 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). The spatial variation in these environmental changes (Supplementary S8) is an inversive pattern of the supporting services maps presented in Fig. 7c and 7 g, 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 Supplementary S9.

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 and 6. For the pastoral area, to maximise the NPV over the 30 year 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

---

[1] The amount of annual soil loss on a pixel is given by the revised universal soil loss equation (RUSLE).

[2] The amount of sediment eroded from a pixel that reaches the stream (i.e., RUSLE * Sediment delivery ratio) (See Hamel et al., 2015).

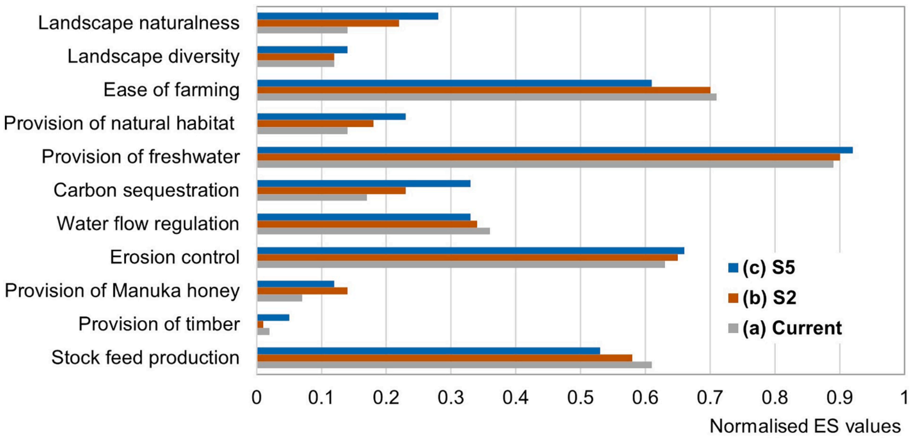


Fig. 6. Provision of ecosystem services under different land use scenarios: (a) current land use, (b) land use scenario 2 (S2), and (c) land use scenario 5 (S5).

