Mosaics testing Model

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Introduction

Mosaics exist when a range of land use activities occur within a landscape. Whether a mosaic exists is dependent on the scale used. At the national scale we have a mosaic of land uses, but as you decrease in scale monocultures become more prevalent – such as dairying in Taranaki or horticulture in Pukekohe. At the farm scale monocultures are the rule rather than the exception in modern agricultural production in New Zealand, with only arable land use in Canterbury including a mosaic of land uses and forestry with sheep and beef having some degree of integrated mosaic structure. At the paddock scale monocultures are almost universal.

Our Land and Water wish to test the hypothesis that a transition to more diverse mosaics of land use will, under scenarios of different socio-environmental – economic circumstances, deliver better environmental, economic, cultural, and social outcomes, enhancing Te Taiao.

Background

Agriculture has been successful in addressing fibre and food requirements of the world's growing population for many years (Hendrickson et al., 2008) using specialised farms that are predominantly monocultures (Pearson, 2007). Intensification and high yields have increased over the last few decades, in a New Zealand (NZ) context our dairy herd has nearly doubled in the past three decades (Scarsbrook, 2015). This increase also equates to NZ having one of the highest rates of intensification, an increase of 82% dairy numbers (animals) nationally between 1990 and 2019 (Statistics-NZ, 2023).This increase has put significant pressure on the environment (freshwater, animal welfare and GHG emissions). The evidence has now led many to ask what cost does intensification have on our environment and are our current agricultural systems 'fit for purpose'?

Throughout the literature mosaics are seen as the answer to this question because they are perceived to achieve increased resilience, lower vulnerability and increased robustness. These systems also offer adaptability by reducing environmental footprints placing leaky systems on areas that are less prone to loss (McDowell, 2022). One issue facing this assumption is that there are many confusing terms used to define and explain mosaics (see Table 1 - Terminology associated with MosaicsTable 1).

Table 1 - Terminology associated with Mosaics

Term	Definition
Mosaic	Mosaic, as defined by Paul Weber (2017) in the context of integrating trees, was defined as compartments of land use within a farm.
Diversification	Diversification involves the production of multiple products to manage risk and market downturns. Sometimes this is shown through one area of the property been used for a 'niche' product (Bayne, 2021).
Mixed Farming	A system which involves growing of crops and livestock at the same time (Bayne, 2021).
Intensified Diversification	Producing more products off the same piece of land with minimal additional inputs (Bayne, 2021).
Diversified Specialization	Defined by Bayne (2021) as when landowners become specialised land managers, providing a service to several land owners. This would allow the whole property to be in multiple land uses with specialists looking after each land use.
Land Sparing	Identifying certain areas of land that will be preserved for conservation or biodiversity (Waggoner, 1995). This idea was on the back of zoning policies and enhancing local biodiversity
Land Sharing	A type of system that promotes within field biodiversity (i.e., organic, regenerative farming) (Bayne, 2021).
Patchwork	Defined by Bayne (2021) as the maximum footprint possible of any one land use.

In order to test the performance of mosaics in terms of desired metrics of catchment outcomes, it is necessary to first understand what is meant by a mosaic, and then to generate a mathematical description of those important determinants of mosaics. Mosaics can be a confusing concept because their meaning and outcomes are highly context-specific and vary depending on user. The interpretation and the results of a mosaic are highly influenced by each individual's perspective and needs.

A stakeholder group was developed that provided feedback on what they considered mosaics to be, and what the benefits they saw from mosaics. With their input we derived three measures of mosaics that reflected the stakeholder group's perception of spatial arrangements that were more mosaic-y.

- Patch Richness (PR) is the simply the number of classes.
- Total Core Area (TCA is the area of patches that are not at the edge of the patch; and

- Patch Density (PD) equals the number of patches in the landscape, divided by total landscape area[1].

Modelling mosaics

The model developed in order to assess mosaics integrates two predecessor models, the National Water Economic Model (LWP Ltd) and the spatial modelling and optimisation framework LUMASS[2] (Herzig et al. 2013, Herzig et al. 2018). The approach adopted was to implement and further develop the NWEM both externally and within the LUMASS framework. Within the LUMASS framework it is able to leverage LUMASS interoperability, modelling, and optimisation capabilities and NWEM's hydrological representation of catchments and water quantity and quality FMUs as well as its implementation of NPS-FM objectives. Modelling work undertaken within LUMASS that incorporated microbial losses and transport were integrated into the combined framework.

The model developed for the project is the National Water, Environment and Economic Land use Model in LUMASS (NWEELUM), and it addresses the following elements:

- Water use – contains a comprehensive network of catchments, river reaches and freshwater management units (FMUs), together with estimates of irrigation water use, irrigation schemes and water sources, and reliability of those sources.
- Water quality parameters – including definition of FMUs for management of water quality objectives, reductions required to meet NPS-FM objectives, losses of nitrogen (N), phosphorous (P), and microbial contaminants (M) losses from land, and their accumulation through the river and groundwater systems and their modification by mitigation actions.
- Profitability of land uses – including revenue, profit, the impact of water reliability on profit, and the costs of mitigation of different contaminants.

Although in this project we have undertaken only regional assessments, the model was developed to operate at a national scale. There are a number of caveats associated with a model at this scale that should be taken into account when considering the results. These include the difficulties with realistically modelling land use change, the limitations on accurately representing agricultural practice and outcomes with a limited set of representations for each land use, the uncertainties around estimates of contaminant losses from different land uses on a range of landscape types, and limitations on representation of forestry and biodiversity and their flow on impacts to the biophysical environment.

Scenarios

The approach we have adopted is to force land uses to occur as monocultures at three different scales. For each of these scenarios we modelled three different land use placement options, assigning monocultures of land-use to small Spatial Decision Units (SDU) which are areas of common soils, climate and landscape unit, Farm, and REC2 (REC Order 2 catchments) mosaic units respectively. We refer to these different scales as "mosaic units". We have used two different approaches to the placement of land uses in these mosaic units, one demonstrated in a case study of the Ruamahunga catchment in Greater Wellington region, and one demonstrated in a case study of the plains areas of the Canterbury region.

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[1] https://fragstats.org/index.php/fragstats-metrics/patch-based-metrics/aggregation-metrics/l8-patch-density#:~:text=Description,the%20landscape%20border%2C%20if%20present.

[2] https://manaakiwhenua.github.io/LUMASS

For the Ruamahunga catchment we modelled two approaches which varied the objective of the placement of land use. One approach aimed to maximise profit (“max. Profit”) and the other scenario (“min. N loss”) assessed the potential for N loss reduction while at least achieving 70% of the total catchment profit at baseline. We utilised the genetic algorithm (GA)-based implementation of the NWEELUM model in LUMASS to assign the land use randomly to each mosaic unit using a weighting based on the proportion of individual land use expected by the local minimum (s. Table 8).

For the Canterbury example we implemented a simple algorithm approach where we placed land uses in a priority manner based on their operating profit, so that the highest value land uses were placed in their most profitable locations until the constraint area of that land use was reached. The constraint on each land use was set at its current area apart from horticulture and vegetable growing, which were allowed to increase to 3 times their current area in order to give reasonable options for mosaics to occur.

Results

Figure 2 shows the Ruamahunga case study results for selected outcome indicators across all modelled scenarios and land placement options. For the “max. Profit” scenario (Fig. 2, top), based on the average result across all repetitions, land placement by the SDU mosaic units achieves the highest total profit (Fig. 2, top, a)), followed by the Farm and REC mosaic units, respectively. Figure 11 shows the same results for the Canterbury Plains case study. Because the algorithm used in the Canterbury case study is deterministic, there are no error bars around the results.

The results from both case studies show that the smaller spatial scales of land use placement (more mosaic-y) result in better outcomes in respect of the function for which the model is optimising when the optimisation was aiming for profit. So for Ruamahunga max. Profit case study and the Canterbury Plains case study this is profit, and the SDU scenario profit is higher than the Farm scenario, which in turn is higher than the REC2 scenario. However for the Ruamahunga case study when the model aimed to minimise N loss, the REC2 scenario resulted in the lowest N loss because the model algorithm resulted in greater areas of native land being placed in this scenario than in the SDU scenario. We consider this result to be an artefact of the modelling process rather than a reliable indication of the impact of mosaics on N loss.

Considering the scenarios where maximising profit was the aim, the impacts on N and P loss were inconsistent. The N and P loss were higher in SDU scenario than the Farm and REC2 scenarios for the Ruamahunga case study when maximising profit, but for the Canterbury Plains case study N loss was lower and P loss higher for the SDU scenario. For the Ruamahunga case study the differences were substantial, but are confounded by the fact that the placement algorithm has resulted in different areas in each land use across the scenarios. For the Canterbury case study the area of each land use is identical across the SDU, Farm and REC2 scenarios, and the differences in profit, N and P loss are very small. The data for Canterbury indicates that one benefit of the more mosaic-y land placements was that the N and P losses were more spread out. When intensive land uses were placed in larger parcels of land, there was greater potential for very high and very low N and P losses in subcatchments.

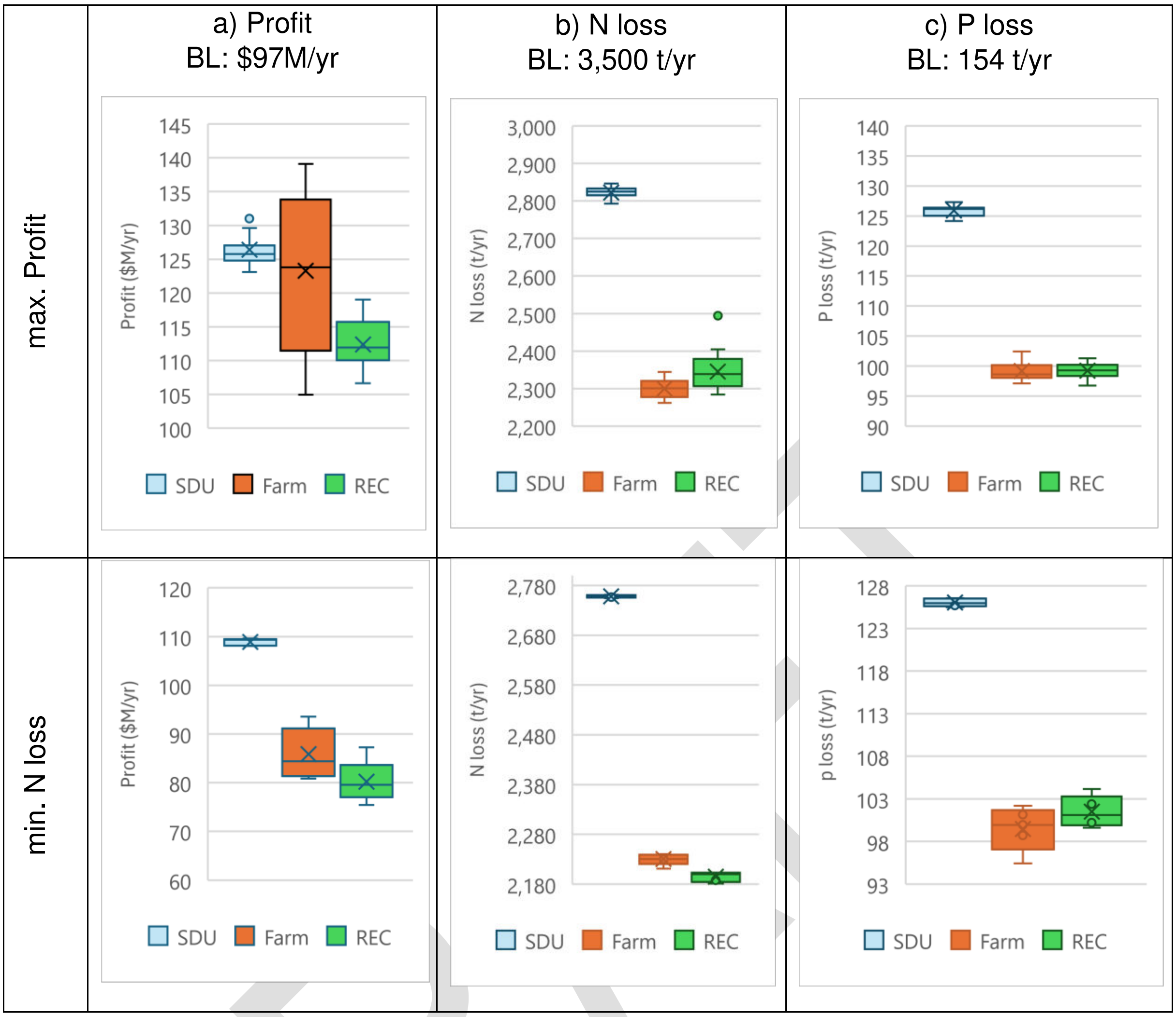

Figure 1. Land use performance indicators by mosaic unit option (a) total profit, b) N loss, and c) P loss) for the 15 modelled repetitions of the “max. Profit” (top) and “min. N loss” (bottom) scenarios. BL indicates the baseline performance for each indicator.

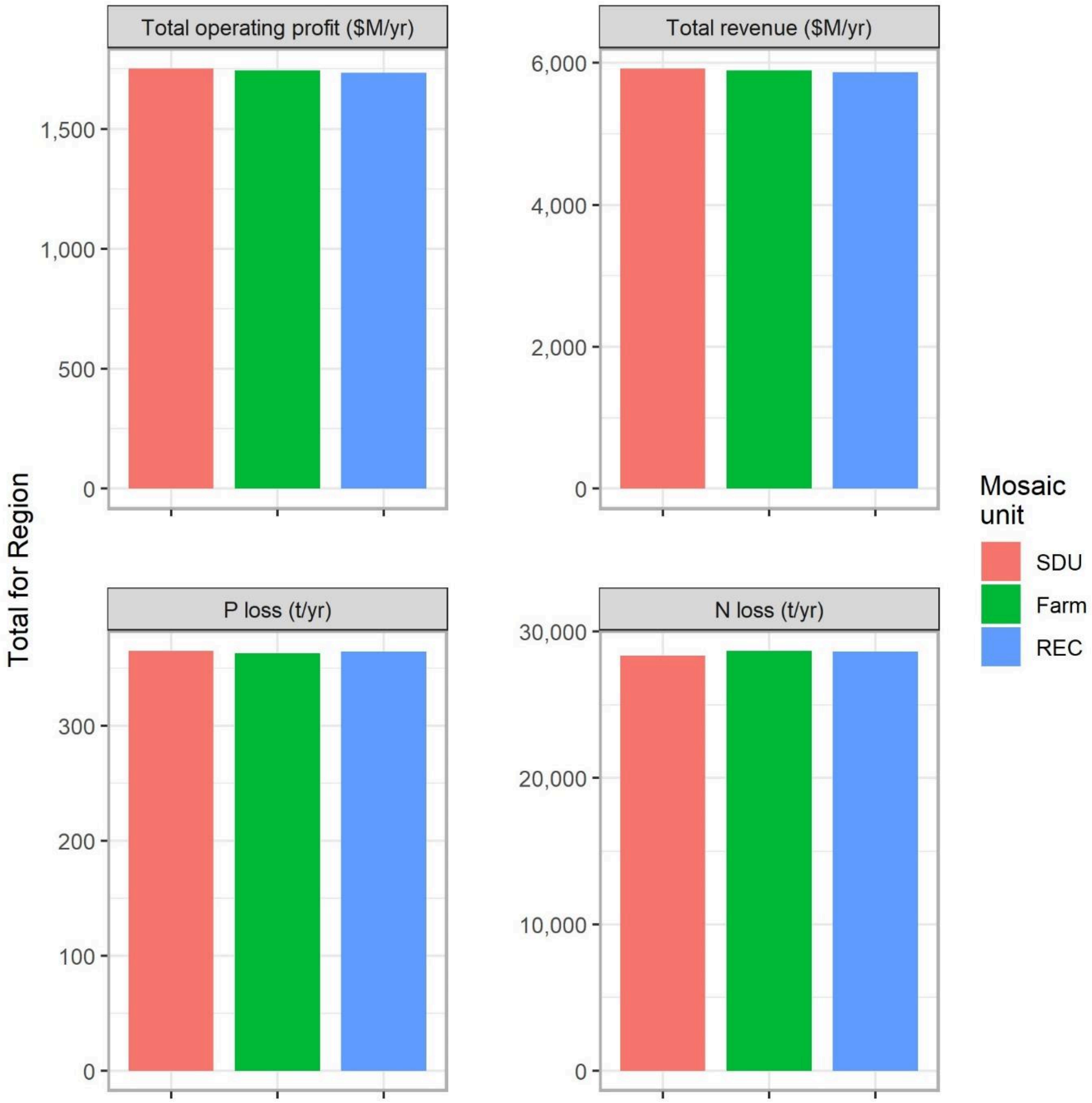

Figure 2: Total (regional) Profit, Revenue, N and P loss by mosaic unit for the Canterbury Plains scenario.

Discussion and conclusion

The project has had two outcomes – the development of modelling capability, and the assessment of the importance of mosaics in achieving desired community outcomes. In respect of the model development the project has developed layers of underlying data to populate the models, and extended their capabilities LUMASS to incorporate P, sediment and E.coli and their mitigation. For LUMASS the project has implemented new approaches to optimisation including non-linear optimisation and genetic algorithms. These two models are useful to assess the implications of a range of primary sector issues and potential policy responses. For example, a version of the NWEM is already being used by ECan to assess the potential implementation of three scenarios for the development of their new Regional Policy Statement.

The primary aim of assessing mosaics involved defining mosaics with the stakeholder group, and assessing the impact of varying the sizes of monocultures of land uses across the landscape. The project has not reached a definitive conclusion about what constitutes a mosaic and why they are considered beneficial, since there did not appear to be a universal or non-contradictory set of views about mosaics. However we did develop indicators that enable us to assess landscape patterns that were considered by the stakeholders to visually represent mosaics.

The models were able to successfully vary the size of monocultures within which land uses are implemented as a means of testing different mosaic patterns. The increasing size of the mosaic units is associated with a decrease in mosaic-ness as defined by the indicators we have used to assess mosaics.

The outcome for these different levels of mosaics defined with the models was only moderately variable. The largest land uses were sheep and beef, dairy and forestry, which within the case study areas are relatively insensitive to the soil and climate combinations. Analysis of the Ruamahunga data for sheep and beef showed low mosaic-ness in the spatial distribution of sheep and beef profits, which is reflected in the low variation of profit across different placement scenarios. Because dairy and sheep and beef make up the bulk of the total profit, the overall result was not highly sensitive to their placement. Horticulture was highly sensitive to less suitable soils, but because the total area and total profit from the horticultural land uses were smaller, the overall impact was not as large.

The process of modelling is inherently reductionist, and we need to be able to represent mosaics within a model structure, which means that the biophysical reality has to be reduced to an approach that is mathematically tractable. The results of modelling such as this reflect the underlying data structure of the model, and care should be taken in their interpretation. We think however that there are a number of concepts that have been surfaced in the course of this project that deserve further attention.

- ***Resilience.*** The concept of resilience is not captured in our modelling. Resilience is a concept that was referred to by a number of the stakeholders in their thinking about mosaics, but because of the static nature of the models we have developed it is not possible to capture how changes over time will affect the performance of different arrangements of land use. We suspect that given the relative insensitivity of the largest land uses to the climate and soil combinations at a small scale, even with a dynamic model we would not discern significant differences at the landscape scale without changing the mix of land uses between scenarios. . However, for individual properties having a mix of land uses may make the performance of the business more resilient across a number of dimensions, including resilience to drought, pests and diseases, and market fluctuations.
- ***Area of land uses is more important than their arrangement.*** The way in which the genetic algorithm has proven sensitive to the scale of the placement of land uses gives a useful insight into the key factors affecting the profitability at the landscape scale. It has demonstrated that the overriding factor in profitability at the landscape scale is the total area in high influence land uses, rather than the way in which they are arranged. For larger landscape scale assessments it is rare that there is insufficient suitable land for at least some high value land uses, so total area is likely to be constrained by capital availability, labour requirements, infrastructure, skills and markets.
- ***Scale and management focus.*** The model suggests that, all other things being equal, there is a small economic and environmental benefit from arranging land uses in

smaller more distributed blocks. However, for individual land managers, this may be far from optimal. Many of the gains in productivity come from increasing scale and management skills. With increasing scale of land use comes more efficient use of labour, equipment, transport and management skills. Furthermore, spreading management focus across multiple land uses will inevitably result in poorer performance at each land use than if the same manager focused on a single land use. We urge policymakers and land governance entities to consider therefore that multiple small land uses in an enterprise may not always be the best option, particularly for smaller blocks of land.

- ***Monocultures may be the best use of land.*** In our modelling of mosaics in Canterbury, we found that high value land uses tended to group together regardless of the scale at which we placed land, because these high value land uses were able to perform optimally in specific combinations of soil and climate, and because those combinations were not distributed across the landscape but rather tended to clump together in specific locations. We also note that the prevalence of a single land use in a region tends to lead to support services and infrastructure that is more tailored to that land use, which in turn enhances the efficiency of the industry overall. Examples would include kiwifruit in Bay of Plenty, apples in Hawke's Bay, and viticulture in Marlborough.
- ***Te Ao Māori.*** We recognise that Te Ao Māori incorporates a range of concepts and values around the use of land that we cannot capture in this modelling. We think that models are able to inform aspects of this value system, but because of the holistic nature of Te Ao Māori we do not think that a reductionist modelling approach is necessarily a useful way of approaching its incorporation into land use decisions.

