Rising Sea Levels and Agriculture in New Zealand

A new Natural Capital and Inundation Module for MERIT and application to a national case study

Technical report for the Future Coasts Aotearoa Research Programme

m.e research

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Report authors: Nicola McDonald, Leslie Dowling, Garry McDonald, Emily Harvey

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Glossary

CGE (Computable General Equilibrium) A class of applied economic models often used to illustrate an economy's responses to changes in policy, technology or other external shocks. Typically CGE models recognise a number of different types of economic agents (usually different types of industries, households and government), conceptualised as either profit or utility maximisers. Optimisation algorithms are employed to determine the set of prices for all commodities and factors of production that would prevail subject to selected constraints (e.g. all commodity and factor markets clear, and total income equals total expenditure for all agents).

DEM (MERIT Dynamic Economic Model) A multi-sectoral and dynamic economic model that traces the demand and supply of goods, services and factors of production within an economic system, as well as the flow of income between economic agents.

ERI (Economics of Resilient Infrastructure) A four year research programme funded by the Ministry of Business, Innovation and Employment.

GDP (Gross Domestic Product) The total market value of goods and services produced in an economy after deducting the cost of goods and services utilised in the process of production, but before deducting allowances for the consumption of fixed capital.

MERIT (Modelling the Economics of Resilient Infrastructure Tool) A new analytical tool developed in the four-year Economics of Resilient Infrastructure (ERI) research programme that enables quantification of the economic impacts of infrastructure failure, and evaluation of the consequences of resilience-enhancing strategies.

NCIM (Natural Capital and Inundation Module) The new economic modelling tool developed in this study to generate estimates of the economic impacts of sea level rise for coastal farms.

System Dynamics A methodology for understanding certain kinds of dynamic systems. The methodology concentrates on mapping the feedback relationships between different components or relationships within a system, and simulating changes in systems over time.

Value Added The value added to goods and services by the contributions of capital and labour, i.e. the value of output after the cost of bought-in materials and services has been deducted. It includes the national accounts categories 'gross operating surplus', 'compensation of employees', 'other taxes on productions' and 'subsidies'. The sum of all value added is equal to Gross Domestic Product (GDP), excluding taxes on products and import taxes net of subsidies..

Abstract

This report presents an assessment of the economic impacts of sea-level rise (SLR) on New Zealand's coastal lowland agriculture, conducted as part of the Future Coasts Aotearoa research programme. The study introduces a new Natural Capital and Inundation Module (NCIM), designed to simulate farm-level responses to SLR—including adaptation decisions and land use changes.

The analysis employs a national-scale case study, focusing on pastoral farming (dairy, sheep and beef) within rural coastal lowlands identified as vulnerable to inundation. Synthetic datasets of representative farm locations and size, financial accounts, and drainage schemes were generated to overcome data limitations, and a multi-step geospatial process delineated areas at risk, and changes in risk over time.

The NCIM models losses in productive capacity, risks to critical farm capital, and increasing drainage costs, while allowing for landowner behavioural responses. The NCIM produces estimates of net changes in farm performance (measured in EBITDA) as a result of sea level rise out to 2080.

Results indicate that, under a range of SLR scenarios, the direct economic impacts on agriculture are relatively modest at the national scale (e.g. an estimated loss in total EBITDA across all farms of approximately $11.7 million per annum by 2080 under RCP 4.5, and $19.5 million under RCP 8.5). The impacts are not evenly felt over the country or among economic sector, with the dairy cattle farming industry experiencing losses approximately four times greater than sheep and beef farming, and approximately 28% of the impact is in the Waikato region.

A large proportion of farmland subject to the most severe impacts of sea level rise is already contained within drainage and defence schemes, and assuming that these schemes are maintained and upgraded for increasing sea levels and rising groundwater, this avoids what might otherwise be a need for land de-intensification or abandonment in response. Sensitivity analysis suggests that only substantial increases in drainage costs above those included in the modelling would trigger significant changes in land use or scheme abandonment. Nevertheless, it is acknowledged that the methods used to estimate the way in which drainage costs will increase in this national-level study under rising sea levels and groundwater are coarse and approximate. This national scale analysis also cannot account for the the nuances of operational and capital requirements of individual drainage schemes, and also that the future of such schemes will be driven by considerations that extent beyond financial. Importantly, should groundwater become increasingly saline, this is not considered in the drainage costings.