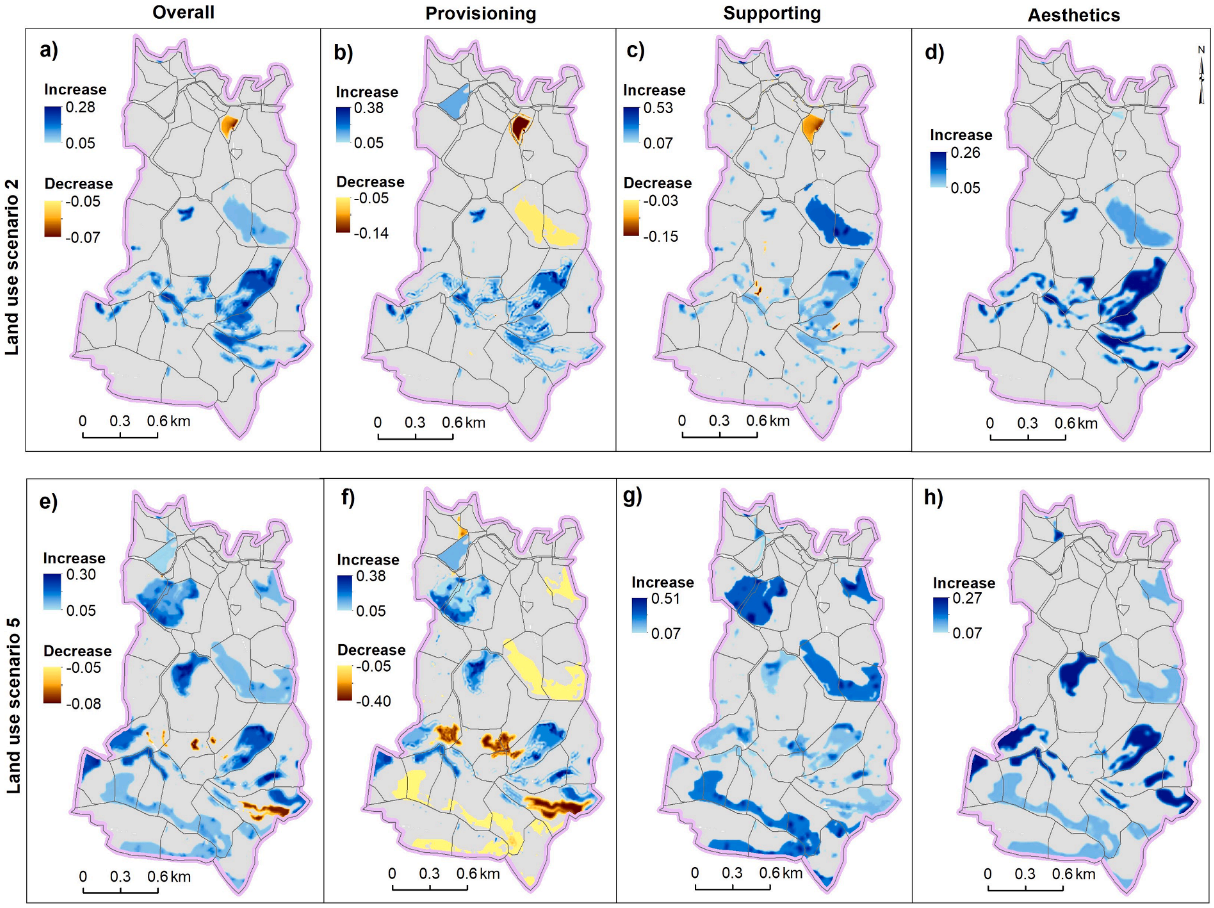


Fig. 7. Changes in landscape multifunctionality (MFC) and ecosystem services (ES) provision in the case farm under land use scenario 2 (7a-d) and land use scenario 5 (7e-h). The grey color denotes areas that have experienced very little or no change in MFC and ES.

that of the current base farm operation, showing that the model has capability to maximise pasture resource use for economic returns.

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.

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 6). 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 6).

Table 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

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

Table 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

Table 5
AgInform production outputs for the base (current) and future land use scenarios over 30 years for the case farm.

	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.

Table 6
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.

4.3. Decision making on future land use

The results obtained from stages 5 and 6 (sections 4.1 and 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 6), 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. Discussion

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 (Figs. 6 and 7, Table 6). 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 and Warner, 2013; Ouin et al., 2022; Rallings et al., 2019; Slámová and 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.

5.2. 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 and 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 Fig. 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 and 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 a 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).

5.3. 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., 2020). 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 ensure farmers are 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 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 change 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 and 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 use of fertiliser 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 and 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 regulation 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.

5.4. 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., 2021; 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 how the 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 as a climate-smart solution to adapt to changes and disturbances arising 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). 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., 2022a, 2022b). 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 model’s 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.

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.

CRediT authorship contribution statement

Duy X. Tran: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Diane Pearson:** Conceptualization, Writing – review & editing. **Alan Palmer:** Writing – review & editing. **Estelle J. Dominati:** Writing – review & editing. **David Gray:** Writing – review & editing. **John Lowry:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank the landowners for agreeing to use their farm as a case study, providing necessary farm information and participating in this study. Acknowledgement is also given to Massey University and AgResearch SSIF funded Bioeconomy in the Digital Age (BIDA) programme for supporting this research. The authors would like to thank the anonymous reviewers who provided valuable comments and suggestions to improve this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109762.

References

Abdourahamane Illiassou, S., & Oeba, V. O. (2020). Ecosystem-based approach for sustainable agricultural development in addressing food security and nutrition. In *Zero Hunger* (pp. 252–262). Springer.

Beef and Lamb, 2022. Land and Environment Planning. Available online: https://beeflambnz.com/sites/default/files/factsheets/pdfs/RB2-LEP-level-2-guidelines.pdf. (accessed on 8 August 2022).

Blaschke, P.M., Trustrum, N.A., DeRose, R.C., 1992. Ecosystem processes and sustainable land use in New Zealand steeplands. Agr. Ecosyst. Environ. 41 (2), 153–178.