Our modelling indicates that while more mosaicy landscapes are likely to produce somewhat better outcomes in profitability terms, the differences are likely to be small. We think that the areas of high value or low contaminant emitting land uses are more important than the scale of their placement in the landscape. There is no guarantee that placing land uses in smaller more scattered blocks will produce better environmental outcomes, although it will likely tend to ensure a more even spread of impacts with fewer areas of very high impact on waterways. We consider that stakeholders should focus more directly on the values and concepts of importance to them, rather than assume that they are embodied in some undefined concept of mosaics and can be solved by different placement of land uses. For example, if resilience is considered important, stakeholders should focus on resilience rather than assuming that mosaics will provide resilience.

1 Introduction

Mosaics exist when a range of land use activities occur within a landscape. Whether a mosaic exists is dependent on the scale used. At the national scale we have a mosaic of land uses, but as you decrease in scale monocultures become more prevalent – such as dairying in Taranaki or horticulture in Pukekohe. At the farm scale monocultures are the rule rather than the exception in modern agricultural production in New Zealand, with only arable land use in Canterbury including a mosaic of land uses and forestry with sheep and beef having some degree of integrated mosaic structure. At the paddock scale monocultures are almost universal.

Our Land and Water wish to test the hypothesis that a transition to more diverse mosaics of land use will, under scenarios of different socio-environmental – economic circumstances, deliver better environmental, economic, cultural, and social outcomes, enhancing Te Taiao.

To understand the aggregate implications of mosaics, modelling is required. The model will need to:

- Represent catchments in a hydrologically accurate manner.
- Incorporate land uses and the values associated with their implementation in different contexts (climate, soil, location etc).
- Assess the implications of N, P, sediment, and microbial contamination of waterways, together with the greenhouse gas implications of different types of land use and different intensities of land use.
- Assess the economic and social consequences of land uses.
- Allow placement of land uses to represent mosaics at different scales.

2 Background

Agriculture has been successful in addressing fibre and food requirements of the world's growing population for many years (Hendrickson et al., 2008) using specialised farms that are predominantly monocultures (Pearson, 2007). Mechanical and technological advances, and the cheap supply of external inputs such as fertiliser, have sustained and increased yields in specialised farms (Björklund et al., 1999). In their review of the Swedish Agricultural sector, Björklund showed an increase in farm size, decrease in the number of farms and farmers, because farms had become more specialised and regionally specific (Björklund et al., 1999). Intensification and high yields have increased over the last few decades, in a New Zealand (NZ) context our dairy herd has nearly doubled in the past three decades (Scarsbrook, 2015). This increase also equates to NZ having one of the highest rates of intensification, an increase of 82% dairy numbers (animals) nationally between 1990 and 2019 (Statistics-NZ, 2023).This increase has put significant pressure on the environment (freshwater, animal welfare and GHG emissions). The evidence has now led many to ask what cost does intensification have on our environment and are our current agricultural systems 'fit for purpose'?

The issue is that these monocultures are associated with higher environmental impacts such as seen in the Trade and Environment Report (2013), which highlights the pressures caused by an increased demand on food supply and environmental concerns associated with this intensification (UNCTAD, 2013). The report also highlighted a move away from intensive monocultures which had a heavy reliance on external inputs more than a diverse system. While there are benefits of diversification as highlighted by Hendrickson et al. 2008 such as managing risk, increasing resilience to market and climate shocks, there are disadvantages such as complexity of having to balance several objectives and increased demand in skills required.

Throughout the literature mosaics are seen as the answer to this question because they are perceived to achieve increased resilience, lower vulnerability and increased robustness. These systems also offer adaptability by reducing environmental footprints placing leaky systems on areas that are less prone to loss (McDowell, 2022). One issue facing this assumption is that there are many confusing terms used to define and explain mosaics (see **Error! Reference source not found.**).

Table 2 - Terminology associated with Mosaics

Term	Definition
Mosaic	Mosaic, as defined by Paul Weber (2017) in the context of integrating trees, was defined as compartments of land use within a farm.
Diversification	Diversification involves the production of multiple products to manage risk and market downturns. Sometimes this is shown through one area of the property been used for a 'niche' product (Bayne, 2021).
Mixed Farming	A system which involves growing of crops and livestock at the same time (Bayne, 2021).
Intensified Diversification	Producing more products off the same piece of land with minimal additional inputs (Bayne, 2021).
Diversified Specialization	Defined by Bayne (2021) as when landowners become specialised land managers, providing a service to several land owners. This would allow the whole property to be in multiple land uses with specialists looking after each land use.
Land Sparing	Identifying certain areas of land that will be preserved for conservation or biodiversity (Waggoner, 1995). This idea was on the back of zoning policies and enhancing local biodiversity
Land Sharing	A type of system that promotes within field biodiversity (i.e., organic, regenerative farming) (Bayne, 2021).
Patchwork	Defined by Bayne (2021) as the maximum footprint possible of any one land use.

As Table 1 above shows mosaics are context specific and can change based on the output or end result someone is looking for.

Whether a system is ‘fit for purpose’ can often be answered through policy and market signals. Policy has had major influence on landowners moving towards more mosaiced farming systems, because they are seen as a way to mitigate some of the negative impacts of intensification on land, water and air. In New Zealand, environmental policy has strengthened in response to declines in freshwater and high greenhouse gas emissions, exemplified by the National Policy Statement for Freshwater Management (NPSFM) (MFE 2014) and Carbon Zero Act[3].

Diversification is possible at various scales from farm to catchment, but the specific spatial arrangement that yields the greatest ecological benefit is an ongoing research question (Forman et al., 1995). Considering the concepts of land sharing and land sparing, we see transitions between mosaics at the catchment scale and specialisation at the farm scale. Land sharing involves generating multiple functions from the same piece of land, while land sparing sets aside specific areas for distinct purposes.

Determining where these mosaics should exist in terms of scale requires identifying all internal and external factors driving these changes. For instance, at the farm scale, monocultures are often chosen due to biophysical constraints in land use options, market access, or capital availability (Hunt, 2021). At the catchment scale, freshwater policy can pressure the ability to diversify.

Considering scale inevitably involves trade-offs. For example, organic farming represents a form of diversification that can enhance biodiversity and improve water quality (especially when stocked at lower rates) compared to conventional agricultural systems. However, organic farming typically produces lower yields than conventional methods, leading to reduced economic returns unless there is a premium for organic products (Tscharntke et al., 2021) (Jahanshiri et al., 2020).

3 Mosaics Definition

In order to test the performance of mosaics in terms of desired metrics of catchment outcomes, it is necessary to first understand what is meant by a mosaic, and then to generate a mathematical description of those important determinants of mosaics. Mosaics can be a confusing concept because their meaning and outcomes are highly context-specific and vary depending on user. The interpretation and the results of a mosaic are highly influenced by each individual’s perspective and needs.

A stakeholder group was developed that consisted of a range of user’s sector representatives (Dairy NZ, Beef and Lamb), regional councils (Waikato, Greater Wellington, Canterbury) and Māori landowners. Throughout the various discussions we had with the stakeholder group it was clear that people’s interpretation of what mosaics are differed depending on their view of what outcomes should be achieved. The discussions also highlighted the variation in the motivations for mosaics, such as: biodiversity conservation, sustainable land management, cultural values, intergenerational outcomes, knowledge sharing economic benefit and climate resilience. One member of the group defined mosaics as ‘*different land-use opportunities for different outcomes that fit within a criteria*’. These criteria could include social, environmental, cultural and financial objectives. Mosaics are about those opportunities fitting in with the aspirations of our whenua”.

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[3] **Climate Change Response (Zero Carbon) Amendment Act 2019 No 61, Public Act Contents – New Zealand Legislation**

The group also identified the considerations when investigating with mosaics such as;

- Understanding impacts at different scales and levels
- Recognizing interactions between land uses (Inter-connections)
- Ensuring there is a mix of land uses (Diversity)
- Assessing effects on the environment and biodiversity (Environmental Impact)
- Ensuring Sustainable Practices (Sustainability)
- Data availability
- Multi-view and outcome focus, ensuring engagement with a wide range of stakeholders is undertaken.

One significant point the group made was to ensure the definition of mosaics is clarified, so that everyone has the same understanding. This in turn will ensure the feedback provided from individuals can be useful.

The stakeholder group had a wide range of perspectives and backgrounds, which leads to a very wide range of considerations and objectives that the model developed is unlikely to answer. One of the challenges this programme faced was to manage expectations around what the model could produce as there are limitations with the model and not everything could be included. Additionally, some of the some Māori concepts/values will not be included in the model. In order for the model to be effective only a small number of elements can be included.

Throughout the discussions with the stakeholder group, we have narrowed the definition of mosaics and also the range of scenarios to address the objectives of the stakeholder group.

The first step in achieving this was to generate land use patterns that respond to their objectives. There are many landscape metrics that capture different aspects of a landscape's heterogeneity. They include metrics of patch shape and complexity, the configuration of the landscape, its diversity and finally its connectivity.

Various authors have tested a range of indices to identify the key or most useful ones. Plexida et al. (2014) note four components of spatial heterogeneity: patch complexity (area, edge and shape metrics), configuration, diversity and connectivity. Cushman, McGarigal, and Neel (2008) note that many metrics confound landscape composition (i.e. the variety and abundance of classes within a landscape) and configuration (spatial arrangement of patches). Cushman, McGarigal, and Neel (2008) identify 7 "components" of landscape level metrics that are universal - but each of these is a combination of metrics. Riitters et al. (1995) did a principal components analysis on 55 metrics identifying five factors, each of which could be represented by a single metric. The first four factors describe compactness of patches, image texture, shape type, shape complexity. The first two are represented by average patch perimeter-area ratio, and contagion. The 5th factor is number of attribute classes (i.e. PR). In their study of simulated landscapes, Hargis, Bissonette, and David (1998) found that Contagion and other metrics, e.g. mean patch distance, perimeter-area fractal dimension were not sensitive to landscape pattern. Wei et al. (2017) also found that contagion was correlated with other measures of landscape level metrics.

We tested a number of metrics of mosaic-ness with a stakeholder group to see how they responded to representations of mosaics that differed in respect of key characteristics – patch shape, patch size, land use proportion, number of land uses, and mixes of patch size and number of land uses, and patches of high variability against more scattered variability. This analysis simulates landscapes to test the relevance of various landscape metric (for use in the OLW mosaic project)[4].The representations used to test mosaics with the stakeholder group are shown in Appendix D.

There were few consistent messages from the stakeholder group about which metrics contributed most to mosaics, although it was clear that the richness of the landscape (number of land uses), and their diversity (patchiness) were consistently ranked higher by stakeholder members for mosaic-ness. While the measure of richness is relatively simply dealt with by counting land uses, diversity is more difficult. Plexida et al. (2014) recommend the use of Patch Density (PD), Area-Weighted Mean Fractal Dimension Index (FRAC_AM) and Patch Cohesion Index (COHESION). The first two are patch complexity indices, the third one is Connectivity which is not as relevant to our study. 'FRAC_AM and MESH were found to have additional information beyond their baseline metrics (PR and proportion of each category). In a comprehensive study Frohn (1998) recommends using Patch Per Unit area (same as PD) to describe landscape clumping and Square Pixel (SqP) for quantifying patch complexity.

Patch Richness (PR) is the preferred measure of diversity due to weaker correlation with the other indices. This is simply the number of classes.

Two measure of patch diversity were tested, Patch Density (PD) and Total Core Area (TCA). Total core area is the area of patches that are not at the edge of the patch, and PD equals the number of patches in the landscape, divided by total landscape area[5]. PD appears to not distinguish situations where one class is a) dominant and dispersed and b) dominant but very clumped (for example the difference between the two representations in Figure 22), while Total core area (TCA) did appear to distinguish between these two scenarios. Although they perform similarly in most situations, we have chosen both PD and TCA for use in our representation of mosaics.

The team therefore concluded that the use of patch richness (PR), patch density (PD) and total core area (TCA) would be used to mathematically represent mosaics in our modelling programme.

4 The model

The model developed in order to assess mosaics integrates two predecessor models, the National Water Economic Model (LWP Ltd) and the spatial modelling and optimisation framework LUMASS[6] (Herzig et al. 2013, Herzig et al. 2018).

- The NWEM is a hydrologically connected model that represents all the catchments and water quantity and quality (N) FMUs in the country. It includes currently irrigated areas and schemes, estimates of water supply reliability, Te Ture Whenua Māori Act 1993 land (includes other types of land registered as Māori land), farms, soils, climate zones. It includes environmental impacts of water use, estimates of GHG and N emissions, and estimates the economic impact of different scenarios of land use, either using a rules-based approach or optimisation. The model currently includes the NPS-FM limits for N, but not for P, sediment or E. coli.

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[4] Uses https://github.com/ropensci/NLMR/. See https://docs.ropensci.org/NLMR/articles/overview_tips.html#selection-of-possible-merges

[5] https://fragstats.org/index.php/fragstats-metrics/patch-based-metrics/aggregation-metrics/l8-patch-density#:~:text=Description,the%20landscape%20border%2C%20if%20present.

[6] https://manaakiwhenua.github.io/LUMASS

- LUMASS is an interoperable spatial modelling and optimisation framework. It has been used for optimisation-based land-use scenario generation, environmental modelling (e.g. SedNetNZ), and integrated modelling and optimisation applications, e.g. sediment mitigation optimisation. LUMASS' interoperability interfaces enable its use as part of integrated component models as well as the development and execution of integrated component models within its modelling framework. It is able to incorporate a range of inputs from different data sources as spatial layers, and implement this data within a range of different modelling strategies. This enables flexible integration of ecosystem services models and indicators including biodiversity and important native habitats. LUMASS has been used as platform for the development of end-user tools for regional councils and industry and is actively used and further developed as modelling and optimisation platform within MBIE Endeavour and SSIF-funded research projects.

The approach adopted was to implement and further develop the NWEM both externally and within the LUMASS framework. Within the LUMASS framework it is able to leverage LUMASS interoperability, modelling, and optimisation capabilities and NWEM's hydrological representation of catchments and water quantity and quality FMUs as well as its implementation of NPS-FM objectives. Modelling work undertaken within LUMASS that incorporated microbial losses and transport were integrated into the combined framework.

The approach adopted enables more complex interaction between spatial optimisation and modelling, as is required within the context of this project. Furthermore, LUMASS's fine-grained data provenance tracking (Spiekermann et al. 2019) and availability as free and open-source software ensure transparency and availability for wider use outside of this project.

The model developed for the project is the National Water, Environment and Economic Land use Model in LUMASS (NWEELUM), and it addresses the following elements:

- Water use – contains a comprehensive network of catchments, river reaches and freshwater management units (FMUs), together with estimates of irrigation water use, irrigation schemes and water sources, and reliability of those sources.
- Water quality parameters – including definition of FMUs for management of water quality objectives, reductions required to meet NPS-FM objectives, losses of nitrogen (N), phosphorous (P), and microbial contaminants (M) losses from land, and their accumulation through the river and groundwater systems and their modification by mitigation actions.
- Profitability of land uses – including revenue, profit, the impact of water reliability on profit, and the costs of mitigation of different contaminants.

This approach is similar to other modelling undertaken in the freshwater arena – for example Denne (2020) used a least cost method for estimating the impact of the NPS-FM (2020), which essentially optimises the response through mitigation or land use change and takes no consideration of the likelihood of this occurring. Doole (2016) used an optimising model in the Healthy Rivers project that allows for land use change in response to profit differentials up to a maximum change in any land use, with no specific controls on the rate of that change occurring. The approach adopted here allows the free movement of land uses among parcels and likely overestimates the changes that will occur in response to any policy stimulus. However, since the purpose of this study is to test hypothetical scenarios of land uses, this limitation is not thought to be significant. The model results are most useful in comparing the relativities between different scenarios modelled under the same conditions.

4.1 Brief model description

The model divides all productive land into farms and then each farm is divided into Spatial Decision Units (SDU). Each SDU is defined by its: climate zone; catchment; surface water (SW), groundwater (GW) and nutrient (N) Freshwater Management Units (FMU); and whether it is within the command area of an irrigation scheme. The SDU also subdivides the land within a farm depending on whether it is non-irrigable (steeper land) or irrigable (flatter land more suited to intensive land uses), and then into three soil characteristic categories based on plant available water (PAW). Each SDU is also a member of a subcatchment, defined by the REC Order 2 subcatchment in which it is located, and has a current land use for tracking of land uses such as exotic and native forestry which may occur within the elements described above, but need to be treated separately as they cannot be changed by the model.

For each SDU, there are a number of possible land uses: sheep and beef; dairy; arable; horticulture (apples, avocado, blueberries, cherry, kiwifruit gold, kiwifruit green, maize, vegetables, wine grape pinot noir, wine grape sauvignon blanc); forestry; native/retired. Native/retired land includes land taken out of production, or alternate land uses that are productive. On irrigable land sheep and beef, dairy, arable and horticulture can also be either irrigated or dryland.

The model is capable of reducing N losses within each land use, with a corresponding reduction in profit, revenue and labour. It also is able to mitigate the losses of P, S and M by introducing four categories of mitigation – a Farm Environment Plan, and measures to address overland flow through the introduction of wetlands and riparian planting into a REC Order 2 subcatchment.

The model uses an independent measure such as profit, jobs, or catchment water quality outcomes to determine whether a scenario is better or worse than others. Profit in the context of this model and reporting is the operating profit minus the opportunity cost of capital used for each land use. Operating profit is revenue minus operating expenses and deprecation, but excluding interest, tax, lease payments, amortisation and any other capital related costs. Baseline profit and responses to changes in water reliability and changes in N loss through mitigation are defined for each of the possible SDU combinations.

An optimisation model is used to simulate a steady-state/equilibrium outcome by maximising the an objective function for each catchment under various constraints on the other measures in the model For example we might maximise profit whilst meeting the NPS-FM objectives for nitrogen and phosphorus and limiting the total area of horticulture, dairy and irrigation in the catchment. . The model does this by changing the area of each land use in the SDUs, whether they are irrigated or dryland, as well as varying the water use and N loss mitigation that occurs on each of those land uses. The simulation repeatedly makes these changes, checking that it has not exceeded the water or N loss limits or land use change that is allowed, until it has reached the highest level of profit it can achieve. The advantages of this approach include (Parsons et al, 2015):

- the complexity of the model can be altered depending on the quality and quantity of resources available;
- the use of optimisation allows the use of a consistent and structured objective to select between multiple alternative outcomes within a complex decision problem, encompassing multiple decision makers and complexities regarding diversity in relative profit.

The model represents the biophysical conditions within which the placement of land occurs with the following features:

- Nutrient loss relationships are generated for each land use by region and climate zone and soil PAW, allowing different land management systems to be used to describe each combination.
- Profit estimates are derived from spatial layers for each land use and irrigation source, either derived from recent work completed by OLW, or from lookup tables that relate profit to SDU characteristics (Bright et. al. 2018).

The reliabilities of the water supply are defined for each FMU and irrigation scheme. These can be updated if total water use changes (i.e., fewer SW takes will lead to increased reliability for the remaining takes), although this was not implemented for this project. Profit responds to the use of irrigation water through the reliability and the rate of application of water to land. Profit also responds to the use of N loss mitigation practices to reduce N losses.

4.2 Assumptions and Limitations

Although in this project we have undertaken only regional assessments, the model was developed to operate at a national scale. The assumptions underlying the model development and the associated limitations they imply are outlined below.

Caveats.

- The algorithms used for developing land use scenarios in this model means that land use and mitigation can occur even if it only produces a very small additional gain in the objective. This implies that land manager behaviour is determined by the objective of maximising the objective (profit, labour, environmental outcomes) and that they will change their practices (i.e., land use and its distribution and mitigations) to any option that can better achieve the objective (no matter how small) within the constraints for the farm and FMUs that it is within. In reality, the rate of land use change and implementation of mitigation will be affected by a range of factors, and it is unlikely that the full amount of change will be seen. This feature of the model limits the extent to which the absolute level of results should be relied upon, and the scenarios are more appropriately considered relative to each other using the same algorithm to define land use placement.
- Economic and contaminant loss parameters are described by the combinations of farm sub-unit characteristics (i.e., Climate, soil, land use, irrigability) and their categories. The degree to which these were subdivided into separate units was based on a balance between increasing resolution, the ability to parameterise additional characteristics, and the increased computational demand that more categories would incur. The number of categories affects the accuracy and reliability of the model outputs.
- The N loss estimates used in the model have been modelled using Overseer. Their accuracy is therefore determined by the limitations of Overseer, and there are therefore considerable limitations on the ability of the model to accurately predict whether a combination of land use and mitigation will meet the NPS-FM limit.
- Only contaminant losses from land uses were incorporated in the model. It is assumed that all other discharges (e.g., point sources) would also be required to make equal proportional reductions in discharges in order to achieve the NPS-FM targets. This was a pragmatic solution as there is not a usable national scale dataset describing contaminant loads from point sources. Similarly, we have assumed 4kgN/ha loss rate for non-productive land. Different magnitudes of N loss from non-productive land affect the reductions in N loss for productive land that must be implemented to meet NPS-FM limits.
- The costs, profits, and N losses are based on current farming systems and mitigations. We have not considered any technological advances, innovations or new land uses that might come about.
- We assume that additional forestry introduced into the model does not influence the availability and reliability of water supply for other users. We have not quantified either the production effects nor the environmental impacts that may occur due to reduced water yields associated with increases in forestry.

- Land use placement is assumed to be driven by profitability. It does not estimate the cost of transition between any two land uses, so initial state of the land use is ignored in the mosaics modelling in respect of placement of land.
- The model does not assess land-use impact on biodiversity, e.g. habitat networks, hence is does not reflect the impact of land-use placement on biodiversity.

5 Modelling

The model domain is discretised into a number of land parcels that we refer to as farm subunits (SDU). SDUs are defined by unique combinations of categorical properties. Details of the definitions and sources of these properties are described in Table 5.

Management units:

c	catchment
fsw	surface water FMU (always equal to or a subset of C)
fgw	groundwater FMU
fn	nutrient FMU (always equal to or a subset of C)
f	Farm
rec	REC order 2 watershed

Physical characteristics that influence profits and contaminant losses (these crosscut management units):

cl	climate zone
s	soil plant available water (PAW) category
irg	irrigability (binary; 0: non-irrigable, 1:irrigable)
irs	irrigation scheme (binary; 0: not in scheme, 1:in irrigation scheme)

A note on notation simplification

To reduce notation burden, we define a group of these categorical variables:

Farm sub-unit: SDU: dependencies: *c,fsw,fgw,fn,cl,s,f,rec,irs,irg*

When the sum of surface water use (SW) for all SDUs is required across, for example, surface water FMUs, we have used a shorthand notation that represents this as:

$$\sum_{FSU} SW_{FSU,fsw}$$

rather than: $\sum_{c,fgw,fn,cl,s,f,rec,irs,irg} SW_{c,fsw,fgw,fn,cl,s,f,rec,irs,irg}$

This means that in some equations subscripts that are present in SDU are duplicated in the equation. In these cases, the duplicated subscript should be considered as deleted in all instances from the group of subscripts that comprise SDU.

5.1 Base contaminants

5.1.1 Nutrients

Base N and P losses for each SDU in the model were derived from lookup tables that relate nutrient losses to land use, PAW, irrigability, irrigation status and climate (Bright et al., 2018).

5.1.2 E.coli

The *E.coli* (M) losses are based on losses from overland flow and direct stock access following the approach of Dymond et al. (2016) and adapted to national scale by Herzig (2018). Runoff

M from each SDU is based on the assumed concentrations of M from pastoral land uses, multiplied by overland flow estimates. M contributions from direct access vary by LU (only cows will walk in the streams) – and is scaled by the proportion of stream length accessible based on the stock exclusion calculations in Section5.2.4.

5.1.3 Greenhouse gases

Greenhouse gas emissions are calculated based on an average emission per stock unit. The national level emissions by land use are divided by either the number of stock units or the area of a land use nationally. This gives an average emissions per stock unit and can be used to calculate the change in GHG emissions as land use changes. This is discussed further in Appendix B. Stock units change with N mitigation and land use changes.

5.2 Mitigations

5.2.1 N Mitigation

N mitigation is a decision variable that is unique to each combination of Region x Land Use (with the exception sheep and beef, which varies by climate zone). The N mitigation variable ranges between 0 and a maximum value are defined in a lookup table derived from Bright et al. (2018) and modified to reflect regional council specific information obtained from Hawkes Bay and Taranaki regional councils from consents database of farm plan processes. (Fraser et al., 2017). Details are provided in Appendix A.

Many of the N mitigations are associated with reductions in stock numbers, which in turn has implications for E. coli generation and greenhouse gases. Appendix B describes the derivation of dSUdN, the change in % stock units with change in %N.

5.2.2 P Mitigation/FEP

A review of literature regarding on farm mitigation of P has not revealed any compelling data on the costs and mitigations achieved. There is little consistency with what data is available, and it would be difficult to draw a curve of % change in operating profit with % change in P loss. We have therefore determined that the most useful approach will be to implement a P package approach. This will assume the use of a basket of mitigations (excluding stock exclusion, riparian planting and wetlands, which are dealt with explicitly by the model), which will achieve an average reduction at the RECo2 subcatchment level of 5%. In the model P mitigation/FEP is a decision variable at the RECo2 catchment level. It describes the proportion of a RECo2 catchment with a Farm Environment Plan (FEP) and varies between 0 and 1 (100% implementation of FEPs).

We have taken the 5% from a DairyNZ study of the Waipa (Kalaougher et al 2019) where they undertook a detailed study of possible actions by 285 farms under a Farm Environment Plan (FEP) . This included Overseer estimates of change in P losses for 198 farms. They found that at full implementation there would be a 9% reduction in P. The range of measures in their FEPs included stock exclusion and riparian planting, which were among the most effective mechanisms for removing P (21% for stock exclusion and 47% for riparian planting), with 16% and 12% respectively of farms intending to use these mechanisms. Given that our FEP would exclude these mechanisms, as they are addressed separately, we have reduced the likely impact of FEPs to 5% overall (including sheep and beef farms). It should be noted that the effluent management mechanisms available to dairy farms would not be implementable by sheep and beef farms. While this approach is not ideal, lacking detailed justification, the reality is that many individual on farm mechanisms produce changes in P loss that are very small (1

– 2%) in the context of the overall errors in estimates of P losses, and the use of even 5% as an overall estimate is difficult to justify given the paucity of data in this area regarding the actual availability and efficacy of individual P mitigation mechanisms for real farms.

The cost implementing FEPs is estimated at 5% of operating profit, based on Matheson et al (2018) M1 bundle of mitigations, which are the set of mitigations that can be implemented at less than 10% impact on operating profit but with at least low effectiveness. We consider that the mitigations in their M1 bundle corresponds broadly to the DairyNZ mitigation likely to occur within a FEP, which is generally a voluntary or quasi voluntary mechanism. Requirements for more stringent actions are likely to require specific regulatory action.

5.2.3 Riparian planting mitigation

Riparian planting is implemented at the RECo2 level and describes what proportion of the RECo2 catchment stream length has been planted in either 5m (F5) or 15m (F15) wide planting beside waterways. The sum of F5 + F15 must be less than or equal to 1. For the baseline we assumed no existing riparian planting.

The modelling assumes that riparian planting occurs on both sides of the stream or river and is not applied to native or forestry land uses. The costs of riparian planting are based on the MPI Stock Exclusion Report (Agribusiness Group, 2017).

$$RipCost_{SDU} = UnitRipCost \times StreamLength_{REC} \times \frac{A_{SDU}}{A_{RECo2}} \times (10 \times F_5 + 30 \times F_{15})$$

Equation 1

Where:

UnitRipCost	cost per m^2 of riparian planting (\$1.47/m^2)
$StreamLength_{RECo2}$	Length of stream in a RECo2 subcatchment
A_{SDU}	Area of an SDU
A_{RECo2}	Area of the RECo2 subcatchment.

5.2.4 Stock exclusion mitigations

Stock exclusion is a decision variable at the RECo2 * LUS level. It is comprised of the proportion of streams with fencing only (F_0), plus the proportion with riparian planting (F5 and F15) which also have fencing that excludes stock. The costs of fencing differ for dairy and S&B & Arable[7]. For fencing only, this is represented with F_0sba (proportion of S&B + Arable excluded from rivers) and F_0dai (proportion dairy excluded from rivers). From these, we can define the total proportion of stream length that is fenced (including fencing associated with riparian planting) as shown in *Equation 2* and Equation 3.

$$PSE\_dai = F\_0dai + F\_5 + F\_15$$

Equation 2

$$PSE\_sba = F\_0sba + F\_5 + F\_15$$

Equation 3

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[7] We assume that most arable farms also have a sheep and/or dairy grazing component so require sheep and beef fencing. We have set stocking rate at 5% of dairy support, based on the income from grazing is 5% - 10% of the total income, and they will not always be undertaking dairy grazing on land adjacent to waterways.

Where:

PSE_dai	Proportion of dairy land in a RECo2 subcatchment where stock are excluded from streams and rivers.
PSE_sba	Proportion of sheep and beef and arable land in a RECo2 subcatchment where stock are excluded from streams and rivers.
F_0dai	Proportion of dairy land in a RECo2 subcatchment where fencing only occurs to exclude stock from streams and rivers.
F_0sba	Proportion of sheep and beef and arable land in a RECo2 subcatchment where fencing only occurs to exclude stock from streams and rivers.
F_5	Proportion of land where riparian planting of 5m width occurs.
F_15	Proportion of land where riparian planting of 15m width occurs.

The stock exclusion is constrained so that the total proportion fenced is greater than the initial conditions, and so that the proportion of streams fenced are no greater than 1. The stock exclusion initial conditions by land use (fencing only) are specified by Table 4-1 in Semadeni-Davies and Elliot (2020). Following Semadeni-Davies and Elliot (2017), we have only applied sheep and beef fencing on accord streams in areas with slopes less than 16°. Where the initial conditions of F5 are greater than one, the F_0 initial conditions were reduced so that PSE_dai and PSE_sba equalled the proportions indicated in table 2.

Table 3: Current level of stock exclusion (percent of stream length fenced) estimated by super region (reproduced from Semadeni-Davies and Elliott (2017))

Super-Region	**Enterprise type**	**Estimated current level of fencing**
National summary	Dairy	95
	Deer	50
	Grazing	71
	Other pastoral	83
	Sheep/Beef	50
Northern North Island	Dairy	97
	Deer	65
	Grazing	60
	Other pastoral	96
	Sheep/Beef	60
Southern North Island	Dairy	93
	Deer	54
	Grazing	89
	Other pastoral	78
	Sheep/Beef	44
South Island	Dairy	94
	Deer	46
	Grazing	72
	Other pastoral	63
	Sheep/Beef	49

The cost of fencing is estimated separately from the cost of riparian planting, but it includes the lengths of fences added with the riparian planting – so for example if there is existing fencing with 0m width riparian planting, and there is a change to 5m riparian planting, then a new fence must be installed to protect the 5m riparian planting. The fencing cost is based on a unit cost multiplied by an area prorated length of RECo2 stream length, multiplied by the new proportion of fencing.

$$FCostDAI_{SDU} = UnitFCost_{dai} \times StreamLength_{REC2} \times \frac{A_{SDU,dai}}{A_{REC2}} \times \left(F_5 + F_{15} + dF_{0,dai} \times \frac{(1 + tanh(dF_{0,dai} * 100))}{2} \right)$$

Equation 4

$$FCostSBA_{SDU} = UnitFCost_{sba} \times StreamLength_{REC2} \times \frac{A_{SDU,sba}}{A_{REC2}} \times \left(F_5 + F_{15} + dF_{0,sba} \times \frac{\left(1 + tanh\left(dF_{0,sba} * 100\right)\right)}{2}\right) \quad \text{Equation 5}$$

Where:

UnitFCost	Cost per m of fencing, as shown in Table 4
StreamLength$_{RECo2}$	Length of accord stream in a RECo2 subcatchment
$dF_{0,LU}$	change in proportion of waterways in RECo2 catchments with fencing without riparian buffer
F_5	Proportion of waterways in the RECo2 catchments with fencing with a 5m riparian buffer
F_{15}	Proportion of waterways in the RECo2 catchments with fencing with 15m riparian buffer

Table 4: Unit costs for stock exclusion fencing (UnitFCost$_{lus}$) (Source:Grinter and White, 2016 updated using CGPI, StatsNZ). Costs include stock water where likely to be required.

Simple land use	Irrigable ($/m)	Non-irrigable ($/m)
S&B, arable	$7.65	$37.08
Dairy	$4.73	$5.43

5.2.5 Wetland mitigation

Wetlands are used to mitigate overland flow contaminants (P, S and M). Wetland as a mitigation is defined at the RECo2 level and is specified as the proportion of the RECo2 catchment in wetland (Prop_Wetland).

Prop_Wetland can vary between 0 and a maximum which varies by RECo2 catchment. The maximum possible proportions are defined in a look up table and are restricted to the smaller of 5% of total area or the area of the catchment that is flat enough to accommodate wetlands (given by the irrigable area). The Current State is defined based on the GIS layer of current wetlands[8] (MFE 2018), and where the existing wetland area is greater than 5%, will be limited to 5% as this is considered to be the maximum mitigation that can be achieved from the inclusion of wetlands in a catchment (Tanner et al 2022).

We have also included historical areas of wetland (MFE, 2017), as wetlands in these areas will have a lower cost since they involve wetland ***restoration*** rather than wetland ***construction***. Wetlands in historical areas of wetland are termed Facilitated Wetlands, while in other areas they are termed Constructed Wetlands. When implementing mitigation using wetlands, the model first includes Facilitated Wetlands, then once all the available area for facilitated wetlands has been used up, it includes Constructed Wetlands.

The cost of wetlands is taken from Lowe et al[9] (undated) and is estimated at $6/m^2 for facilitated wetland and $12/m^2 for constructed wetlands based on the Wetland Practitioners

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[8] Note that this does not take into account constructed wetlands.

[9] Lowe, H., McNab, I., and Brennan, J. 2018. Mitigating nutrient loss from pastoral and crop farms: A review of New Zealand Literature. Horizons Regional Council.

Guide (Tanner et al, 2022). There are some additional maintenance costs, but these are below the margins of error (<1%) of the total cost.

$$WetlandCost_{SDU} = PropWetland_{REC} \times A_{SDU} \times WetlandUnitCost_{wt} \qquad \textit{Equation } 6$$

Where:

PropWetland	Proportion of a catchment in wetland
WetlandUnitCost	Cost per m^2 of wetland construction
wt	Wetland type, being constructed or facilitated wetland

5.2.6 Loss of productive land

The model includes a scalar (*RedArea*) that takes into account the reduction in productive area associated with riparian planting width and wetland area. Note that riparian planting is not applied to forestry or native areas, while wetlands can occur on all land areas.

$$RedArea = 1 - \frac{StreamLength_{REC} \times (F_5 \times 10 + F_{15} \times 30)}{A_{REC2}} - PropWetland \qquad \textit{Equation 7}$$

Where:

$StreamLength_{RECo2}$	Length of stream in a RECo2 subcatchment
A_{RECo2}	Area of the RECo2 subcatchment.

5.3 Profit, Operating profit and Revenue

Spatial layers of base Operating Profit per ha (*OPpha*) and Revenue per ha (*Rpha*) for each land use and potential irrigation status ((0: dryland, 1: irrigated-surface water, 2: Irrigated-groundwater) are an input to the NWEELUM model. OPpha used here includes depreciation but excludes interest, tax, and wages of management. These layers were obtained from previous studies, as described in Table 5. We estimated the reductions to maximum irrigated OPpha associated with reductions in supply reliability based a spatial layer describing surface water supply reliability (Fraser et al, 2017) and through interpolation of curves that relate change in profit to supply reliability, by land use, from Bright et al. (2018). The same proportional reductions were applied to the revenue.

Each LU was also associated with an annualised capital cost (opportunity cost of capital), which also varies based on the use of water from an irrigation scheme. Finally, *OPpha* is reduced to represent costs of N, P, S and M loss mitigations. For N loss this is based on a slope of change in OPpha for change in N loss (slope varies by LU). For P, S, and M OPpha is reduced by the discrete costs of mitigations. Profit is the *OPpha* less opportunity cost of capital ($r_{disc} = 3\%$[10]) and then multiplied by the area in that land use and water source.

A generalised equation to describe the total Profit (*Pr*) accounting for mitigations for any unique SDU is given by:

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[10] Discount rate based on the returns to dairy farming excluding capital gains over the last five years. Source DairyNZ Economic Farm Survey.

Equation 8

$$\begin{aligned} Pr_{SDU} = \Bigg[\sum_{lu,ws} & L_{SDU,lu,ws} \\ & \times \left(\left(OPphaADJ_{SDU,lu,ws} \times \left(1 - Nmit * dOPdN_{SDU,lu}\right)\right.\right. \\ & \left.\left. \times \left(1 - FEP * PMit\_slp\right) - cap_{SDU,lu,ws}\right) \times RedArea_{SDU,lu,ws}\right)\Bigg] \\ & - \left(FCostDAI_{SDU} + FCostSBA_{SDU} + RipCost_{SDU}\right. \\ & \left. + WetlandCosts_{SDU}\right) \times r_{disc} \end{aligned}$$

Where:

Pr	Profit ($)
L	Land area (ha). L is adjusted endogenously by the model when in simulation mode.
cap	Opportunity cost of capital associated with each land use within a SDU ($ ha^{-1} yr^{-1}) (Appendix D) [varies based on *lu* and *ws* (irrigated on not irrigated), and assigned to each SDU based on *cl, irs, ls*]
dOPdN	Slope of the N mitigation curve for profitability (% change OP/% change N loss) [varies by *lu* and *ws* (irrigated on not irrigated), and assigned to each SDU based on *cl, s, ls*]
RedArea	The area of land after the removal of land from production for riparian planting and wetlands (see below).
FCostDAI	The cost of new stock exclusion for dairy cattle
FCostSBA	The cost of new stock exclusion for sheep and beef and arable land
RipCost	The cost of riparian planting.
WetlandCost	The cost of wetlands
r_{disc}	Discount rate (%)

5.4 Calculating water use and mitigation of contaminant loss

5.4.1 Water use

The total GW use (l/s) for the SDU is given by:

$$GW_{SDU} = \sum_{lu} L_{SDU,lu,ws=2} * w_{SDU,lu}$$

Equation 9

Where:

w	application rate (l/s) for a lu (Bright et al. (2018)).
$L_{SDU,lu,ws=2}$	Land area for a given land use being irrigated from groundwater in a SDU

The total SW use (l/s) for the SDU is given by:

$$SW_{SDU} = \sum\nolimits_{lu} L_{SDU,lu,ws=1} * w_{SDU,lu} \qquad \text{Equation 10}$$

Where:

$L_{SDU,lu,ws=1}$	Land area for a given land use being irrigated from surface water in a SDU

5.4.2 SDU N loss

The N loss from each land use is affected by the implementation of N mitigation measures

$$N_{SDU} = Nwetland_{RECo2} \sum\nolimits_{LU}^{\square} N_{SDU,LU}^{base} \times (1 - Nmit_{LU}) \times Nfence_{RECo2,LU} \qquad \text{Equation 11}$$

Where:

$N_{SDU,LU}^{base}$	the baseline N loss for a land use in an SDU.
Nmit$_{LU}$	The efficacy of FEPs for mitigation of P, set to 5%
Nfence	The reduction in N loss from fencing and riparian planting for different land uses as shown in Equation 12 to 15.

Nwetland$_{RECo2}$ is estimated by fitting a functional form to the wetland efficiency plot for TN from the wetland practitioners guide (Figure 6, Tanner et al. 2022), shown in Equation

$$Nwetland_{RECo2} = 1 - (\log(Prop_{Wetland} * 100 + 0.293227) \times 16.02756 + 30.082)/100 \qquad \text{Equation 12}$$

$$Nfence_{RECo2,dai} = F_{0,dai} \times r_{P0} + F_5 \times r_{P5} + F_{15} \times r_{P15} \qquad \text{Equation 13}$$

$$Nfence_{RECo2,sba} = F_{0,sba} \times r_{P0} + F_5 \times r_{P5} + F_{15} \times r_{P15} \qquad \text{Equation 14}$$

$$Nfence_{RECo2,hf} = F_5 \times r_{P5} + F_{15} \times r_{P15} \qquad \text{Equation 15}$$

$$Nfence_{RECo2,native} = 1 \qquad \text{Equation 16}$$

Where:

r	the efficacy for contaminant removal of a given riparian width $r_{P0} = 0.9$, $r_{P5}=0.8$, $r_{P15}=0.7$

5.4.3 SDU P loss

The P loss from each land use is affected by wetlands, FEPs and fencing/riparian planting.

$$P_{SDU} = Pwetland_{RECo2} \times \sum\nolimits_{LU}^{\square} P_{SDU,LU}^{base} \times (1 - Pmit_{LU} \times P\_FEP_{RECo2}) \times Pfence_{RECo2,LUS} \qquad \text{Equation 17}$$

Where:

$P_{SDU,LU}^{base}$	the baseline P loss for a land use in an SDU.
Pmit	The efficacy of FEPs for mitigation of P, set to 5%

Pfence	The reduction in P loss from fencing and riparian planting for different land uses as shown in*Equation* to *Equation* .
P_FEP	The proportion of farms in a RECo2 subcatchment with FEPs.

$\text{Pwetland}_{\text{RECo2}}$ is estimated by fitting a functional form to the wetland efficiency plot for TP from the wetland practitioners guide (Figure 6, Tanner et al. 2022), shown in Equation .

$$Pwetland_{REC2} = 1 - (\log(Prop_{Wetland} * 100 + 0.169868) \times 32.618 + 25.11226)/100 \quad \text{Equation 18}$$

$$Pfence_{RECo2,dai} = F_{0,dai} \times r_{P0} + F_5 \times r_{P5} + F_{15} \times r_{P15} \quad \text{Equation 19}$$

$$Pfence_{RECo2,sba} = F_{0,sba} \times r_{P0} + F_5 \times r_{P5} + F_{15} \times r_{P15} \quad \text{Equation 20}$$

$$Pfence_{RECo2,hf} = F_5 \times r_{P5} + F_{15} \times r_{P15} \quad \text{Equation 20}$$

$$Pfence_{RECo2,native} = 1 \quad \text{Equation 21}$$

Where:

r	the efficacy for contaminant removal of a given riparian width $r_{P0} = 0.7$, $r_{P5}=0.6$, $r_{P15}=0.4$

The mitigation effectiveness of fencing is derived from Low et al (undated) and assumes no effect of fencing for horticulture or urban, and assume no reductions from fencing or riparian planting for forestry or native land uses ("other").

5.4.4 SDU microbial export

PSE_dai and PSE_sba are used to determine the proportional reduction in access of stock to waterways. Land use and stocking rate reductions associated with N mitigations are used to determine SDU stocking rates. .As the stocking rates and stock exclusion change, the M exports will update through the Dymond model which includes these factors.

5.4.5 SDU GHG emissions

Emissions from SDUs with livestock are reduced by

$$GHG_{SDU} = \sum_{LU} GHG^{base}_{SDU,LU} \times (1 - Nmit_{LU} \times dSUdN) \quad \text{Equation 21}$$

Where:

$GHG^{base}_{SDU,LU}$	the baseline GH emission for a land use in an SDU.
dSUdN	Slope of the N mitigation curve for stock units (% change SU/% change N loss) (0.77 for dairy, 0.44 for sheep and beef)

5.5 Data

The data for the model was obtained from a range of sources and shown inTable 5. The layers of data and relationships developed are useful in themselves, and are largely available to other parties. More detail on the data is included in the appendices.