Bretagnolle, V., Berthet, E., Gross, N., Gauffre, B., Plumejeaud, C., Houte, S., Gaba, S., 2018. Towards sustainable and multifunctional agriculture in farmland landscapes: lessons from the integrative approach of a French LTSER platform. Sci. Total Environ. 627, 822–834.

Brooks, E.B., Coulston, J.W., Riitters, K.H., Wear, D.N., 2020. Using a hybrid demand-allocation algorithm to enable distributional analysis of land use change patterns. PLoS One 15 (10), e0240097.

Bürgi, M., Ali, P., Chowdhury, A., Heinimann, A., Hett, C., Kienast, F., Mondal, M.K., Upreti, B.R., Verburg, P.H., 2017. Integrated landscape approach: closing the gap between theory and application. Sustainability 9 (8), 1371.

Burns, E.A., 2021. Placing regenerative farming on environmental educators' horizons. Aust. J. Environ. Educ. 37 (1), 29–39.

Capodaglio, A.G., Callegari, A., 2018. Can payment for ecosystem services schemes be an alternative solution to achieve sustainable environmental development? A critical comparison of implementation between Europe and China. Resources 7 (3), 40.

Chopin, P., Blazy, J.-M., Guinde, L., Wéry, J., Doré, T., 2017. A framework for designing multi-functional agricultural landscapes: Application to Guadeloupe Island. Agr. Syst. 157, 316–329.

Crofoot, A., 2016. Impact of Government and regulatory policy on hill country farming. NZGA Res. Pract. Ser. 16, 29–32.

De Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7 (3), 260–272.

Delacámara, G., O'Higgins, T. G., Lago, M., & Langhans, S. (2020). Ecosystem-based management: moving from concept to practice. In *Ecosystem-based management, ecosystem services and aquatic biodiversity* (pp. 39-60). Springer, Cham.

Dominati, E.J., Maseyk, F.J., Mackay, A.D., Rendel, J.M., 2019. Farming in a changing environment: Increasing biodiversity on farm for the supply of multiple ecosystem services. Sci. Total Environ. 662, 703–713.

Dominati, E.J., Mackay, A.D., Rendel, J.M., Wall, A., Norton, D.A., Pannell, J., Devantier, B., 2021. Farm scale assessment of the impacts of biodiversity enhancement on the financial and environmental performance of mixed livestock farms in New Zealand. Agr. Syst. 187, 103007.

Doswald, N., Munroe, R., Roe, D., Giuliani, A., Castelli, I., Stephens, J., Reid, H., 2014. Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. Clim. Dev. 6 (2), 185–201.

Eastwood, C.R., Rue, B.D., Gray, D.I., 2016. Using a 'network of practice' approach to match grazing decision-support system design with farmer practice. Anim. Prod. Sci. 57 (7), 1536–1542.

ESRI, 2022. How Hot Spot Analysis (Getis-Ord Gi*) works? https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/h-how-hot-spot-analysis-getis-ord-gi-spatial-stati.htm. *Acessed on 26 Maracrh 2022.*

Eyhorn, F., Muller, A., Reganold, J.P., Frison, E., Herren, H.R., Luttikholt, L., Mueller, A., Sanders, J., Scialabba, N.-E.-H., Seufert, V., 2019. Sustainability in global agriculture driven by organic farming. Nat. Sustain. 2 (4), 253–255.

Fagerholm, N., Martín-López, B., Torralba, M., Oteros-Rozas, E., Lechner, A.M., Bieling, C., Plieninger, T., 2020. Perceived contributions of multifunctional landscapes to human well-being: Evidence from 13 European sites. People Nat. 2 (1), 217–234.

Frei, B., Renard, D., Mitchell, M.G., Seufert, V., Chaplin-Kramer, R., Rhemtulla, J.M., Bennett, E.M., 2018. Bright spots in agricultural landscapes: identifying areas exceeding expectations for multifunctionality and biodiversity. J. Appl. Ecol. 55 (6), 2731–2743.