Table 5: Data sources

Data	Source	Date of data and comment.
Climate zone	(Bright *et al.*, 2018, adapted from NZMS 1983)	Altered from Bright 2018 with the NW North Island climate zone further divided into three parts that cover Northland, Taranaki, and those parts of Waikato not in other climate zones.
Region	Statistics NZ[11].	2018
Catchment	River Environment Classification V2 (REC)(Snelder and Biggs, 2002)	REC catchments amalgameted to order 2 streams and above.
Freshwater Management Unit (FMU)	Daigneault et al, (2016), Moreau and Bekele (2012), regional council data	Various dates. GIS maps of FMU boundaries were accessed from Northland, Waikato, BOP, HB, Manawatū-Whanganui, Wellington, Marlborough, Tasman, Canterbury, Otago, and Southland. These were not always comprehensive, and some modifications were necessary for Clutha (Otago), Waikato, Southland, Heretaunga (Hawke's Bay) and Wairoa (Northland).
SW FMU reliability	Regionalised flow duration curves developed by Booker & Woods (2014), updated 2017.	2017 Booker (pers.comm.) supplied flow duration curves, developed following the same method, covering the irrigation season (September – May) only. A default minimum flow of 0.9*MALF was assumed.
Irrigation schemes and reliability	Brown (2012)	2012 Scheme reliability was provided by Brown (pers.comm.)
Farm	LINZ Cadastral database	2020
Irritability	NZLRI (Lynn, et al., 2009)	Slope of < 15 degrees (NZLRI slope A, B, C) and elevation (<600m) used as criteria.
Soil PAW category	SMap and Fundamental Soil Layer (FSL)[12]	SMAP -DATE FSL 1960 – 2000. Accessed 2017.
Current Land use	Monaghan typologies spatial layer for pastoral land uses, with LCDB (version 5.0, released 2020) for hort, arable, and other land uses and covers.	Estimated internally in LUMASS.

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[11] (http://www.stats.govt.nz/browse_for_stats/maps_and_geography/geographic-areas/digital-boundary-files.aspx, June 2018).

[12] https://soils.landcareresearch.co.nz/soil-data/fundamental-soil-layers and the PAW dataset used in this modelling is available at https://lris.scinfo.org.nz/layer/100-fsl-profile-available-water/.

Data	Source	Date of data and comment.
Irrigated area	MFE 2020 (pers.comm)	2020. Used as the primary estimate of current water use, by combining irrigated area with assumed water application rates.
Irrigation application rate	Bright et al. (2018)	
Ratio GW to SW use	PSI database 2018	2018 (https://data.mfe.govt.nz/table/102980-national-water-allocation-statistics-2018-hydroframe/). Primarily used to split water usage determined from irrigated area between surface water and groundwater sources.
Nitrogen loss	Bright et al., 2018, Srinivasan, Monaghan et al 2021.	2018 and 2020. Updated for Taranaki with farm plan data and Hawke's Bay with consent data. Updated also with Srinivasan, Monaghan losses in SI high country, adjustments in Southland for low loss rates.
Phosphorous loss	McDowell et al. 2022, Table 2.	Based on Monaghan et al 2021.
Sediment loss	NZEEM (Dymond et. al. 2010, Herzig, 2018) with modifications from OLW programme.	Available on NZLRIS **NZEEM (Erosion Rates) South Island | WMTS | LRIS Portal (scinfo.org.nz).** Data is modified by land cover (woody vs non-woody)
Microbial loss	Method based on Dymond et al 2016, Herzig 2018.	Includes estimates of volume of overland flow based on soil curves, and concentrations of E.coli in overland flow. Direct deposition from cattle based on proportion of catchment fenced and stock numbers. Overland flow modelling may underestimate on flat areas where soil curve numbers estimate little to no runoff.
Pastoral Profit	Bright et al., (2018), Beef and Lamb NZ, (2021), Dairy NZ (2021), Ministry for Primary Industries, 2020, Thomas et al., (2020).	Lookup table from Aqualinc and AgriBusiness Group Ltd (by climate zone, PAW, irrigation, irrigability), but updated with more recent Beef and Lamb NZ, DairyNZ and MPI monitoring data in 2022. Updates are based on 5-year average data for dairy and sheep and beef.
Non-pastoral Profits		Forestry uses data from Scion and Forecaster online **Home Page - Forecaster Calculator (integral.co.nz)https://integral.co.nz/forecaster/**. Arable and horticulture profits are from 2022 (**Datasets - Whitiwhiti Ora: Land Use Opportunities (landcareresearch.co.nz)**).
Costs of N Mitigation	Various	Case studies of mitigation from various sources see Appendix A

Data	**Source**	**Date of data and comment.**
Fencing and Riparian planting	Grinter and White (2016) Agribusiness Group, 2017	Unit costs for stock exclusion fencing (UnitFCostlus) (Source:Grinter and White, 2016 updated using CGPI, StatsNZ) The costs of riparian planting are based on the MPI Stock Exclusion Report (Agribusiness Group, 2017).
Wetlands	LRIS, Wetland Practitioner Guide (NIWA and DairyNZ)	Current and Historic wetland locations from LRIS, costings from practitioner guide.
Farm Environment Plans	Kalaugher, et al 2019. , Matheson et al (2018).	General estimate of likely impact (Dairy NZ Kalaougher study) and cost (Matheson et al M1 mitigation bundle).

Table 6: Land uses available within the NWEELUM model

Simple land use	Land use	Short name
Dairy	Dairy	dai
Sheep and Beef	Sheep and Beef	snb
Horticulture	Apple	hap
	Avocado	hav
	Blueberry	hbl
	Cherry	hch
	Kiwifruit green	hkgr
	Kiwifruit gold	hkgd
	Wine Pinot noir	hgp
	Wine Sauvignon blanc	hgs
Vegetables	Onion	von
	Potato	vpt
Arable	Maize	amz
	Vining peas	ape
	Wheat	awt
Forestry	Forestry - 28 yr rotation	fst
	Forestry - 55 year rotation	flg
Native	Native	nat

6 Scenario modelling of Mosaics

Scenarios are representations of a particular arrangements of land, water, and assimilative capacity among land uses and land users. In the case of this project the aim is to arrange land use in such a way that different mosaics are created.

The approach we have adopted is to force land uses to occur as monocultures at different scales: SDU, Farm and REC2 subcatchment. This allows us to force the model to create different patterns of land use of increasing complexity. We refer to these different scales as “mosaic units”.

We have used two different approaches to creating mosaics, one demonstrated in a case study of the Ruamahunga catchment in Greater Wellington region, and one demonstrated in a case study of the plains areas of the Canterbury region.

Although the model has a fully operable representation of complex mitigation options, we have not allowed mitigations in either of the case studies. This is primarily to allows clearer interpretation of the effects of land use placement, without the confounding effect of differences in land management within land uses.

6.1 Ruamahunga Mosaics Scenarios

We modelled two different scenarios for the Ruamahunga catchment. One scenario aimed to maximise profit ("max. Profit") and the other scenario ("min. N loss") assessed the potential for N loss reduction while at least achieving 70% of the total catchment profit at baseline. For each of these scenarios we modelled three different land use placement options, assigning monocultures of land-use to SDU, Farm, and REC mosaic units respectively.

We utilised the genetic algorithm (GA)-based implementation of the NWEELUM model in LUMASS.

- For the SDU mosaic units it assigns the land use randomly using a weighting based on the proportion of individual land use expected by the local minimum (s. Table 8).
- For the Farm and REC mosaic units, it chooses a SDU from within the unit, and randomly assigns a feasible land use to the whole Farm or REC2 subcatchment. If no feasible land use can be found for the given SDU, native vegetation is allocated to the entire Farm or REC2 unit.

These land use constraints are set at the level at which the model is run, which in the case of the Ruamahunga is the whole catchment.

In setting the local minimum, the area of each land use category and each land use that is feasible (i.e. operating profit > 0) is calculated within each scale. If there is less area feasible than is specified by the minimum constraint, the constraint is set to the feasible area.

As GA-based optimisation is not exact, we modelled 15 repetitions for each land use placement option , i.e. SDU, Farm, and REC mosaic units.

6.2 Canterbury Plains Mosaics Scenario

A scenario was implemented in the Canterbury Plains area using the same SDU, Farm and REC2 block sized monoculture mosaic units. However, in the Canterbury example we implemented a simple algorithm approach where we placed land uses in a priority manner based on their operating profit, so that the highest value land uses were placed in their most profitable locations until the constraint area of that land use was reached. The constraint on each land use was set at its current area apart from horticulture and vegetable growing, which were allowed to increase to 3 times their current area in order to give reasonable options for mosaics to occur. All other land uses were prorated lower to allow for this increase and to ensure that areas by land use remained the same for all different mosaic unit implementations. Additionally, we used Canterbury specific datasets for profits and nutrients losses on pastoral farms (Harris and Fraser, 2023), which allowed for the inclusion of dairy support as an additional land use option.

Table 7: Minimum proportion of individual land use for scenario definition (before adjustment for feasibility)

	Category	Sheep and Beef	Dairy	Horticulture								Arable					Forestry		
	Individual land use	Sheep and beef and deer	Dairy	Apples (AP)	Avocado (AV)	Cherry (CH)	Grape SB (GS)	Grape PN (GP)	Kiwifruit Gold (KD)	Kiwifruit Green (KN)	Blberry	Wheat and cereals	Vining Peas	Potatoes and squash	Onions	Maize	Forestry Exotic 1	Forestry Exotic 2	Forestry native
Region	Northland	23.4%	14.1%	0.00000%	1.03301%	0.00000%	0.02304%	0.00536%	0.19575%	0.14188%	0.01052%	0.64688%	0.00000%	0.09233%	0.04046%	3.42228%	13.99040%	4.66347%	4.66347%
	Auckland	24.5%	13.1%	0.26699%	2.14086%	0.00000%	0.90252%	0.20993%	1.88335%	1.36501%	0.05091%	1.04962%	0.00000%	0.94071%	0.82336%	1.38825%	11.49938%	3.83313%	3.83313%
	Waikato	17.2%	23.6%	0.06002%	0.07304%	0.00000%	0.01173%	0.00273%	0.32325%	0.23429%	0.00530%	0.00000%	0.00000%	0.41500%	0.44309%	3.34384%	9.51738%	3.17246%	3.17246%
	BayofPlenty	7.9%	11.0%	0.02557%	0.71118%	0.00000%	0.01182%	0.00275%	2.26922%	1.64468%	0.03509%	0.00000%	0.00000%	0.00316%	0.00035%	4.19843%	34.42221%	11.47407%	11.47407%
	Gisborne	33.0%	0.5%	0.44422%	0.06878%	0.00000%	1.46017%	0.33965%	0.31903%	0.23123%	0.02153%	1.12373%	0.00000%	0.45540%	0.00000%	2.62281%	17.79457%	5.93152%	5.93152%
	HawkesBay	37.1%	2.0%	2.42811%	0.00785%	0.00000%	1.26104%	0.29333%	0.03778%	0.02738%	0.03050%	0.00000%	0.47422%	1.12626%	0.20202%	2.39943%	10.19812%	3.39937%	3.39937%
	Taranaki	17.1%	29.0%	0.06242%	0.15158%	0.00000%	0.00000%	0.00000%	0.00000%	0.00000%	0.00161%	2.69430%	0.00000%	0.00000%	0.00000%	1.50764%	3.54174%	1.18058%	1.18058%
	Manawatu-Wanganui	35.3%	7.5%	0.27999%	0.01000%	0.00000%	0.25960%	0.06039%	0.00000%	0.00000%	0.00459%	1.50422%	0.00000%	0.00689%	0.03814%	2.65269%	7.06927%	2.35642%	2.35642%
	Wellington	35.6%	4.8%	0.07592%	0.00483%	0.00000%	0.55156%	0.12830%	0.02121%	0.01537%	0.00600%	0.00000%	0.00000%	3.69078%	0.69202%	0.00000%	9.46021%	3.15340%	3.15340%
	Tasman	16.2%	8.8%	3.98917%	0.00362%	0.00000%	1.24374%	0.28930%	0.43235%	0.31336%	0.04717%	0.00000%	0.00000%	0.96531%	3.23663%	0.00000%	26.63046%	8.87682%	8.87682%
	Nelson	13.9%	4.9%	0.09308%	0.03723%	0.00000%	0.63429%	0.14754%	0.00000%	0.00000%	0.00686%	0.15669%	0.00000%	0.00000%	0.00000%	4.04525%	37.04123%	12.34708%	12.34708%
	Marlborough	38.0%	1.2%	0.00704%	0.00000%	0.00000%	8.07807%	1.87903%	0.00000%	0.00000%	0.07494%	2.98228%	0.00000%	0.05303%	1.16663%	0.00000%	8.18087%	2.72696%	2.72696%
	WestCoast	12.3%	26.2%	0.00000%	0.25594%	0.00000%	0.00000%	0.00000%	0.00000%	0.00000%	0.00000%	2.55811%	0.00000%	0.00000%	0.00000%	1.71813%	11.91501%	3.97167%	3.97167%
	Canterbury	35.0%	7.4%	0.15487%	0.02056%	0.06940%	0.74658%	0.17366%	0.00000%	0.00000%	0.00876%	6.75350%	2.10926%	5.49805%	1.20603%	0.00000%	2.41938%	0.80646%	0.80646%
	Otago	41.6%	3.4%	0.05808%	0.00102%	0.12352%	0.01539%	0.13851%	0.00000%	0.00000%	0.01089%	5.64940%	0.00000%	0.10045%	0.00000%	0.00000%	3.64293%	1.21431%	1.21431%
	Southland	29.7%	12.8%	0.00000%	0.00000%	0.00000%	0.00000%	0.00000%	0.00000%	0.00000%	0.26913%	0.00000%	0.00000%	########	0.00000%	0.00000%	4.90356%	1.63452%	1.63452%
Comment		Half of current	Half of current	Current share times the local minimum for hort	Current share times the local minimum for hort	Current share times the local minimum for hort	Current share times the local minimum for hort	Current share times the local minimum for hort	Current share times the local minimum for hort	Current share times the local minimum for hort	Current share times the local minimum for hort	Current share times the local minimum for arable	Current share times the local minimum for arable	Current share times the local minimum for arable	Current share times the local minimum for arable	Current share times the local minimum for arable	60%o of Current	20% of current forestry	20% of current forestry

7 Results

7.1 Ruamahunga

7.1.1 Land-use mosaics

Figure 1 shows maps of land-use placements for the “max. Profit” and “min. N loss” scenarios in the Ruamahunga catchment for land-use placement for each of the different mosaic units, i.e. SDU, Farm, and REC2. For each scenario and land use placement option, out of the 15 modelled repetitions, we selected the result closest to the average objective function result for the given criterion, i.e. profit and N loss respectively.

The overall variability of the results in indicator space across the 15 modelled repetitions is given in Figure 2. It is greater for the larger mosaic units, i.e. Farm, and REC2. This effect is driven by only testing a single SDU inside a larger Farm or REC2 mosaic unit for its suitability to support a given land use to be allocated to the Farm or REC2 mosaic unit. The variability is smallest for the SDU mosaic units as individual suitability testing is performed and averaging effects across differently performing SDUs are avoided.

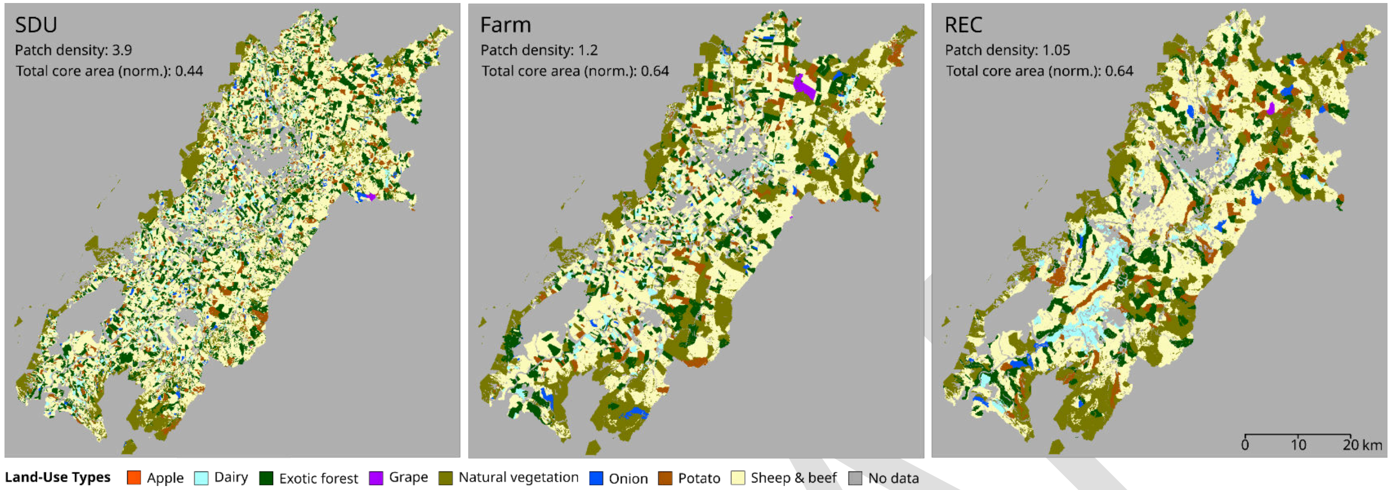
The generation of land-use mosaics is controlled by the shape and size of the mosaic units, i.e. SDU, Farm, and REC2, the minimum area constraints for individual land uses (Table 8) and the genetic algorithm used to allocate the land uses to the SDU, Farm, and REC2 mosaic units across the catchment. We characterise the generated land-use mosaics (Figure 1) using the landscape metrics Patch Density (PD) and normalised Total Core Area (TCA) as well as by the final land-use proportions allocated to the catchment (Figure 3).

Figure 3 depicts the proportions of land uses across the catchment for each of the modelled scenarios and mosaic units. It shows that the proportions are very similar for each mosaic unit option and that the proportions for dairy, sheep & beef, arable, and exotic forestry are slightly higher for the SDU mosaic units compared to the FARM and REC2 mosaic units that show very similar land-use proportions. For the FARM, and REC2 mosaic units, especially native vegetation and sheep & beef are allocated in larger proportions compared with the SDU mosaic units.

Land placement by SDU mosaic units generates the most fine-grained mosaics and show the highest PD value and the lowest TCA for both scenarios (Figure 3). PD decreases with coarser mosaics generated when land placement is to Farm and REC2 mosaic units. However, the TCA for the Farm and REC2 mosaic units is identical. While the overall larger REC2 mosaic units could be expected to yield a higher TCA compared with the Farm mosaic units, the more elongated patches produce relative smaller TCA than more round or square-shaped Farm mosaic units of the same size. At the same time, the Farm mosaic units show a great variability in size, and the large number of relatively small Farm mosaic units reduces the TCA. Overall, both effects seem to balance each other out and yield identical TCA for visibly different mosaics.

Despite the inherent randomness of the GA-based optimisation results, the standard deviation across the computed mosaic-ness indicators was less than one percent across all modelled repetitions. It suggests that in our experiments the value of the mosaic-ness indicators is dominated by the shape and distribution of the mosaic units, i.e. SDU, Farm, and REC2, rather than the actual land-use allocated to them. Hence, we only report one number for each indicator per mosaic unit (Figure 3).

a) max. Profit



b) min. N loss, Profit ≥ 70% of baseline

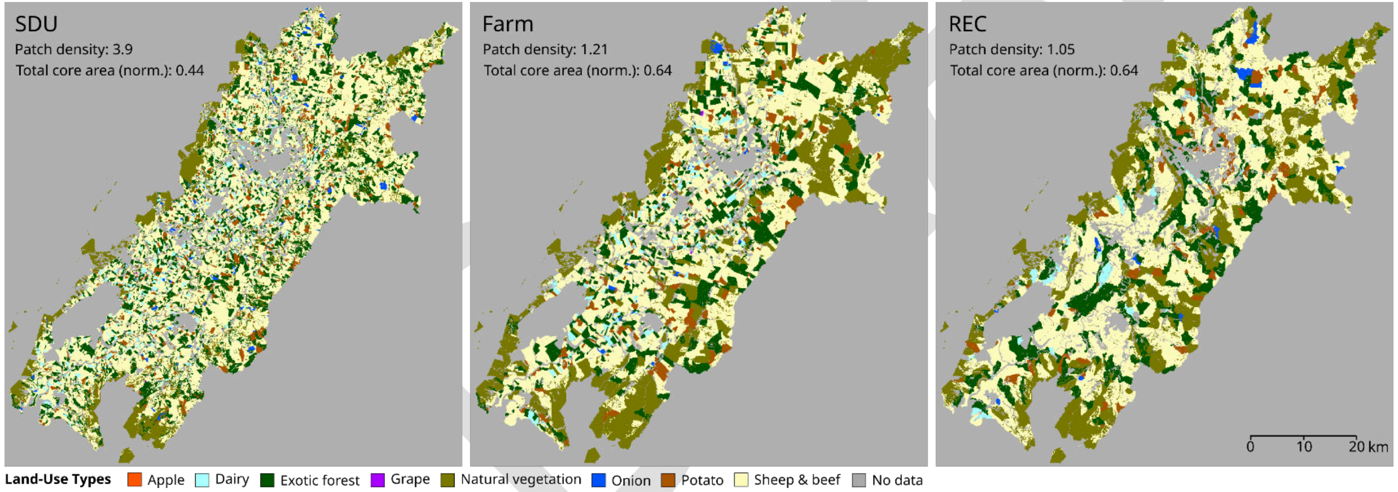


Figure 3. Land use placement for the "max. Profit" (top) and the "min. N loss" (bottom) scenarios in the Ruamahunga catchment. The maps show the results for the respective repetition whose objective function result is closest to the average of all objective function results across all 15 repetitions for a given mosaic unit.

7.1.2 Maximising Profit

Figure 2 shows the results for selected outcome indicators across all modelled scenarios and land placement options. For the “max. Profit” scenario (Fig. 2, top), based on the average result across all repetitions, land placement by the SDU mosaic units achieves the highest total profit (Fig. 2, top, a)), followed by the Farm and REC mosaic units, respectively.

The SDU represents the smallest geometric unit or spatial scale in our dataset and all input data is summarised at this level. Therefore, the SDU scale provides the best representation of spatial variability across a given region. Thus, land-use placement at the SDU scale can achieve best possible results for the targeted outcome (indicator), e.g. the maximisation of profit. Land-use placement at larger scales, i.e. to Farm and REC2 mosaic units, can suffer from averaging effects. These occur when a given set of SDU units that comprise a larger Farm or REC2 unit, show different performances with respect to the given indicator.

Scenario performance regarding associated indicators (outcomes), i.e. those the outcome was not optimised for, are controlled by the land-use placement optimising the primary objective. For the “max. Profit” scenario, it means N and P loss performance is controlled by those land-uses whose combination of profitability and availability (min. area proportion) maximised the overall profit in a given scenario. For the “max. Profit” scenario these land-uses are dairy, arable, and sheep & beef, who also show the three highest N and P losses. As their respective area proportions are lower for the land placement options of Farm and REC2 mosaic units, they show lower profits and losses for those options.

7.1.3 Minimising N loss

The primary objective in this scenario was to minimise N loss while achieving a minimum total catchment profit greater or equal to 70% of the baseline catchment profit (≥ $68 M/yr). In this scenario, based on the average N loss across all modelled repetitions, land-use placement by REC2 mosaic units narrowly achieved the best result of a 37% reduction in N loss that was associated with a 18% drop in total profit at the catchment scale (cf. Fig. 2, bottom). Land-use placement by SDU mosaic unit performed worst regarding the primary objective and only achieved a 21% reduction in N loss that was associated with a 12% increase in profit compared with the baseline (Fig. 2, bottom).

While the result is contradictory to the earlier statement that SDU-based land-use placement would allow for the best exploitation of spatial variability and therefore achieve best possible results, its potential effect is mediated by the actual land-use proportions allocated by the genetic algorithm to Farm and REC2 mosaic units (cf. Section 4.1). The procedure places native vegetation to Farm and REC2 mosaic units if the randomly selected SDU within any of those units is not suitable for any of the other land-uses. This leads to a relatively larger proportion of native vegetation being assigned for the larger mosaic units at the cost of all other land-uses. The difference in land-use proportions leads in turn to a relative better performance regarding N and P losses and worse performance regarding total profit.

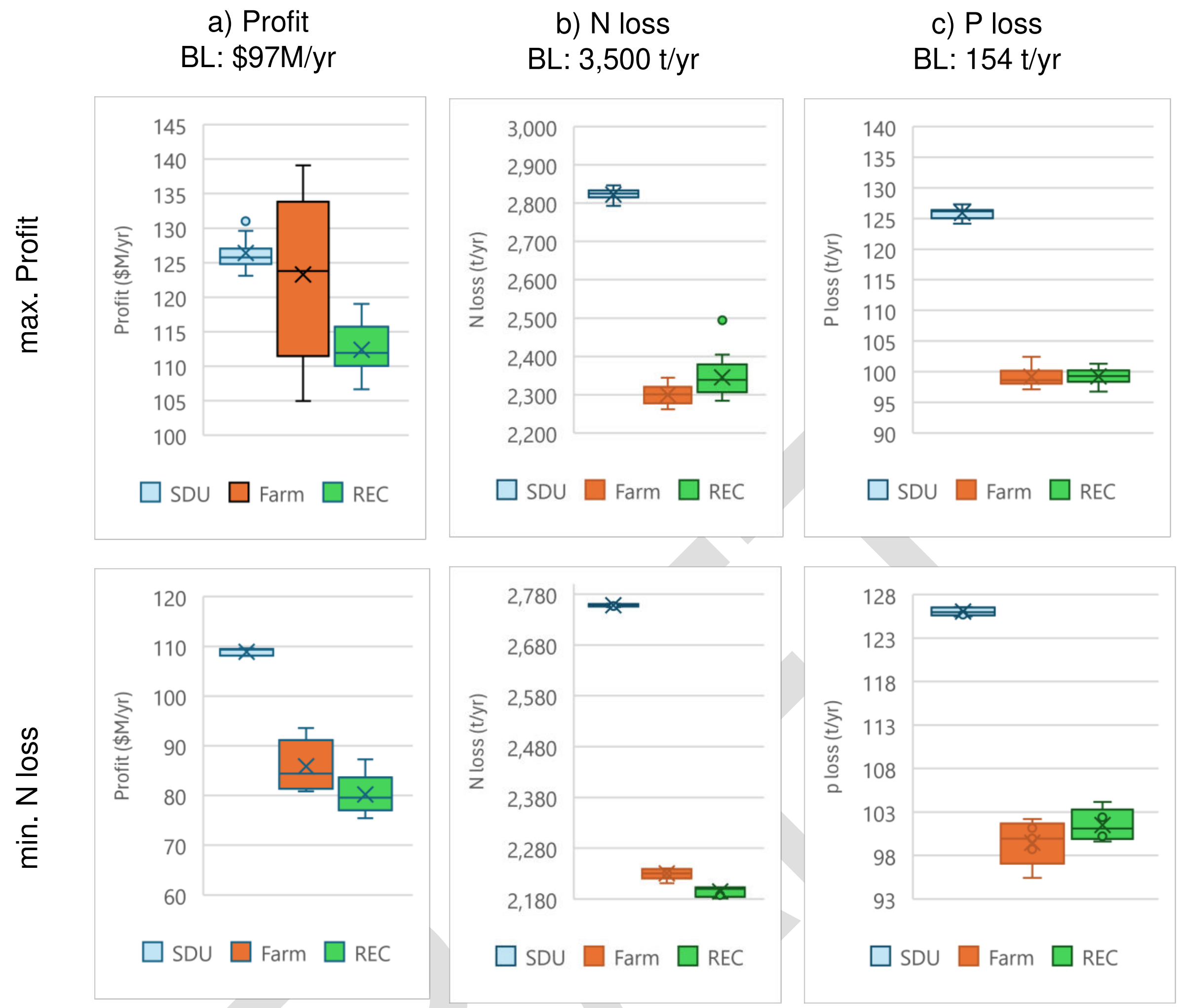


Figure 4. Land use performance indicators by mosaic unit option (a) total profit, b) N loss, and c) P loss) for the 15 modelled repetitions of the "max. Profit" (top) and "min. N loss" (bottom) scenarios. BL indicates the baseline performance for each indicator.

Furthermore, as indicated by Figure 4, the spatial variability of the data underlying the N loss for sheep & beef, the dominant land use in all scenarios, seems less mosaic'ed than the finest-grained mosaic unit, the SDU. According to its PD it seems to fall between the SDU and Farm scale, whereas its TCA puts it on par with the Farm and REC2 mosaic units. This suggests that land-use placement at the SDU scale might not be able to better exploit the spatial variability of the underlying data than placement at the Farm and REC scales, as the averaging effect might not be that large.

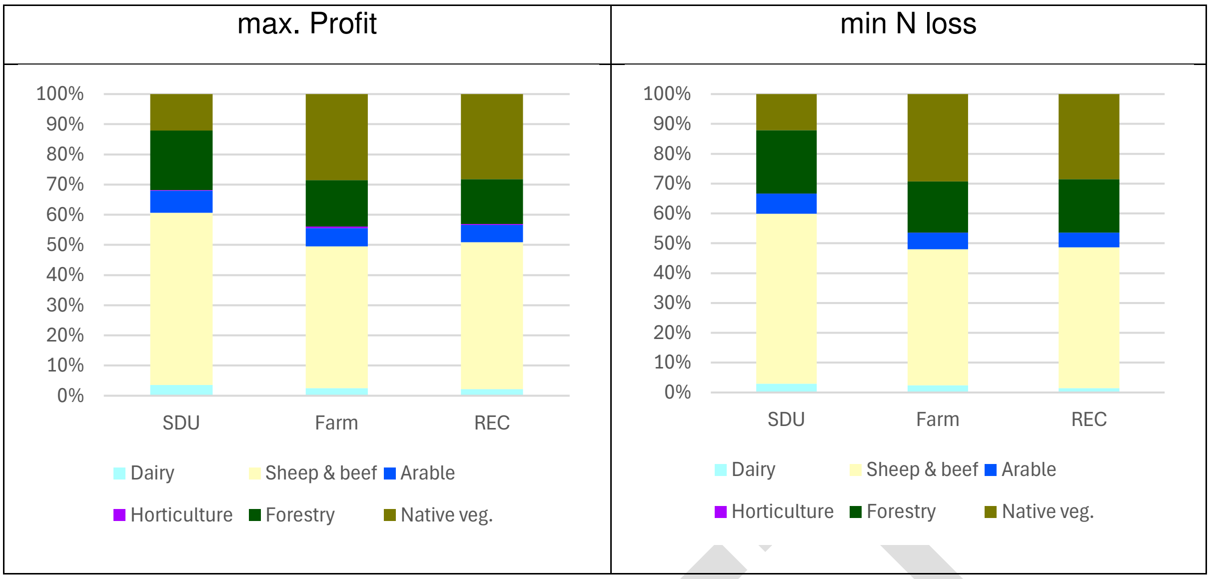


Figure 5 Land use proportions for the "max. Profit" (left) and "min. N loss" (right) scenarios in the Ruamahunga catchment, by mosaic unit option. The graphs show the results for the respective repetition whose objective function result is closest to the average of all objective function results across all 15 repetitions for a given mosaic scenario.

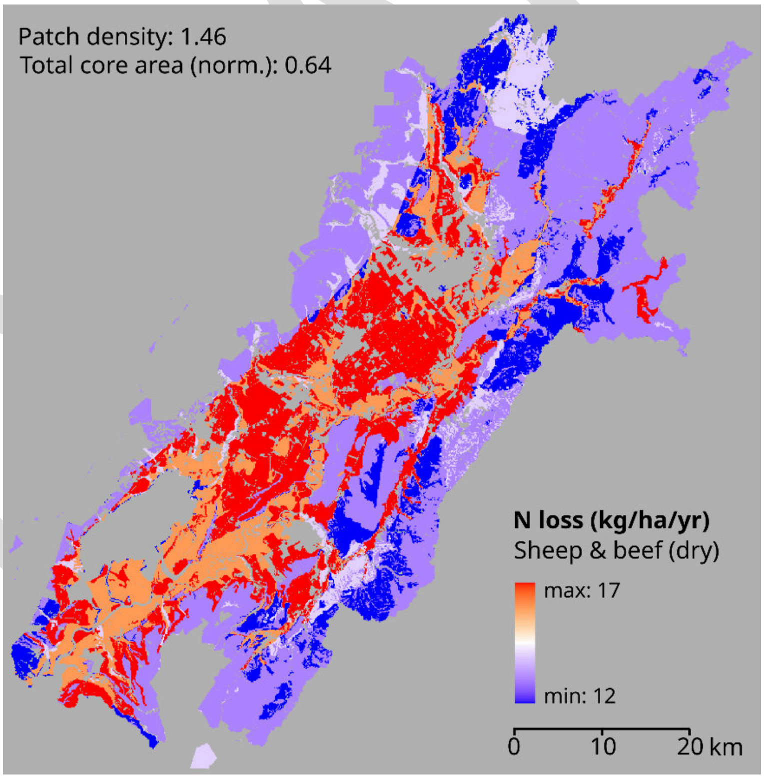


Figure 6. Baseline N loss (kg/ha/yr) for dryland sheep & beef in the Ruamahunga catchment.

7.2 Canterbury Plains Scenario

The placement of land uses to maximise profit for the three different mosaic unit options are shown in Figure 7 and the indicators for mosaic-ness are shown in Figure 8. The maps visually show a more distributed set of land uses, and the indicators show that for Patch Density, land use placement by SDU mosaic units is more mosaic-y followed by the Farm mosaic units and the REC2 mosaic units. This is as expected since the SDU placements are in smaller blocks. Similarly, the Total Core Area indicator is lowest for land use placement by SDU mosaic units and highest for the REC2 mosaic units, indicating that the patch size distribution is most even for the SDU mosaic units. We are confident that the implementation of this scenario has represented different degrees of mosaic as intended.

Although it is not possible to discern it because of the size of the maps, despite the greater mosaic-ness overall of land-use placed by SDU mosaic units, very high value land uses such as viticulture and apples have tended to occur together in fewer, large aggregations. This is likely a result of the placement algorithm used for the Canterbury case study, which gave these land uses preferential access to the locations where they could produce the most profit. Because the soils and climates which are most suitable for producing profit from these land uses occur in a limited number of locations, these land uses end up clumped together. This is not dissimilar to the situation that we see in reality, where there are certain preferred areas for production of kiwifruit, apples and wine varieties.

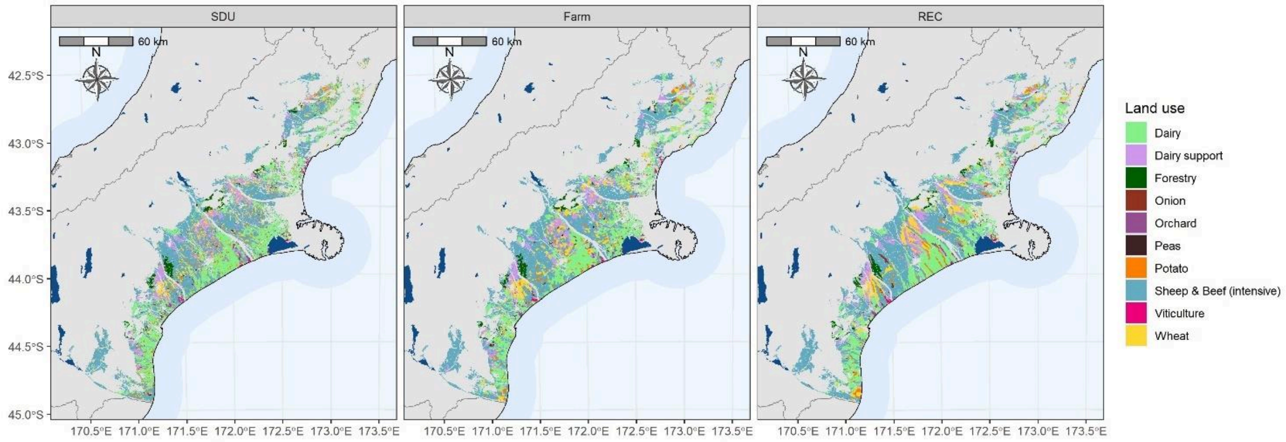


Figure 7: Land use placement by mosaic unit for the Canterbury Plains scenario

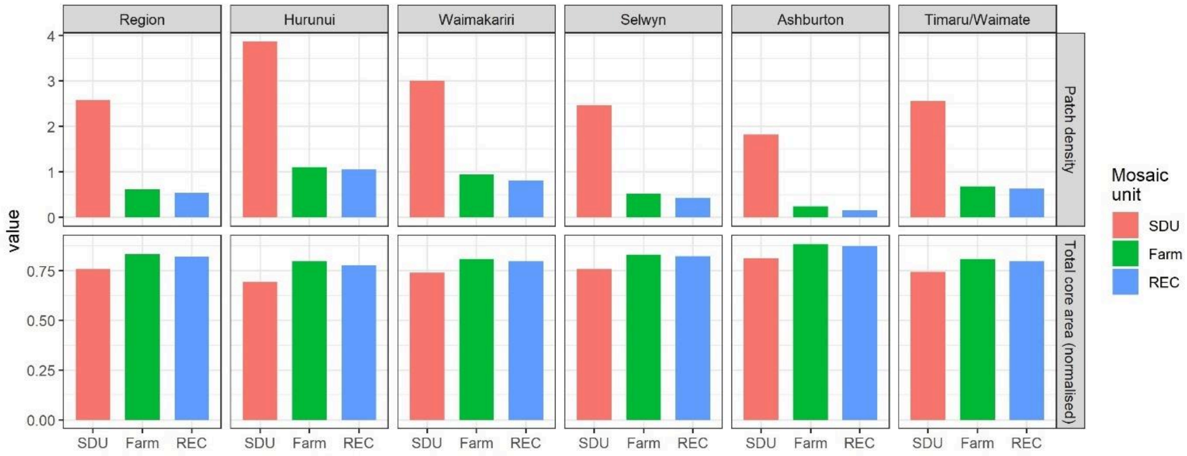


Figure 8: Mosaic indexes by mosaic unit for the Canterbury Plains scenario. Patch Density – Higher = more mosaic-ness. Total Core Area – lower = more mosaic-ness and more evenly distributed

7.2.1 Revenue and Profit

The regional revenue and profit are shown in Figure 9 and for the districts in Figure 10. The data suggests that that at the regional level there are only very minor differences in revenue and profit between land use placement options, with the SDU mosaic units slightly higher than the other two, and the REC2 mosaic units the lowest. This pattern is repeated at the district level.

Figure 11 shows the revenue and profit by land use, with a similar pattern of only very minor differences between land uses apart from Orchard (apples) and Viticulture. The orchard land use shows a distinct reduction in revenue and profit for the land-use placement options by Farm and REC2mosaic units, which is likely because it is more sensitive to placement on less suitable land. When the algorithm assigns orchard to the Farm and REC2 mosaic units, there is a significantly higher probability that at least part of the block will be lower suitability for orchard land use, hence lower profit. A similar but less distinct pattern exists for viticulture for the same reasons.

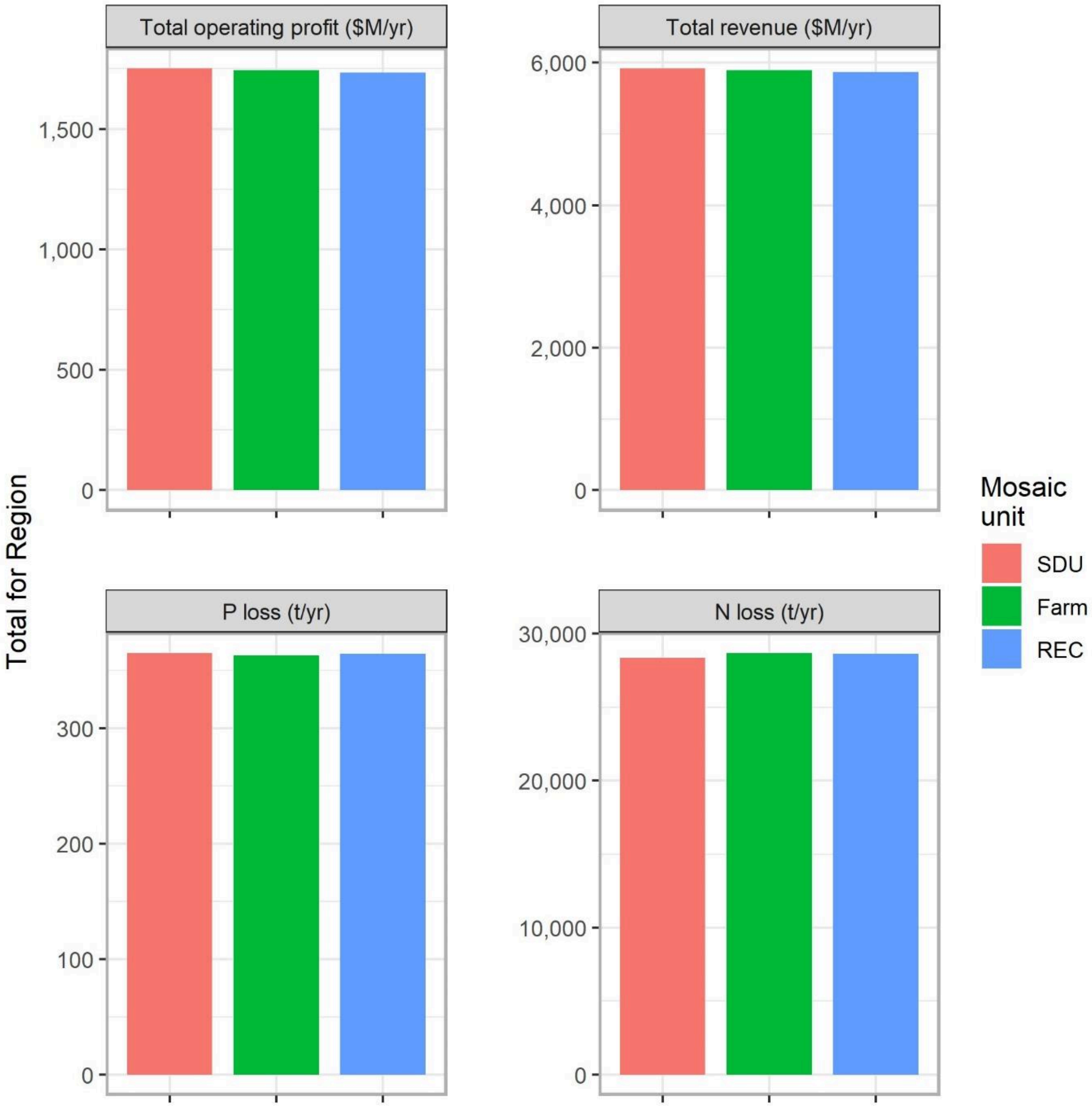


Figure 9: Total (regional) Profit, Revenue, N and P loss by mosaic unit for the Canterbury Plains scenario.