Frei, B., Queiroz, C., Chaplin-Kramer, B., Andersson, E., Renard, D., Rhemtulla, J.M., Bennett, E.M., 2020. A brighter future: Complementary goals of diversity and multifunctionality to build resilient agricultural landscapes. Glob. Food Sec. 26, 100407.

Gómez-Creutzberg, C., Lagisz, M., Nakagawa, S., Brockerhoff, E.G., Tylianakis, J.M., 2021. Consistent trade-offs in ecosystem services between land covers with different production intensities. Biol. Rev. 96 (5), 1989–2008.

Gottwald, S., Brenner, J., Janssen, R., Albert, C., 2021. Using Geodesign as a boundary management process for planning nature-based solutions in river landscapes. Ambio 50 (8), 1477–1496.

Haaland, C., Fry, G., Peterson, A., 2011. Designing farmland for multifunctionality. Landsc. Res. 36 (1), 41–62.

Hamel, P., Chaplin-Kramer, R., Sim, S., Mueller, C., 2015. A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. Sci. Total Environ. 524, 166–177.

Harvey, C.A., Martínez-Rodríguez, M.R., Cárdenas, J.M., Avelino, J., Rapidel, B., Vignola, R., Vilchez-Mendoza, S., 2017. The use of Ecosystem-based Adaptation practices by smallholder farmers in Central America. Agr. Ecosyst. Environ. 246, 279–290.

Huang, J., Tichit, M., Poulot, M., Darly, S., Li, S., Petit, C., Aubry, C., 2015. Comparative review of multifunctionality and ecosystem services in sustainable agriculture. J. Environ. Manage. 149, 138–147.

Huang, L., Xiang, W., Wu, J., Traxler, C., Huang, J., 2019. Integrating GeoDesign with landscape sustainability science. Sustainability 11 (3), 833.

Johansson, M., Pedersen, E., Weisner, S., 2019. Assessing cultural ecosystem services as individuals' place-based appraisals. Urban For. Urban Green. 39, 79–88.

Jordan, N., Warner, K.D., 2013. Towards multifunctional agricultural landscapes for the Upper Midwest Region of the USA. Ecosyst. Serv. Agric. Urban Landsc. 137–156.

Karrasch, L., Maier, M., Kleyer, M., Klenke, T., 2017. Collaborative landscape planning: Co-design of ecosystem-based land management scenarios. Sustainability 9 (9), 1668.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610, 997–1009.

Knook, J., Turner, J.A., 2020. Reshaping a farming culture through participatory extension: An institutional logics perspective. J. Rural Stud. 78, 411–425.

Kok, M.T., Kok, K., Peterson, G.D., Hill, R., Agard, J., Carpenter, S.R., 2017. Biodiversity and ecosystem services require IPBES to take novel approach to scenarios. Sustain. Sci. 12 (1), 177–181.

Lambert, M.G., Devantler, B.P., Nes, P., Penny, P.E., 1985. Losses of nitrogen, phosphorus, and sediment in runoff from hill country under different fertiliser and grazing management regimes. N. Z. J. Agric. Res. 28 (3), 371–379.

Landis, D.A., 2017. Designing agricultural landscapes for biodiversity-based ecosystem services. Basic Appl. Ecol. 18, 1–12.

Larned, S.T., Howard-Williams, C., Taylor, K., Scarsbrook, M., 2022. Freshwater science–policy interactions in Aotearoa-New Zealand: lessons from the past and recommendations for the future. Aust. J. Water Res. 1–22.

Lavorel, S., Grigulis, K., Richards, D.R., Etherington, T.R., Law, R.M., Herzig, A., 2022. Templates for multifunctional landscape design. Landsc. Ecol. 37 (3), 913–934.

Lee, D.J., Dias, E., Scholten, H.J., 2014. Geodesign by integrating design and geospatial sciences (Vol. 111). Springer.

Leining, C., Kerr, S., Bruce-Brand, B., 2020. The New Zealand Emissions Trading Scheme: critical review and future outlook for three design innovations. Clim. Pol. 20 (2), 246–264.

Li, W., Milburn, L.-A., 2016. The evolution of geodesign as a design and planning tool. Landsc. Urban Plan. 156, 5–8.

Lovell, S.T., Johnston, D.M., 2009. Designing landscapes for performance based on emerging principles in landscape ecology. Ecol. Soc. 14 (1).

Lynde, R., 2020. Innovation & entrepreneurship driving food system transformation. Physiol. Behav. 220, 112866.

Macinnis-Ng, C., Mcintosh, A.R., Monks, J.M., Waipara, N., White, R.S., Boudjelas, S., Clark, C.D., Clearwater, M.J., Curran, T.J., Dickinson, K.J., 2021. Climate-change impacts exacerbate conservation threats in island systems: New Zealand as a case study. Front. Ecol. Environ. 19 (4), 216–224.

Mander, Ü., Helming, K., Wiggering, H., 2007. Multifunctional land use: meeting future demands for landscape goods and services. In: Multifunctional Land Use. Springer, Berlin, Heidelberg, pp. 1–13.

McGlone, M., 1983. Polynesian deforestation of New Zealand: a preliminary synthesis. Archaeol. Ocean 18 (1), 11–25.

McGranahan, D.A., 2014. Ecologies of scale: multifunctionality connects conservation and agriculture across fields, farms, and landscapes. Land 3 (3), 739–769.

McKenzie, A.J., Emery, S.B., Franks, J.R., Whittingham, M.J., 2013. Landscape-scale conservation: collaborative agri-environment schemes could benefit both biodiversity and ecosystem services, but will farmers be willing to participate? J. Appl. Ecol. 50 (5), 1274–1280.

MEA (Millennium ecosystem assessment). (2005). *Ecosystems and human well-being* (Vol. 5, pp. 563-563). Washington, DC: Island press. https://www.millenniumassessment.org/documents/document.765.aspx.pdf.

MfE (Ministry for the Environment). (2022a). Agricultural Emissions Calculator. Available online: https://environment.govt.nz/what-you-can-do/agricultural-emissions-calculator/#using-this-calculator.

MfE (Ministry for the Environment). (2022b). Freshwater farm plans. https://environment.govt.nz/acts-and-regulations/freshwater-implementation-guidance/freshwater-farm-plans/.

Monaghan, R., Manderson, A., Basher, L., Spiekermann, R., Dymond, J., Smith, C., McDowell, R., 2021. Quantifying contaminant losses to water from pastoral landuses in New Zealand II. The effects of some farm mitigation actions over the past two decades. N. Z. J. Agric. Res. 64 (3), 365–389.

MPI (Ministry for Primary Insdustries). (2022). Integrated farm planning work programme. https://www.mpi.govt.nz/funding-rural-support/farming-funds-and-programmes/integrated-farm-planning-work-programme/#:~:text=Budget%202021%20allocated%20%2437%20million,farm%20advisers%20to%20provide%20advice.

Natarajan, L., 2017. Socio-spatial learning: A case study of community knowledge in participatory spatial planning. Prog. Plan. 111, 1–23.

Naumann, S., Anzaldua, G., Berry, P., Burch, S., Davis, M., Frelih-Larsen, A., ... & Sanders, M. (2011). Assessment of the potential of ecosystem-based approaches to climate change adaptation and mitigation in Europe. *Final report to the European Commission, DG Environment*.

Naumann, S., Davis, M., Munang, R., Andrews, J., Thiaw, I., Alverson, K., ... & Han, Z. (2013). The social dimension of ecosystem-based adaptation. UNEP Policy Series-Ecosystem Management. Ecologic Institute, United Nations Environment Programme (UNEP), Cornell University.

Nelson, G. C., Rosegrant, M. W., Koo, J., Robertson, R., Sulser, T., Zhu, T., ... & Lee, D. (2009). *Climate change: Impact on agriculture and costs of adaptation* (Vol. 21). Intl Food Policy Res Inst.