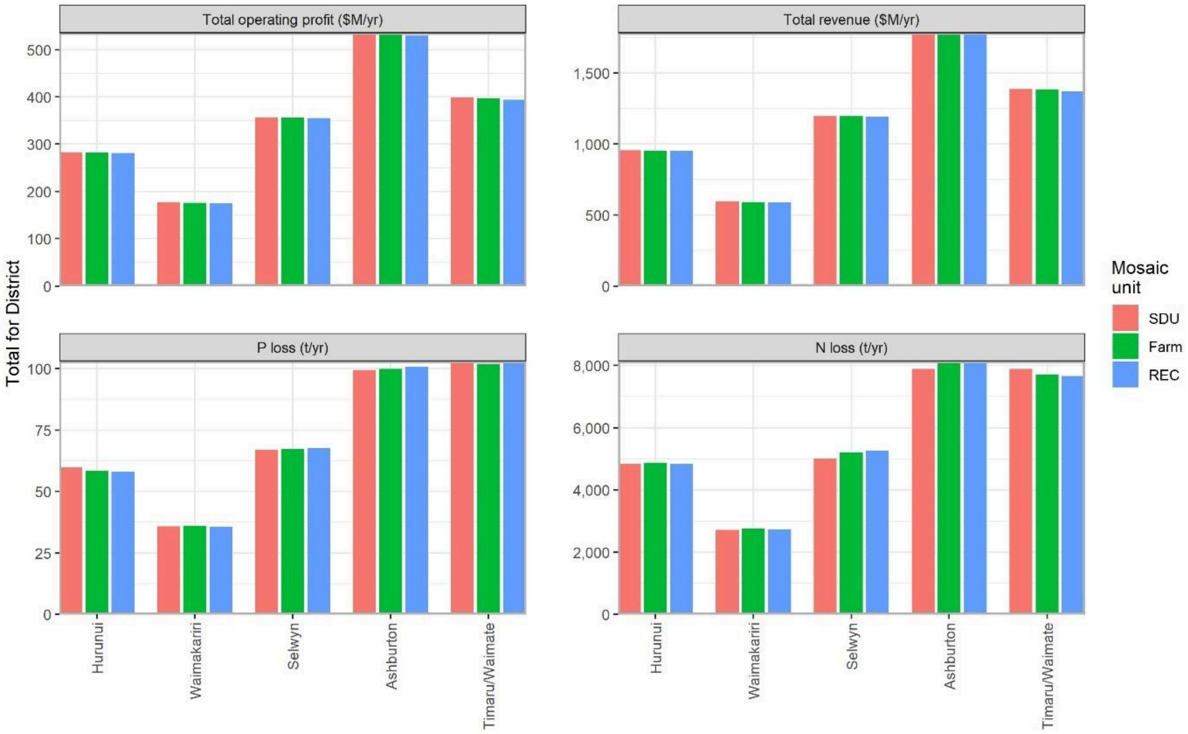


Figure 10: District Profit, Revenue, N and P loss by mosaic unit for the Canterbury Plains scenario.

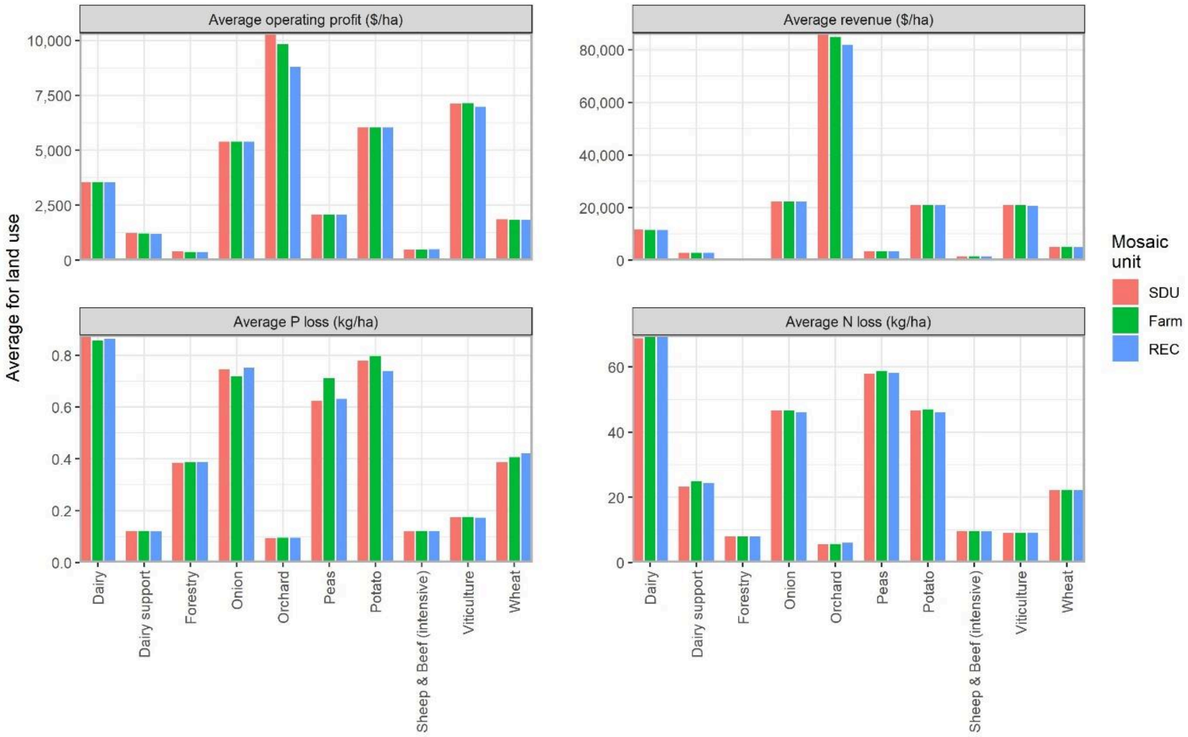


Figure 11: Profit, Revenue, N and P loss by land use and by mosaic unit for the Canterbury Plains scenario.

7.2.2 N and P loss

The N and P loss estimates are shown in Figure 9 and for the districts in Figure 10. They are represented as maps in Figure 12 (N losses) and Figure 13 (P losses). As with revenue and profit there is very little difference between alternative land placement options. However, for these two contaminants the pattern as to which placement option (SDU, Farm and REC2) performs better is not consistent, particularly at the district level where different placement options are best performing across all districts. The patterns of total N and P loss show a more distributed pattern for the SDU mosaic units than the Farm and REC2 mosaic units. The pattern of N and P loss by land use and mosaic unit (Figure 11) does not show any particular pattern of difference by mosaic unit.

Figure 14 shows the proportion of stream length that exceed specified levels of N source loads, subdivided by stream order (REC Order 2 = smaller streams, REC Order 5 = larger waterways). The graph shows that for the Farm and REC2 placement of land uses there is a greater proportion of streams with higher concentrations of N loading, likely because by placing high N emitting land uses in large blocks there is a greater probability that they will be concentrated in some streams. For example, for the REC2 mosaic units each catchment will be a single land use, so some streams will only receive discharges from high emitting land use (typically dairy). For the SDU mosaic units there is a greater probability that a stream will have at least some other land uses diluting the discharges.

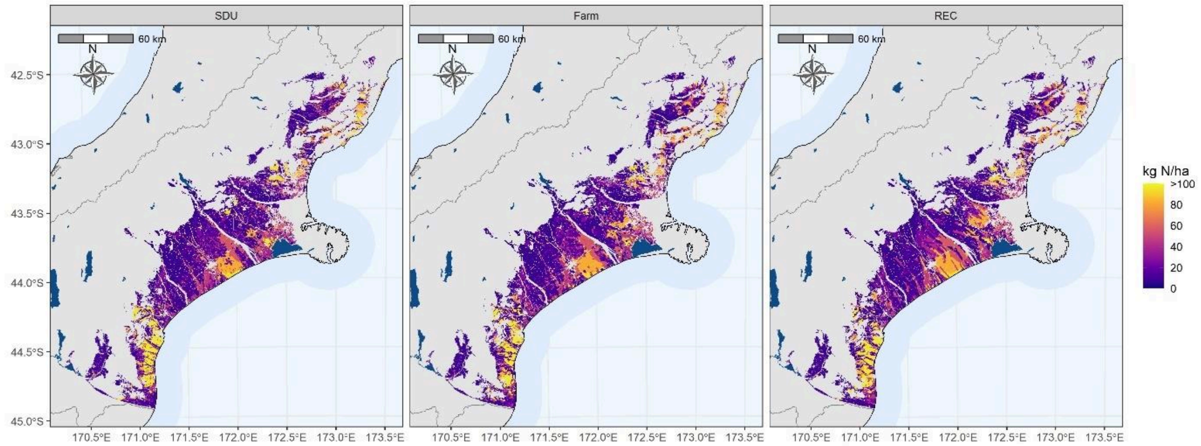


Figure 12: N losses by mosaic unit for Canterbury Plains implementation

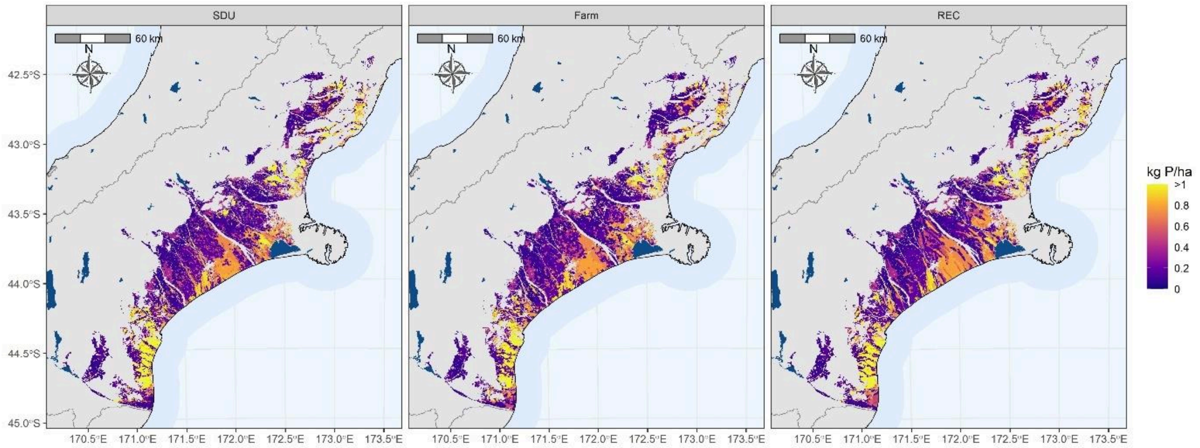


Figure 13: P losses for Canterbury Plains implementation

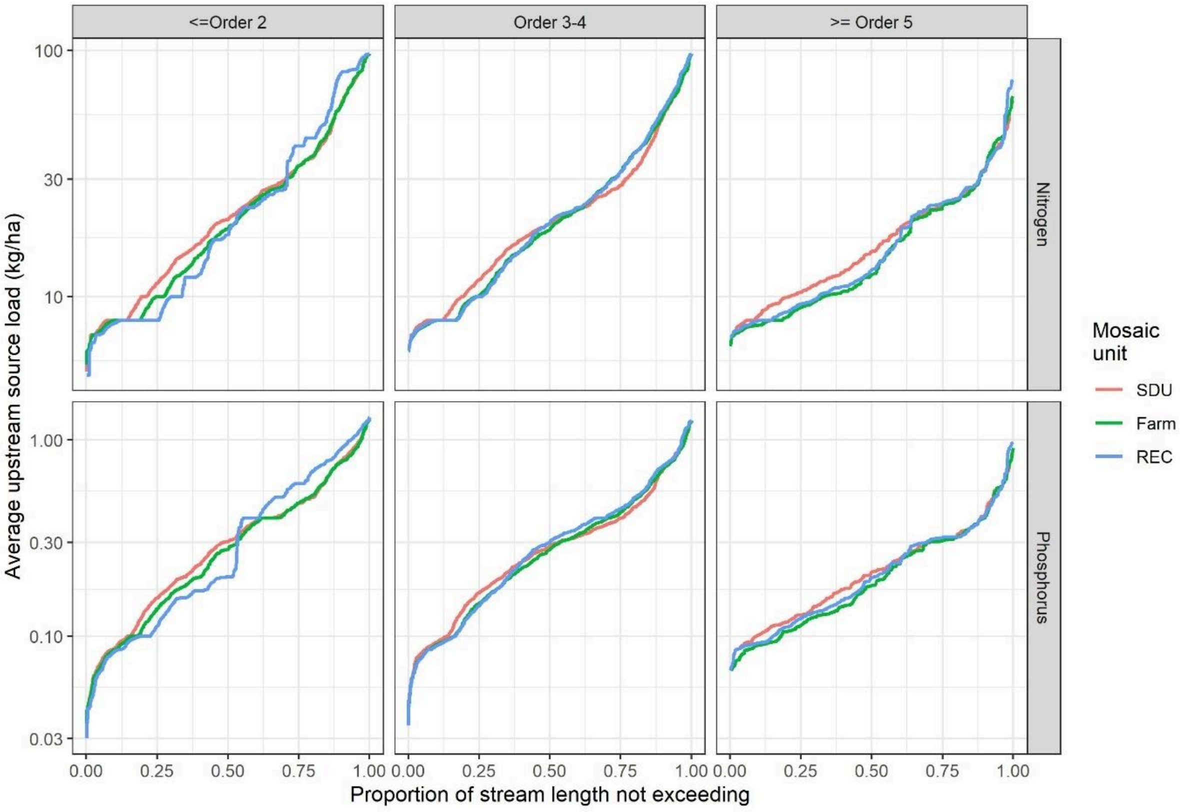


Figure 14: Proportion of stream length at different REC Stream order which exceed specified N loads, by mosaic unit, Canterbury Plains scenario

8 Discussion

The project has had two outcomes – the development of modelling capability, and the assessment of the importance of mosaics in achieving desired community outcomes.

8.1 Model development

In respect of the model develop the project has a legacy of development across two models – LUMASS and NWEM.

8.1.1 LUMASS

The Landcare model built in the LUMASS framework using genetic algorithms to choose optimal outcomes under a given set of constraints. LUMASS is an interoperable spatial modelling and optimisation framework. It has been used for optimisation-based land-use scenario generation, environmental modelling (e.g. .SedNetNZ), and integrated modelling and optimisation applications, e.g. sediment mitigation optimisation. LUMASS' interoperability interfaces enable its use as part of integrated component models as well as the development and execution of integrated component models within its modelling framework. It is able to incorporate a range of inputs from different data sources as spatial layers, and implement this data within a range of different modelling strategies. This enables flexible integration of ecosystem services models and indicators including biodiversity and important native habitats. LUMASS has been used as platform for the development of end-user tools for regional councils and industry and is actively used and further developed as modelling and optimisation platform within MBIE Endeavour and SSIF-funded research projects. The project has extended the capabilities of LUMASS to incorporate P, sediment and E.coli and their mitigation, and has implemented new approaches to optimisation including non-linear optimisation and genetic algorithms.

Further work is required to develop the GA optimisation approach as the solutions reached are significantly less optimal that was achievable by a linear optimisation routine. Because of the nature of the GA approach and the non-linearity of problems it is designed to address, we expect some deviance from a maximum theoretically achievable optimum. However development work is required to understand how the characteristics of the GA approach (populations, iterations, placement algorithms) interact to achieve the solution.

8.1.2 National Water Economic Model

The NWEM is a hydrologically accurate model that represents all the catchments and water quantity and quality (N) FMUs in the country. It includes currently irrigated areas and schemes, estimates of reliability, farms, soils, climate zones. It includes environmental impacts of water use, estimates of GHG and N emissions, and estimates the economic impact of different scenarios of land use, either using a rules-based approach or optimisation. The NWEM model was extended into a Regional Agriculture Economic Model (RAEM) of the Canterbury region using the modelling capability developed in the Mosaics project. Partly as a result of this mosaics project the RAEM additionally incorporates phosphorous, sediment and E. coli emissions from agriculture and mitigation of these contaminants using the RECo2 based overland flow framework developed in the mosaics model. It does not incorporate an optimisation option and uses algorithms to define the likely pathway that a scenario will follow.

These two models are useful to assess the implications of a range of primary sector issues and potential policy responses. For example, the RAEM is already being used by ECan to assess the potential implementation of three scenarios for the development of their new Regional Policy Statement.

8.2 Mosaics

The initial question faced by the research team was definitional – what is a mosaic and why is it considered important? The project brief was broad, so we used a stakeholder group to assist us with understanding what was important in mosaics for people. The central theme around mosaics was the acknowledgement that diversity is beneficial and the negative implications of monocultures. However among stakeholders, there was a wide spectrum of perspectives regarding the crucial aspects of mosaics. These include the concepts of diversity, resilience, Te Ao Māori, varying land uses that are tailored to different outcomes, and the importance of aligning these opportunities with the aspirations for whenua. While stakeholders had a more defined understanding of land use patterns that make up a mosaic, some stakeholders emphasized the importance of ensuring adequate size and scope for specialization and management focus. This specialisation and management focus consideration was considered important, even though it may conflict with the desire for diversity within mosaics. We find it difficult therefore to draw a definitive conclusion about what a mosaic is and why it is considered beneficial.

The project has assessed the impact of varying the size of the monocultures within which land uses are implemented as a means of testing different mosaic patterns. The increasing size of the mosaic units is associated with a decrease in mosaic-ness as defined by the indicators we have used to assess mosaics. While the indicators we used to assess mosaicness generally reflected a gradient of decreasing mosaicness from mosaic units defined by SDU to Farm and REC2 subcatchments, there were variations in some model runs and at different spatial scales, and it is likely that this is due to the size and shape of the parcels for each of these placement options. For example, in Canterbury the results suggest that there were some very large and small farms while the REC2 sub-catchments were perhaps more evenly distributed. We are confident however that the approach we have adopted is able to replicate different conditions of mosaic-ness, as best defined to match the visual expectations of our stakeholders.

The outcome for these different levels of mosaics defined with the models was only moderately variable. In respect of profit, which was the target variable we attempted to maximise, land-use placement to SDU mosaic units generally produced greater profit than to the Farm and REC2 mosaic units, but only by a small percentage. We would expect this to occur because the model algorithms worked by placing land uses preferentially on their best combination of soils, climate, etc. Placing them at the SDU scale ensures that all of the land use is able to occur in its best location, whereas the Farms and REC2 catchments had combinations of soils, slope and climate, not all of which was suitable for all land uses. In the scenarios where we placed single land uses in a whole Farm and REC2 catchment the land use would in some instances necessarily occur on sub-optimal soil and climate combinations, and in some cases was not even feasible on the whole of the Farm or REC2 catchment. We would expect this to result in lower profit, which it did. However, the largest land uses were sheep and beef, dairy and forestry, which within a the case study areas are relatively insensitive to the soil and climate combinations. Analysis of the Ruamahunga data for sheep and beef showed low mosaic-ness in the spatial distribution of sheep and beef profits, which is reflected in the low variation of profit across different placement scenarios. Because dairy and sheep and beef make up the bulk of the total profit, the overall result was not highly sensitive to their placement.

Horticulture was highly sensitive to less suitable soils, but because the total area and total profit from the horticultural land uses were smaller, the overall impact was not as large. The LUMASS based model was very sensitive to the placement of horticulture, because the areas of some land uses were small in relation to the larger Farm and REC2 mosaic units. The placement of a high returning horticultural land use on a large farm or REC2 mosaic unit could result in substantially larger areas in that use than under the SDU mosaic unit based placement. A similar result occurred in the Ruamahunga when optimising for lowest N loss, where the results were very sensitive to the placement of low emitting native land on Farms and REC2 subcatchments which could result in varying total areas, with larger areas of native land resulting in lower N emissions and lower profit. We think therefore that the areas of land use which are influential in the objective function (profit or N loss) are likely to have a much bigger effect on the overall profit from an area of agricultural land than is the pattern of its placement.

The process of modelling is inherently reductionist, and we need to be able to represent mosaics within a model structure, which means that the biophysical reality has to be reduced to an approach that is mathematically tractable. The results of modelling such as this reflect the underlying data structure of the model, and care should be taken in their interpretation because necessary simplifications undertaken in the course of developing the model may have an influence on the outcome that is an artefact of the modelling rather than a reflection of the actual outcome in the real world. There is also the risk that a range of aspects that are more important in real life are not represented in the model. We think however that there are a number of concepts that have been surfaced in the course of this project that deserve further attention.

- ***Resilience.*** The concept of resilience is not captured in our modelling. Resilience is a concept that was referred to by a number of the stakeholders in their thinking about mosaics, but because of the static nature of the models we have developed it is not possible to capture how changes over time will affect the performance of different arrangements of land use. We suspect that given the relative insensitivity of the largest land uses to the climate and soil combinations at a small scale, even with a dynamic model we would not discern significant differences at the landscape scale without changing the mix of land uses between scenarios. . However, for individual properties having a mix of land uses may make the performance of the business more resilient across a number of dimensions, including resilience to drought, pests and diseases, and market fluctuations. We think it likely that a dynamic model based on our framework could discern differences in resilience to market fluctuations, but the impacts of drought would require a considerably more detailed modelling of the soil/climate/land use interactions.
- ***Area of land uses is more important than their arrangement.*** The way in which the genetic algorithm has proven sensitive to the scale of the placement of land uses gives a useful insight into the key factors affecting the profitability at the landscape scale. It has demonstrated that the overriding factor in profitability at the landscape scale is the total area in high influence land uses, rather than the way in which they are arranged. For larger landscape scale assessments it is rare that there is insufficient suitable land for at least some high value land uses, so total area of any given high value land use is likely to be constrained by capital availability, labour requirements, infrastructure, skills and markets.