Newman, G., Malecha, M., Yu, S., Qiao, Z., Horney, J.A., Lee, J., Kim, Y.J., Lee, R.J., Berke, P., 2020. Integrating a resilience scorecard and landscape performance tools into a Geodesign process. Landsc. Res. 45 (1), 63–80.

O'Farrell, P.J., Anderson, P.M., 2010. Sustainable multifunctional landscapes: a review to implementation. Curr. Opin. Environ. Sustain. 2 (1–2), 59–65.

Ouin, A., Andrieu, E., Vialatte, A., Balent, G., Barbaro, L., Blanco, J., ... & Sirami, C. (2022). Building a shared vision of the future for multifunctional agricultural landscapes. Lessons from a long term socio-ecological research site in south-western France. In *Advances in Ecological Research* (Vol. 65, pp. 57-106). Academic Press.

Page, M., Trustrum, N., Brackley, H., Baisden, T., 2004. Erosion-related soil carbon fluxes in a pastoral steepland catchment, New Zealand. Agr. Ecosyst. Environ. 103 (3), 561–579.

Parminter, I., Dodd, M. B., & Mackay, A. D. (2001, January). Economic analysis of poplar planting on steep hill country. In *Proceedings of the New Zealand Grassland Association* (pp. 127-130).

Perrot-Maître, D., 2006. The Vittel Payments for Ecosystem Services: A Perfect PES Case? International Institute for Environment and Development, London, UK.

Pitman, W.D., 2022. Multifunctional landscapes for enhanced ecosystem benefits and productive agriculture in the southeastern US. Landsc. Ecol. 1–15.

Powers, B.F., Ausseil, A.-G., Perry, G.L., 2020. Ecosystem service management and spatial prioritisation in a multifunctional landscape in the Bay of Plenty, New Zealand. Aust. J. Environ. Manage. 27 (3), 275–293.

Quinn, J.E., Brandle, J.R., Johnson, R.J., 2013. A farm-scale biodiversity and ecosystem services assessment tool: the healthy farm index. Int. J. Agric. Sustain. 11 (2), 176–192.

Rajakal, J.P., Tan, R.R., Andiappan, V., Wan, Y.K., 2021. A Hybrid Optimisation Model for Land Allocation and Storage Sizing in Agro-Food System. Process Integr. Optim. Sustain. 5 (4), 729–743.

Rallings, A.M., Smukler, S.M., Gergel, S.E., Mullinix, K., 2019. Towards multifunctional land use in an agricultural landscape: A trade-off and synergy analysis in the Lower Fraser Valley, Canada. Landsc. Urban Plan. 184, 88–100.

Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., Biggs, R., Norström, A.V., Pereira, L., Aceituno, A.J., 2020. Seeds of good anthropocenes: developing sustainability scenarios for Northern Europe. Sustain. Sci. 15 (2), 605–617.

Rendel, J.M., Mackay, A.D., Smale, P.N., 2017. The value of legumes to a Whanganui hill country farm. J. N. Z. Grasslands 79, 35–41.

Renwick, A., Dynes, R., Johnstone, P., King, W., Holt, L., Penelope, J., 2022. Balancing the push and pull factors of land-use change: a New Zealand case study. Reg. Environ. Chang. 22 (1), 1–16.

Romera, A.J., Bos, A.P., Neal, M., Eastwood, C.R., Chapman, D., McWilliam, W., Clinton, P.W., 2020. Designing future dairy systems for New Zealand using reflexive interactive design. Agr. Syst. 181, 102818.

Saaty, T.L., 1988. What is the analytic hierarchy process?. In: Mathematical Models for Decision Support. Springer, Berlin, Heidelberg, pp. 109–121.

Scherr, S.J., Shames, S., Friedman, R., 2012. From climate-smart agriculture to climate-smart landscapes. Agric. Food Security 1 (1), 1–15.

Schlesinger, W.H., 2022. Biogeochemical constraints on climate change mitigation through regenerative farming. Biogeochemistry 1–9.

Scrimgeour, F.G., 2016. Pathways ahead for New Zealand hill country farming. J. N. Z. Grasslands 73–82.