- ***Scale and management focus.*** The model suggests that, all other things being equal, there is a small economic and environmental benefit from arranging land uses in smaller more distributed blocks. However, for individual land managers, this may be far from optimal. Many of the gains in productivity come from increasing scale and management skills. With increasing scale of land use comes more efficient use of labour, equipment, transport and management skills. Furthermore, spreading management focus across multiple land uses will inevitably result in poorer performance at each land use than if the same manager focused on a single land use. Gaining a skill set in both apple growing and dairy farming is not a trivial exercise, and while specialisation can be achieved by hiring management or consultants, this in itself requires a degree of scale for a land use. We urge policymakers and land governance entities to consider therefore that multiple small land uses in an enterprise may not always be the best option, particularly for smaller blocks of land.

- ***Monocultures may be the best use of land.*** In our modelling of mosaics in Canterbury, we found that high value land uses tended to group together regardless of the scale at which we placed land, because these high value land uses were able to perform optimally in specific combinations of soil and climate, and because those combinations were not distributed across the landscape but rather tended to clump together in specific locations. We also note that the prevalence of a single land use in a region tends to lead to support services and infrastructure that is more tailored to that land use, which in turn enhances the efficiency of the industry overall. Examples would include kiwifruit in Bay of Plenty, apples in Hawke's Bay, and viticulture in Marlborough. The combination of soils, climate, infrastructure and support services has enabled world class industries to emerge in each of those locations.

- ***Te Ao Māori.*** We recognise that Te Ao Māori incorporates a range of concepts and values around the use of land that we cannot capture in this modelling. We think that models are able to inform aspects of this value system, but because of the holistic nature of Te Ao Māori we do not think that a reductionist modelling approach is necessarily a useful way of approaching its incorporation into land use decisions.

We are confident, to the extent possible with the data available, in our conclusion that while more mosaicy landscapes are likely to produce somewhat better outcomes in profitability terms, the differences are likely to be small. We think that the areas of high value or low contaminant emitting land uses are more important than the scale of their placement in the landscape. There is no guarantee that placing land uses in smaller more scattered blocks will produce better environmental outcomes, although it will likely tend to ensure a more even spread of impacts with fewer areas of very high impact on waterways. We consider that stakeholders should focus more directly on the values and concepts of importance to them, rather than assume that they are embodied in some undefined concept of mosaics and can be solved by different placement of land uses. For example, if resilience is considered important, stakeholders should focus on resilience rather than assuming that mosaics will provide resilience, which is an untested and likely unprovable proposition.

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Appendix A Estimates of the cost of nitrogen loss mitigation

The costs of mitigating N loss were estimated using case study data for dairy and sheep and beef land uses.

Ten datasets of mitigation costs have been accessed to assess the cost of mitigation. These cover data from limit setting work undertaken in Waikato, Wellington, Taranaki, Canterbury and Southland. While other datasets are available these tend to be mitigation activity focused rather than farm focused. The data used here represent estimates of mitigation costs undertaken on actual case study farms or on representative farms collated from actual farm data. As such they take into account the actual farm systems and any mitigation activities that have already been undertaken.

The data have been collated into tables which relate the percent change in operating profit for the associated percent reduction in N. This standardises the costs across a range of different leaching rates, where a $/kgN cost of reduction is highly dependent on the initial leaching rates associated with the farm system.

Some difficulties exist with the Canterbury dataset for which the starting point for losses is a Good Management Practice (GMP). GMP has a standard definition within the Canterbury Land and Water Regional Plan (LWRP). In a number of cases individuals will be already leaching at or better than the leaching associated with GMP, while in others there is considerable mitigation required to achieve GMP. While GMP was intended to be set at a level where no costs are associated with its achievement – i.e., all practices can be adopted without a negative change in operating profit, in practice this may not be the case, particularly where upgrades to irrigation infrastructure are required to achieve standards of irrigation efficiency. However, it should be noted that the greatest change in GMP losses in Canterbury are generally associated with changes to irrigation practice, and while these reduce the load of N lost, they may not reduce the concentration of N in receiving SW bodies. The concentration may not be reduced because the reduced N load with more efficient irrigation practices is associated with a reduction in recharge from the irrigated area. This also is potentially problematic for studies of N losses from the Ruamahunga area where irrigation changes have been adopted as a method of reducing N losses.

For the purposes of this study, we have ignored the impact of GMP on any losses and adopted the changes directly. This may result in an overestimate of the cost of mitigation in Canterbury and may result in an underestimation of the costs of mitigation to achieve specified concentrations in Ruamahunga, but given the overall level of errors in estimation of the changes required to achieve targets, and of the costs of achieving those changes, these errors are not likely to be significant.

The dairy mitigation studies used a least cost approach to defining the mitigation costs for each level of mitigation (10%, 20%, 30% reduction in N loss) and these have been adopted directly. However, the drystock modelling tended to adopt a less directed approach and reported the impacts of various common mitigation approaches on different case study farms. These could have minimal or no impact on the N losses for considerable costs. We have therefore removed any data points where no change in N was achieved, on the basis that these mitigation practices would not be implemented, and we similarly limited the cost of any mitigation practice to the cost of removing a percentage of area from production that achieved the desired reductions, on the basis that the removal of land from production would be a more rational approach to mitigating N loss than adopting a more expensive practice. There was a set of data points from the case studies where increased profit was associated with reducing N losses. There were also instances in the Olubode-Awasola et al. (2014) paper in a drystock system where sheep were substituted for beef animals, and the analysis showed an improvement in profitability. The Olubode-Awasola et al. (2014) paper noted that questions were raised by farmers involved in their case studies on the feasibility of the proposed system and on that basis that specific set of mitigations from the Olubode-Awasola et al. (2014) paper were removed. However, we do note that this is a potentially feasible approach to reducing N losses in drystock systems that may be implementable on a number of properties, and as such our results may overestimate the costs of mitigation on these land uses.

No further feasible mitigations were included for horticulture and arable farming because no reliable data was available on cost-effective mitigations for these land uses[13]. We understand that there are potentially some mitigations available for horticulture based on recent work undertaken in the Manawatū-Whanganui region, but this has not yet been accessed. We also understand that vegetable and arable modelling in the version of Overseer used was not considered to be very reliable (Ford, S. Agribusiness Group, pers.comm. 2019), so some caution is warranted for these land uses. We use the national level estimates of mitigation costs used in the from Harris et al., (2017) for these land uses.

The mitigation approach adopted here uses case studies of mitigation modelled in a range of contexts and aggregates these. It is also not directly comparable with the approach adopted in the recent impact work on the NPS-FM (2020) (Denne, 2020) which uses packages of mitigation practices that are common across all farms and regions, and assumes a constant cost per package rather than a proportional cost as used in this analysis.

The slopes of the N loss mitigation relationship with profit were modelled in Excel using simple linear regression using only region, profit and N reduction. Other explanatory variables including soil drainage, soil PAW and stocking rate were tested, but did not improve the model's robustness. Non-linear regression equations failed to produce a better fit, other than in Canterbury where a 2nd order polynomial regression had a slightly higher r^2 value (0.55 vs 0.45). For simplicity of modelling the simple linear form was adopted for all regions and land uses. The mitigation slope, goodness of fit (r^2), maximum mitigation from the dataset, and number of data points are shown in Table 8.

Table 8: Mitigation estimates used for abatement modelling

Land use	**Region**	**Slope of mitigation curve**	**r^2**	**Maximum mitigation N**	**Number of data points**	**References**
Dairy	Waikato	0.52	0.67	0.40	97	Olubode-Awasola et al. 2014, DairyNZ Economic Group 2014
	Taranaki	0.64	0.69	0.63	14	DairyNZ 2015, Ogle, G., and Stantiall, J. 2015.
	Wellington	0.55	0.44	0.45	12	Parminter and Grinter 2016
	Canterbury	0.72	0.44	0.27	44	Ogle, G. 2014, DairyNZ Economic Group. 2017a, DairyNZ Economic Group. 2017b
	Southland	0.70	0.47	0.46	145	Journeaux, P. and Wilson, K. 2014, Moran, Pearson, Couldrey, & Eyre, 2017
Drystock	National	0.87	0.51	0.46	128	As above excluding DairyNZ.

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[13] The only modelling data for arable to date has shown no gains in N loss for different practices.

We tested the linearity of the mitigation curves by calculating for the national dataset the difference in slope between each sequential increasing pair of data in a case study – so from 0% reduction to the first tested level of reduction, then from the first level of reduction to the next level of reduction. These slopes were then regressed against the first of the pair. While the regression analysis has suggested a very small increase in slope, the R^2 value is so low that it cannot be considered reliable. We therefore conclude that for dairy within the bounds of the data the mitigation slope does appear to be linear. We were unable to assess the linearity of slope for drystock because of lack of differentiation in the data, but alternate functional forms did not produce a higher R^2 than the linear form. The slope of the abatement curve for dairy also did not appear to be related to the production levels at which the farm operated.

Appendix B Greenhouse Gas estimation Emissions from farming

B1 GHG emissions from farming

For GHG emissions from farming a simplified approach has been adopted. This involves:

- Estimation of an average per stock unit carbon emission from sheep and beef, and a per cow emission from dairy land uses. These are approximated by using the total agricultural emissions from livestock in the Greenhouse Gas Emissions Inventory (Ministry for the Environment, 2019), and dividing this by the estimated total stock numbers in our model (based on survey data average per ha stock numbers by climate region). For estimating the total agricultural emissions by land use class the non enteric emissions, including manure, soil, and fertiliser emissions are pro rated according to the enteric emissions. Arable emissions are based on burning losses, with the pro rated emissions from manure, soil and fertiliser.

Table 9: Total emissions used by land use

Land use	Emissions from sector (tCO2 eq)
Dairy	23894
Sheep, beef, other	23109
Arable	31

- Estimation of initial stock units is derived from the initial farm models, reconciled with national datasets of dairy stock. We do not attempt to reconcile
- Estimation of stock unit reductions from the mitigation database. This is a partial set of data because not all mitigation studies reported the reductions in stock units. Furthermore not all mitigations involved a reduction in stock numbers. The reduction curve for drystock (Figure 15) has a slope of 0.66*%N reduction, but with a very low r^2 value. The slope for dairy (Figure 16) is lower at 0.23*%N reduction, but has a significantly higher r^2 value. Note that the data points are very disparate, with some mitigations requiring no stocking rate reductions, while other do require significant reductions. The slope should be seen as representing an average stocking rate reduction.
- The total GHG reductions are calculated based on the reductions in stock and the average emissions per stock unit or per cow, taking into account whether the final mitigation includes land use change (which is assumed to remove all stock from the land).

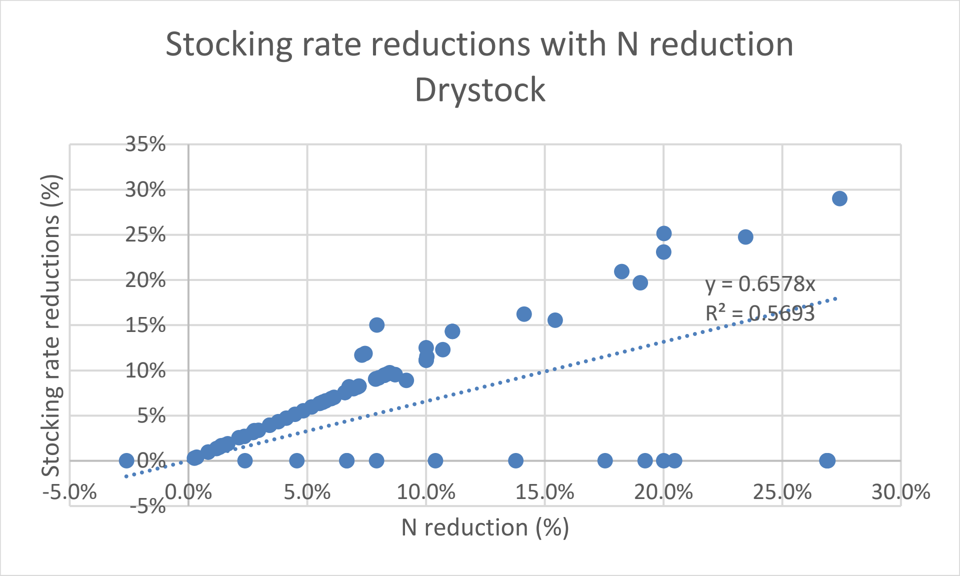

Figure 15: Stocking rate reductions with N mitigation - drystock

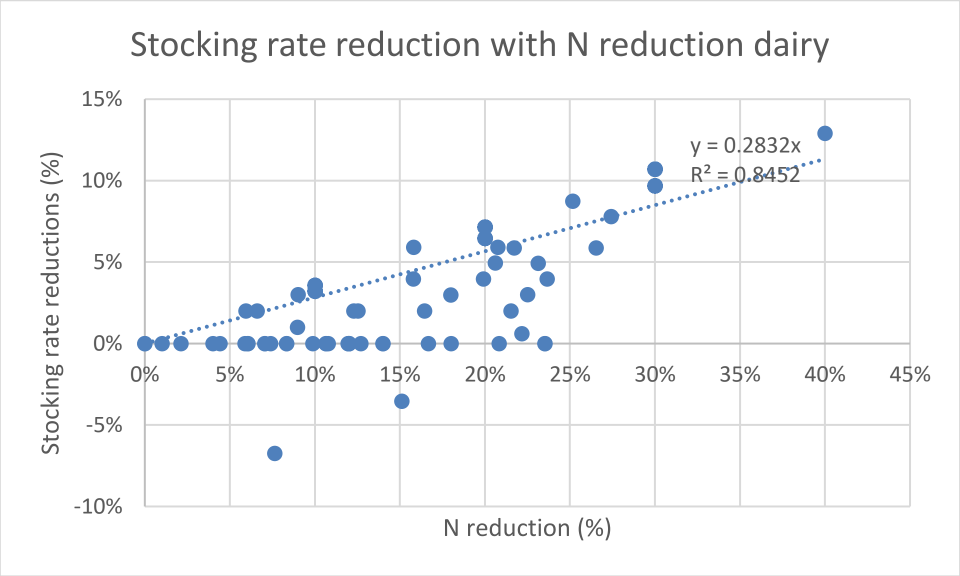

Figure 16: Stocking rate reductions with N mitigation - dairy

B2 GHG absorption

Forestry is assumed to be eligible for the ETS under the post 1990 regime. The emissions absorbed by forestry are based on the ETS lookup tables for forestry, assigned by region. The averaging approach to ETS participation is assumed, with a rotation of ~28 years for exotic and an average carbon accumulation at year 16 for exotic and 50 for native forests (Ministry for the Environment, 2018). The stream of cashflows from GHG absorption are transformed into an NPV at the 5% discount rate, and annuitised over 50 years.

The model does not take into account the ETS costs associated with deforestation of permanent forest or pre 1990 forest.

Appendix C Estimation and Parameterisation of Land Use, Operating Profit and Opportunity cost of Capital

Three main factors are used to estimate the Profit in this report. These are land use, operating profit and opportunity cost of capital. Operating profit is defined as revenue minus working expenses and including depreciation, and is the same as EBITA (earning before interest, tax and amortisation).

The three subsections in this Appendix describe the source of the operating profit and the basis for estimating the opportunity cost of capital and their calibration to reflect available datasets. Because no comparable data is available for the model outputs, which have a charge for capital deducted, validation focused on ensuring that the underlying land use and profit information was calibrated to available data.

C1 Estimation and Paramaterisation of land use information

We combined the LCDB version 5.0 (released 2020) updated land cover data following the methodology described in Grinter & White (2016).

In order to validate this data we have compared it with other land use data available from other sources. The data we have used differs from other available 2019 land use data as described below.

- The NZ Dairy Statistics are a census of dairy farms based on information from the Herd Improvement Database, New Zealand dairy companies, Animal Evaluation database, TB Free New Zealand, Real Estate Institute of New Zealand and Statistics New Zealand. The dairy area in our model of 2.11m ha is 21% higher than the NZ Dairy Statistics (2019) effective area. We consider this likely to be because of the inclusion of dairy support and other non-dairy associated areas in our data, whereas the NZ Dairy Statistics data excludes dairy support blocks. Our data source for the profit information from DairyNZ uses the data from all dairy farm entities associated with a farm, and we consider therefore that the profit estimate we use more closely matches the land area including dairy support associated with dairy farms. Our larger area for dairy is therefore adequate for the purposes of this project.
- Horticulture area for our project is estimated at 114,000 ha, compared with the planted area estimated in Fresh Fact (Aitken and Warrington, 2019) (excluding vegetable seed production[14]) of 124,867 ha. We consider this difference to be accounted for by a combination of the pixel size used (minimum 4ha), the exclusion of small lifestyle blocks unless they were specifically noted as horticulture, which would have omitted a number of properties that were mixed use, and errors in estimation from the Landcover database. We note that there are significant discrepancies between datasets. For example Fresh Facts 2019 records 12,747 ha planted in kiwifruit which is the same as the Zespri estimate of producing kiwifruit (Zespri, 2019), while the StatsNZ Agricultural Production Statistics (2019) record 15,520ha planted. Fresh Facts includes data from a range of sources including Stats NZ, while the Stats NZ data is sourced from surveys of growers. Differences between StatsNZ data and Fresh Facts data for 2019 for the three largest crops in our project (kiwifruit, apples, and viticulture) vary between +14% and -8%, which is likely the difference between producing suppliers to Zespri and a combination of non-producing orchards and orchards supplying other marketing

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[14] We consider vegetable seed production as likely to occur within arable farms than in our horticulture land use type.

companies. We consider the difference between our horticultural land use estimate and comparative data is within the likely error margins around the comparator data. Unfortunately we do not think there is any more accurate data with which to compare.

- We have no comparable recent data with which to compare the sheep and beef areas. However we note that the exclusion of properties deemed to be lifestyle blocks will produce a lower area of sheep and beef relative to the actual area of grassland excluding dairy land.
- We do not have specific data with which to compare the area of arable farms, but we note that the combined total of the arable and horticulture land areas in our model is 479,700 ha which compared closely with the StatsNZ estimate for an equivalent grouping of 473,857 ha (StatsNZ, 2021). As noted above separating horticulture and arable land is not a straightforward process.
- The forest area estimated in our model of 1.94m ha is 14% greater than the National Exotic Forest Description (MPI, 2019) estimate for production forestry of 1.697m ha in 2019 and 10% greater than the Climate Change Commission estimate of 1.754m ha for 2019 (He Pou a Rangi Climate Change Commission, 2021). The forestry land use in the model is adjusted from the LCDB exotic forest area, which includes production forest but also other types of plantings. While we have excluded conservation and reserve land, we have no basis for defining production forestry only, so our forest land use will overestimate the actual area of production forest. We consider that the Climate Change Commission data is likely to be more accurate as they have attempted to include estimates of changes in stocks with planting and harvesting. Given errors around the stocked and unstocked areas (recently harvested), we consider this error acceptable.

The land use layer is combined with bio-geographic information which determines the magnitude of the operating profit and capital costs for each land use.

- Climate zone to give an indication of the climatic conditions which determine the system type for sheep and beef, horticultural and arable land use.
- Region, which determines the system type for dairy and horticulture land use.
- Soil information, to give the Plant Available Water (PAW) on which the land use is undertaken.
- Irrigation scheme, which determine the magnitude of capital costs for undertaking irrigation.
- FMU, which gives the reliability of surface water supplied for irrigation.

C2 Estimation and paramaterisation of profit information

Aqualinc (Bright *et al.,* 2018) provided point estimates of the water use, N loss and cash operating surplus (revenue minus working expenses) for a range of application rates and reliabilities for each land use, soil PAW and climate zone combination (see Appendix A of their report for the point estimates).

Calibration of the original Aqualinc data was undertaken following the peer review using comparisons with available estimates of per ha performance for the land uses from other data sources. The data were compared with longer term averages where available in order to remove the impact of short term climatic and market events on reported profitability. The calibration was undertaken on a per ha basis at the level of land use by region and climate zone.

- For sheep and beef 5 year averages were generated for Beef and Lamb NZ (B&LNZ) survey data and more specific recent data for the Waimakariri zone which had been adjusted from area specific Beef and Lamb NZ survey data. Aqualinc (Bright *et al.*, 2018) provided data for each climate zone, so it was necessary to calibrate the B&LNZ Farm Classes to the Aqualinc data for each climate zone. The B&LNZ Farm Class data was related to climate zones and therefore the Aqualinc data as shown in Table 10. We first calculated the average of the original Aqualinc data from all the climate zones that were related to each B&LNZ Farm Class. Then for each individual climate zone we took the ratio of the original Aqualinc data to the average Aqualinc data related to the appropriate B&LNZ Farm Class. The B&LNZ Farm Class was then adjusted for each climate zone by multiplying it by this calculated ratio. For example for NI East Coast climate zone the original sheep and beef data for this zone from Aqualinc was divided by the average of all NI intensive sheep and beef data from Aqualinc. This was then multiplied the B&LNZ NI Finishing Class 5 data. This approach allowed the relativities between climate zones, where present, in the Aqualinc data to be maintained in the data used for the modelling reported here.
- All sheep and beef on non-irrigable land was adopted directly from the B&LNZ models for NI hill country, NI hard hill, SI hill country, and SI High Country model as shown in the third column of Table 10.

Table 10: Beef and Lamb NZ models used to adjust profitability for sheep and beef.:

Climate zone	Beef and Lamb NZ Farm Class and adjustments for irrigable land	Beef and Lamb NZ Farm Class adopted for non-irrigable land
NI-BoP	NI Intensive finishing, proportional to the original data/average for NI. Irrigated pro-rated up	NI hill
NI-central	NI Intensive finishing, proportional to the original data/average for NI. Irrigated pro-rated up	NI hill
NI-EC	NI Intensive finishing, proportional to the original data/average for NI. Irrigated pro-rated up	NI hill
NI-lower-hillcountry	NI Intensive finishing, proportional to the original data/average for NI. Irrigated pro-rated up	NI hill
NI-Mountains	NI Intensive finishing, proportional to the original data/average for NI. Irrigated pro-rated up	NI hard hill
NI-NW	NI Intensive finishing, proportional to the original data/average for NI. Irrigated pro-rated up	NI hill
NI-SW-Coast	NI Intensive finishing, proportional to the original data/average for NI. Irrigated pro-rated up	NI hard hill
SI-EastCoast-650	Prorated off SI-East Coast 750 based on Aqualinc original 650/ original 750 multiplied by the revised SI-East Coast 750.	SI hill
SI-EastCoast-750	Analysis undertaken for the Waimakariri zone in Canterbury Land and Water Regional Plan - Proposed Plan Change 7.	SI hill
SI-EastCoast-850	Prorated off SI-East Coast 750 based on Aqualinc original 850/original 750 multiplied by revised SI-East Coast 750.	SI hill
SI-EC-Marlborough	SI Finishing breeding (Class 6) proportional to original/average of northern SI. Same approach used for dryland and irrigated.	SI hill
SI-Hillcountry	SI Finishing breeding (Class 6) proportional to original/average of northern SI. Same approach used for dryland and irrigated.	SI hill
SI-InlandBasins	SI Finishing breeding (Class 6) proportional to original/average of northern SI. Same approach used for dryland and irrigated.	SI hill
SI-InlandOtagoSouthland	SI Intensive finishing (Class 7) proportional to original/average of southern SI. Same approach used for dryland and irrigated.	SI hill
SI-Mountains	SI Finishing breeding (Class 6) proportional to original/average of northern SI. Same approach used for dryland and irrigated.	SI high
SI-SouthCoast	SI Intensive finishing (Class 7) proportional to original/average of southern SI. Same approach used for dryland and irrigated.	SI hill
SI-Tasman	SI Finishing breeding (Class 6) proportional to original/average of northern SI. Same approach used for dryland and irrigated.	SI hill
SI-WestCoast	SI Finishing breeding (Class 6) proportional to original/average of northern SI. Same approach used for dryland and irrigated.	SI hill

- Arable figures were adjusted to Beef and Lamb NZ Class 8 Mixed Finishing in proportion to the original profit provided for that location/average of the arable profits. Beef and Lamb NZ Class 8 Mixed Finishing represents a typical arable farm that is a mixture of cropping and sheep and beef and earns approximately 70% of its revenue from cropping. NI East Coast, Central and SW coast for light soils dryland was set to $0 to ensure it wasn't implemented in those areas and the non-irrigable arable adjusted to the non-irrigable sheep and beef operating profit because arable was not considered a viable land use in these contexts.

- Dairy profit figures were adopted from the 5 year average of the most relevant DairyNZ model.

- Horticulture operating profit and capital were adopted from the data produced by Whitiwhiti Ora project **Datasets - Whitiwhiti Ora: Land Use Opportunities (landcareresearch.co.nz)**.

- No non-irrigated horticulture was allowed in the South Island outside coastal Otago, Southland and the West Coast. We consider that non-irrigated horticulture was largely not viable in low rainfall parts of the South Island. This does omit some areas where dryland horticulture is viable, but because we cannot differentiate smaller subregional areas in our data this is an unavoidable underestimate for those areas.

- The operating profit relativities between dryland and irrigated (for all land uses) were adjusted so that the low reliability and low system capacity irrigated land uses were always higher than dryland (on the basis that any irrigation will produce additional production). However irrigated profit after the opportunity cost of capital could still be lower than dryland.

C2.1.1 Forestry profitability

- Per m3 revenue was taken from the MPI Wood Product markets data for log returns by grade, using the weighted average data with the most recent period being June 2022 quarter[15] (Table 11).

- A site index, 300 index, recovered volume and log value was estimated using the Forecaster Calculator (**Simulate - Forecaster Calculator (integral.co.nz)**) for a 24 polygons spread randomly across the country. An equation of recovered volume and returns. The r2 for these equations was 0.90 for volume and 0.82 for value, indicating that these indices can reasonably be used to estimate the returns from forestry.

- Data for site index and 300 index was sourced from Scion (www.koordinates.com).

- The equations to estimate the Recovered Volume and Log Sale Revenue are shown in the two bullet points below. The variables used in the calculations below are shown in brackets.
  - Recovered Volume m3 = 164 - 12.7*SiteIndex + 37.36* 300Index (ForestVolume)

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[15] https://www.mpi.govt.nz/forestry/new-zealand-forests-forest-industry/forestry/wood-product-markets/

    - Forestry Revenue $ = $18631 - 1912.79*SiteIndex + 4843.68*300Index (ForestValue)

- The carbon absorption associated with forest growth on each of these polygons was estimated using the MPI lookup tables for forestry (MPI, 2018)[16].
- A distance from port was assigned to each of the modelling units using a direct line measurement and a road travel factor of 1.41, which is the average of the sites for which the Forecaster calculator estimates were made. This should be considered an indicative road distance only.
- Data from BakerA[17] was used to estimate local expenditure and employment for radiata forestry. Harvest costs (Table 12) were obtained from and NZ Farm Forestry Association[18] survey of grower returns from harvest. These data were updated using PPI to September 2022 and are shown in Table 12 below. Te Uru Rakau estimates the planting costs for natives at $22,314 per ha[19] under the average scenario.

The base cost of $72.4/NZU is the current (3 February 2023) spot market price CommTrade Carbon).

Table 11: Log prices (August 2022 weighted average, MPI)

Log grade	Current log prices ($/m3)(Source: MPI)
S1	$140
S2	$131
S3	$117
L1	$120
L2	$120
L3	$117
Pulp	$59

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[16] MPI, 2015. Look-Up Tables For Post-1989 Forest Land In The Emissions Trading Scheme. https://www.mpi.govt.nz/dmsdocument/4762-A-guide-to-Look-up-Tables-for-Forestry-in-the-Emissions-Trading-Scheme

[17] Harrison and Bruce, 2019. Socio-economic impacts of large-scale afforestation on rural communities in the Wairoa District. BakerAg contract report prepared for Beef and Lamb NZ, August 2019.

[18] West, G. 2019. Small scale Grower Harvest costs and returns. https://www.nzffa.org.nz/farm-forestry-model/the-essentials/roads-earthworks-and-harvesting/reports/report-small-scale-grower-harvest-costs-and-returns/.

[19] Forbes Ecology, 2022. Review of Actual Reforestation Costs, 2021. Contract report prepared for Te Uru Rakau – New Zealand Forest Service. ISBN No: 978-1-99-102657-6 (online)

Table 12: Rotation forest harvest assumptions (West, 2019 updated using PPI 2019 - 2022)

Item	Assumption	Variable
Harvest cost ($/m3)	$58	HarvestCost
Roading cost ($/ha)	$2,743	RoadCost
Trucking cost ($/m3/km)	$0.23	TruckCost
Rotation length (years)	28	RotationLength
Forestry discount rate	0.05	ForestDisc

C3 Estimation of the impact of opportunity cost of capital on profitability

Because capital costs are likely to be a significant issue in the decision on whether to convert between land uses, their inclusion is essential to correctly estimate potential long run land use change.

The modelling undertaken here adopts a long run approach that assumes that both existing and new land uses must return sufficient profit to pay for the costs of capital invested. The capital invested in each land use for irrigated and dryland were estimated by Stuart Ford (pers.comm. 2017) who was a co-author of the Aqualinc 2018 report, and scaled to reflect changes made during calibration for the 2018 report. Capital for horticulture was adjusted to reflect the actual horticultural land use for a location, based on information provided by Journeaux (pers.comm. 2018).

An assumption was made in the case of irrigated land uses within irrigation schemes command areas, that the cost of accessing water was $1000/ha less than for other irrigation sources.

We considered the inclusion of an alternative option involving a transition matrix to address the different costs involved in moving from one land use to another. This was considered likely to introduce discontinuities that prevented the model from solving efficiently, which is a major consideration given the number of catchments that have to be solved for. The transition matrix approach also tends to overestimate the cost of land use change in a long run model, because it does not take into account the need for renewal of major capital items in a farm system, such as a dairy shed or vine training structures in a kiwifruit orchard. Given the trade-offs it is considered the approach adopted satisfies the requirements for the modelling project and policy questions under consideration.

The capital costs used for each land use are shown **Error! Reference source not found.**. T hese were estimated for each situation of: irrigated; irrigated land use located within an irrigation scheme (which will have lower cost of water access); and dryland. The values for within an irrigation scheme are not shown, as they were fixed at $1000 less than the irrigable-irrigated capital costs across all land uses and climates. There are three mechanisms for including the costs of capital in an analysis of this type. These are: 1) for discounted cash flow analysis the capital cost can be included at the time of expenditure, and then a residual value included at the last year of the analysis; 2) the opportunity cost of capital and depreciation can be included on an annual basis for long run analyses; and 3) an equal payment loan for life of the asset, which includes interest and capital repayment, can be included as an annual payment. Option 1 is not suitable given that the modelling reports the annual impacts of a long run stable state, and options 2 or 3 return effectively the same answer. We have utilised option 2 because our profit calculations already include depreciation and some of the items in the capital associated with the land uses such as animals do not decline. The capital associated with the land use is multiplied by a rate of return of 3.6% which is the average rate of return on dairy assets (excluding capital gains) for dairy properties from 2013/14 – 2017/18 (DairyNZ 2019). For the 2017 contract the capital costs were scaled to reflect the changes made in profitability following the peer review of the Aqualinc data, and these changes were retained for the 2020 data.

Appendix D Mosaic representations

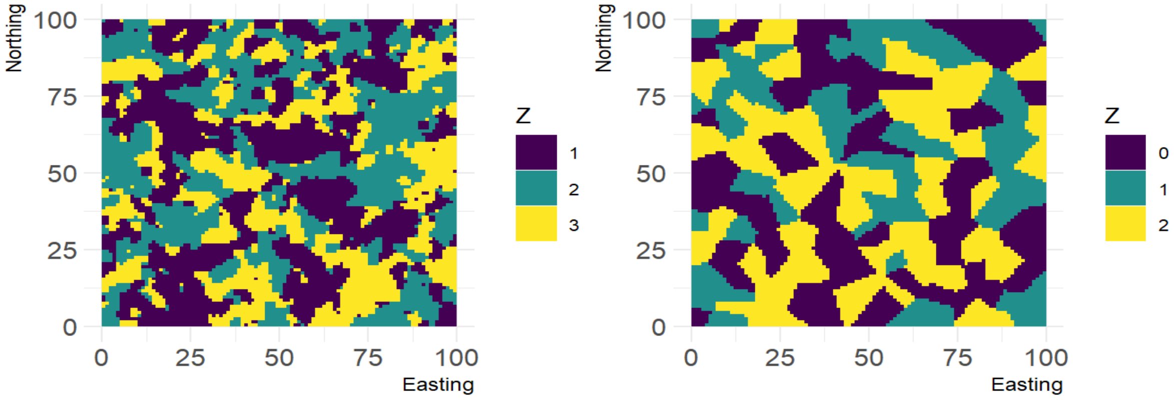

Figure 17: Importance of patch shape (Left: complex, Right: simple)

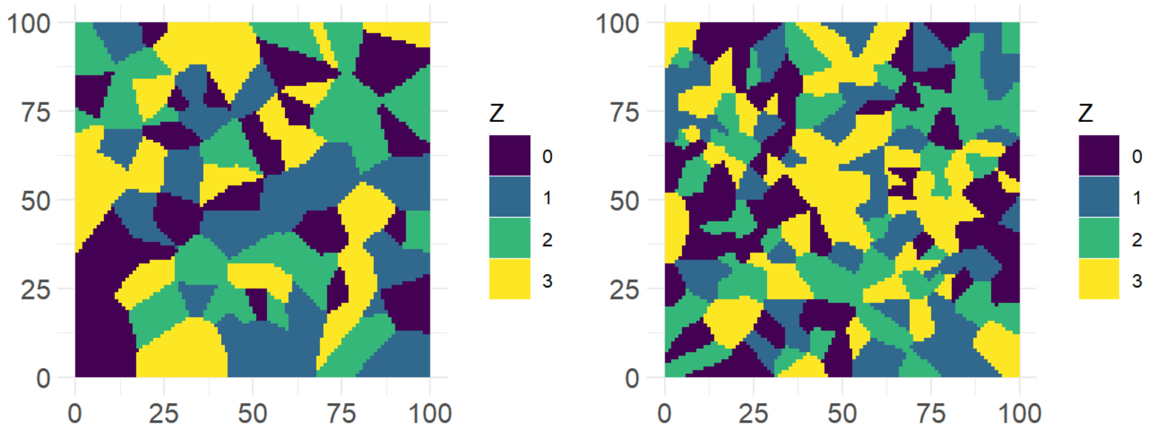

Figure 18: Importance of patch size (Left: larger patches, Right: smaller patches)

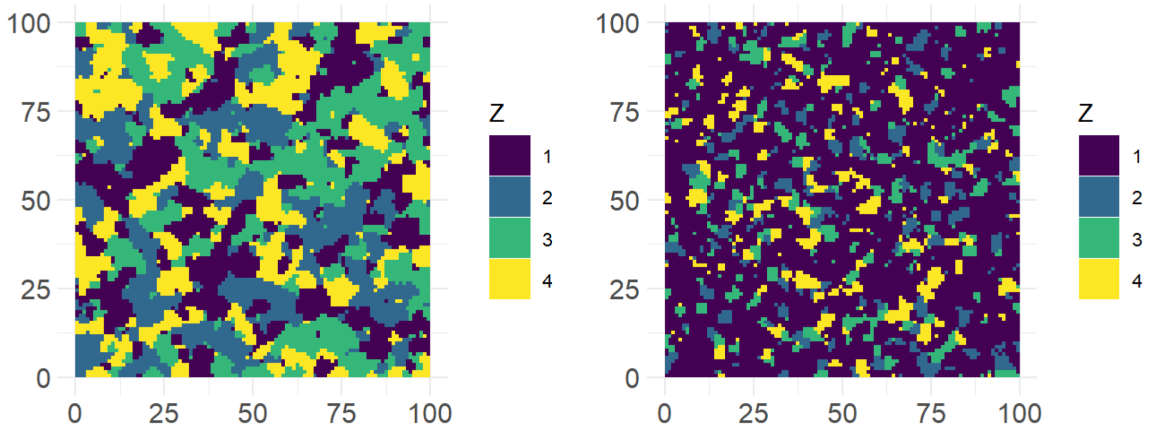

Figure 19: Land use proportion (Left: even spread, Right: one dominant land use)

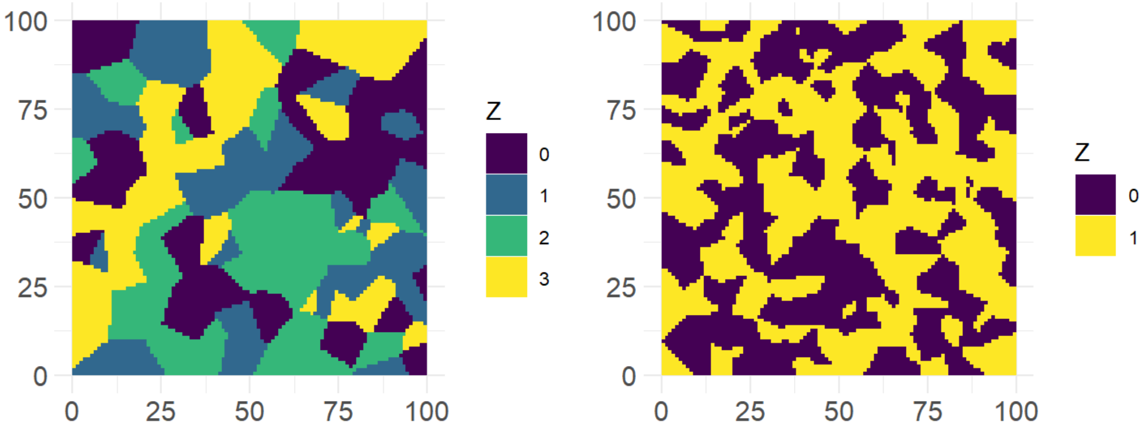

Figure 20: Number of land uses (Left: 4 land uses, Right: 2 land uses)

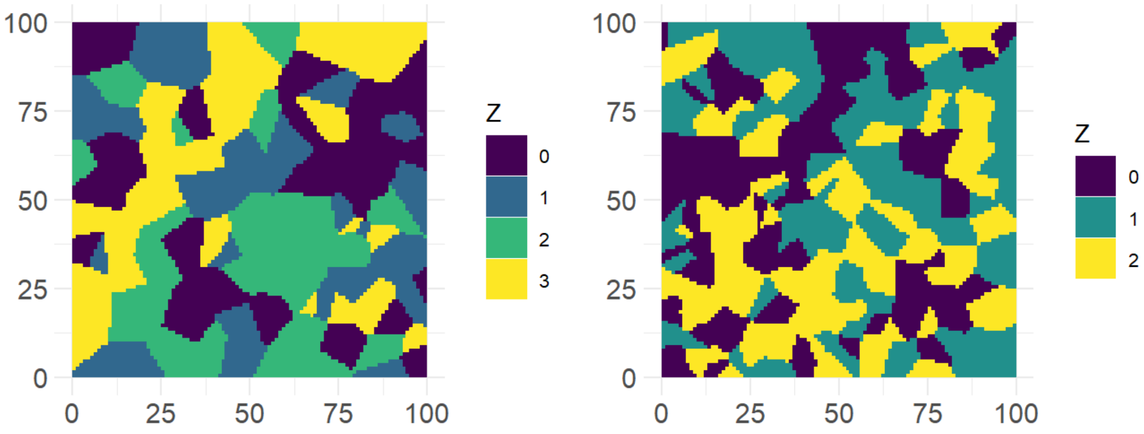

Figure 21: Change in number of land uses and patch size (Left: (four classes in larger patches, Right: 3 land uses in smaller patches)

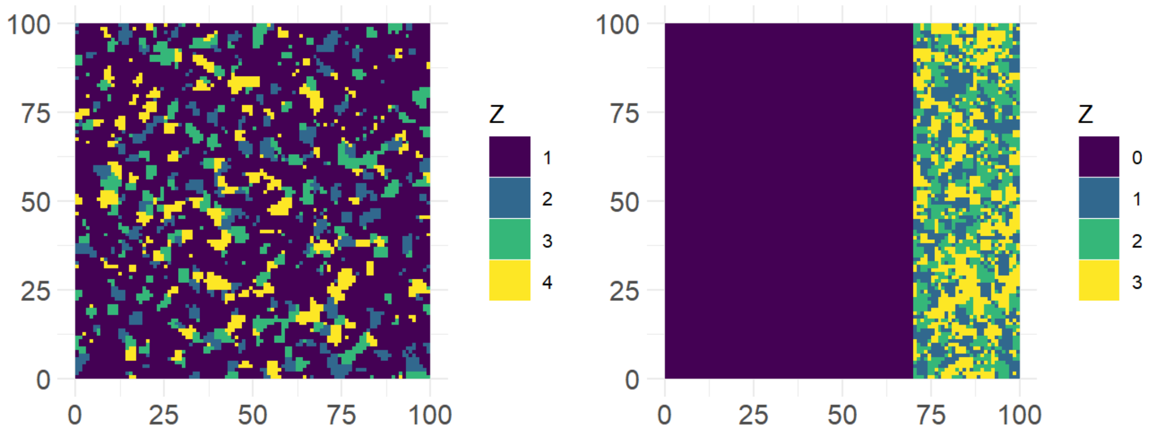

Figure 22: Diversity (Left: evenly mixed, Right: one block of land use with remaining three highly mixed)

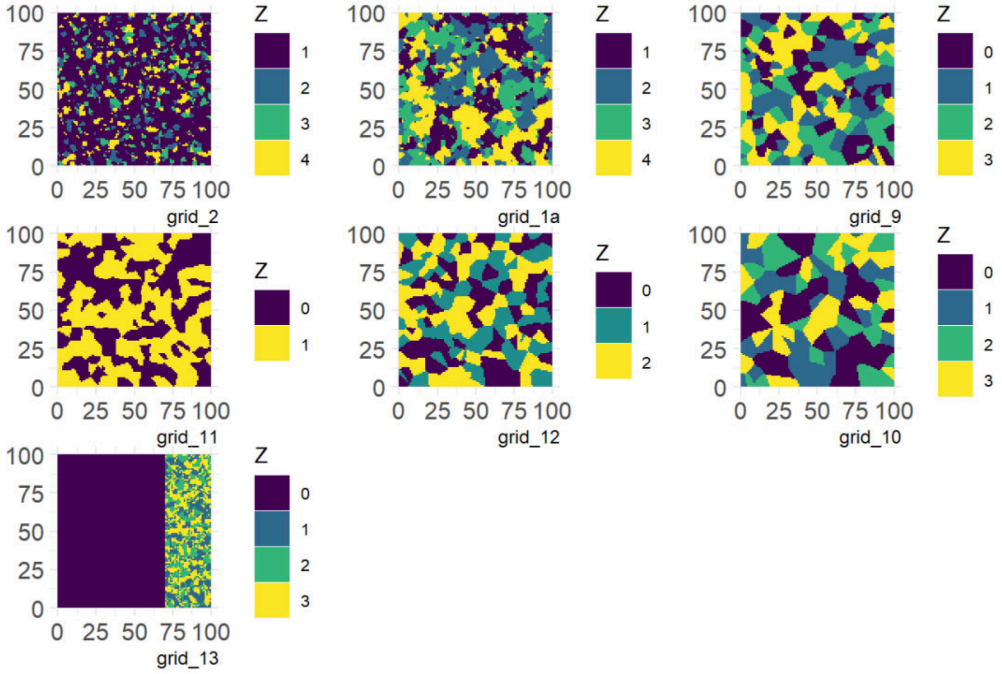

Figure 23: Ranking of mosaics using TCA metric (highest to lowest patch diversity)

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