Sharp, R., , H. T., Ricketts, T., Guerry, A. D., Wood, S. A., Chaplin-Kramer, R., ... & Vogl, A. L. (2014). InVEST user's guide. *The Natural Capital Project: Stanford, CA, USA*.

Slámová, M., Belčáková, I., 2019. The role of small farm activities for the sustainable management of agricultural landscapes: Case studies from Europe. Sustainability 11 (21), 5966.

Slotterback, C.S., Runck, B., Pitt, D.G., Kne, L., Jordan, N.R., Mulla, D.J., Reichenbach, M., 2016. Collaborative Geodesign to advance multifunctional landscapes. Landsc. Urban Plan. 156, 71–80.

Smith, P., Ashmore, M.R., Black, H.I., Burgess, P.J., Evans, C.D., Quine, T.A., Orr, H.G., 2013. The role of ecosystems and their management in regulating climate, and soil, water and air quality. J. Appl. Ecol. 50 (4), 812–829.

Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Tittonell, P., 2014. Gaming for smallholder participation in the design of more sustainable agricultural landscapes. Agr. Syst. 126, 62–75.

Ssegane, H., Negri, M.C., Quinn, J., Urgun-Demirtas, M., 2015. Multifunctional landscapes: Site characterization and field-scale design to incorporate biomass production into an agricultural system. Biomass Bioenergy 80, 179–190.

Steinitz, C. (2012). A framework for geodesign: Changing geography by design. Esri, Redlands, California, United States.

Stringer, L.C., Fraser, E.D., Harris, D., Lyon, C., Pereira, L., Ward, C.F., Simelton, E., 2020. Adaptation and development pathways for different types of farmers. Environ. Sci. Policy 104, 174–189.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., Van Der Heijden, M.G., Liebman, M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6 (45), eaba1715.

Todd, M.D., 2018. Learnings from ten years of hill country farm plan mapping. In: Farm environmental planning – Science, policy and practice. (Eds L. D. Currie and C. L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 31. *Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand*. 14 pages.

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.

Tran, D.X., Pearson, D., Palmer, A., Lowry, J., Gray, D., Dominati, E.J., 2022a. Quantifying spatial non-stationarity in the relationship between landscape structure and the provision of ecosystem services: An example in the New Zealand hill country. Sci. Total Environ. 808, 152126.

Tran, D.X., Pearson, D., Palmer, A., Lowry, J., Gray, D., Dominati, E.J., 2022b. A comprehensive spatially-explicit analysis of agricultural landscape multifunctionality using a New Zealand hill country farm case study. Agr. Syst. 203, 103494.

Vibart, R.E., Rennie, G., Hutchinson, K., Burtt, A., Chrystal, J., Dynes, R., 2021. Greenhouse gas emissions from New Zealand sheep and beef farms. J. N. Z. Grasslands, 252-232.

Vignola, R., Harvey, C.A., Bautista-Solis, P., Avelino, J., Rapidel, B., Donatti, C., Martinez, R., 2015. Ecosystem-based adaptation for smallholder farmers: Definitions, opportunities and constraints. Agriculture, Ecosystems & Environment, 211, 126–132.Whitehead, D., Schipper, L. A., Pronger, J., Moinet, G. Y., Mudge, P. L., Pereira, R. C., & Camps-Arbestain, M. (2018). Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. Agr. Ecosyst. Environ. 265, 432–443.

Wamsler, C., Luederitz, C., Brink, E., 2014. Local levers for change: mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. Glob. Environ. Chang. 29, 189–201.

Xie, Y., Runck, B.C., Shekhar, S., Kne, L., Mulla, D., Jordan, N., Wiringa, P., 2017. Collaborative geodesign and spatial optimization for fragmentation-free land allocation. ISPRS Int. J. Geo Inf. 6 (7), 226.

Yao, J., Zhang, X., Murray, A.T., 2018. Spatial optimization for land-use allocation: accounting for sustainability concerns. Int. Reg. Sci. Rev. 41 (6), 579–600.