The impacts from the NCIM are also interfaced with the MERIT Dynamic Economic Model (DEM) to quantify economy-wide consequences. The MERIT analysis reveals that while initial losses are concentrated in coastal farms, complex economic interrelationships lead to widespread but moderate impacts across economic sectors. Flow-on losses from the directly impacted farms include those captured in the downstream processing industries (meat and dairy manufacturing), as well as quite widespread losses in the service sector resulting from impacts on supply chains and changes in income and spending within the economy.

As a limitation, the study excludes smaller high-value intensive uses, particularly horticulture, suggesting the total economy-wide flow-on consequences are likely underestimated for coastal

agriculture. It also concentrates on measuring the overall or general trajectory in pastoral agriculture production and income generation as a result of changing sea levels- it does not measure costs to repair/replace assets lost or damaged during episodic inundation (to some extent these losses will be covered by insurance).

To explore additional climate related risks not captured in the core NCIM, the study also considers the potential for saltwater intrusion and soil/ water supply salinisation. Simple exploratory scenarios suggest that even small areas of affected land could substantially amplify economic impacts, as current business-as-usual methods for mitigating inundation and rising groundwater or increasing drainage needs do not combat the losses in productivity faced from increased salinity. These findings underscore the need for improved data and modelling of groundwater–seawater interactions so that the nature, extent and timing of salinity risks can be better understood, along with the potential mitigation options. Increased surface flooding under extreme rainfall events (and the interaction of this with rising sea-levels) are further climate related risks that are not considered in this study.

1 Introduction

1.1 Background

Future Coasts Aotearoa is a five-year (2021-26) research programme that aims to transform coastal lowland systems threatened by relative sea-level-rise into prosperous communities. Coastal lowlands are the shallow gradient and low-lying land (or plains) adjacent to coasts and estuaries. These coastal lowlands are valued for many reasons, including for various agricultural uses.

Future sea-level rise (SLR) will force changes to coastal lowlands and the social and economic systems that interact with these areas. For agriculture, one way to view this is that the natural capital upon which agriculture depends will alter as a result of the interactions between hydrology, land, and ecosystems, and thus the ecosystem services (e.g. provisioning services) upon which agriculture depends will be altered.

As part of the Future Coasts Aotearoa project, M.E Research is tasked with applying the Measuring the Economics of Resilient Infrastructure Tool (MERIT) to investigate economy-wide implications of rising sea levels. The Dynamic Economic Model contained within MERIT (Brown et al., 2023; McDonald et al., 2020; Smith et al., 2019a) is a multi-sector economic model that traces economic pathways through time, generating a variety of economic metrics such as Gross Domestic Product (GDP), household income, and value added by industry or sector. The purpose of this study is to quantify, under a range of assumptions and scenarios, the effect of SLR on agriculture within coastal lowlands, and the scale of changes to the New Zealand economy that this will bring about.

In order to undertake this study, it has been necessary to develop a new interfacing module for MERIT, which we have termed the "Natural Capital and Inundation Model". This module examines direct changes to farm production, accounting for possible adaptation choices (including change in land use), which then serve as an input to the MERIT Dynamic Economic Model enabling the flow-on and economy-wide implications to be calculated.

1.2 Measuring the Economics of Resilient Infrastructure Tool (MERIT)

MERIT is a collection of models that can be used to investigate future changes in the New Zealand economy. Originally, the principal focus for MERIT was on the economic implications of interruptions in the delivery of critical infrastructure services, and related to this, the implications of natural hazards on the economy.

At the core of MERIT is the Dynamic Economic Model (DEM), a multisectoral and multi-regional dynamic economic model (McDonald et al., 2020; Smith et al., 2019a). The model's function is to determine the flow-on and wider economic implications that occur to an economic system, given some type of direct impact or change to that system. The Dynamic Economic Model is designed to imitate the core features of a Computable General Equilibrium (CGE) model. CGE models tend to be the favoured approach and 'state-of-art' in the modelling of regional-and national-level economic impacts. Among the advantages of these types of models are the whole-of-economy coverage, the capture of not only indirect (i.e. the so-called upstream and downstream multiplier effects generated through supply chains) and induced (i.e. as generated through household consumption) economic consequences, but also of the 'general equilibrium' (pricing) impacts. While the model incorporates core features of a CGE model, it is important to note that it differs from a 'standard' CGE model in that it is a System Dynamics model formulated using differential equations that describe how the elements in the system change with time.

Several supporting modules have been developed for MERIT, principally to interface to the Dynamic Economic Model and assist in determining the initial direct impact or change to economic systems. The Business Behaviours Module (Brown et al., 2019) determines the loss in industry production and its recovery through time, given experience of infrastructure and non-infrastructure disruptions, focusing on urban industries. The Agricultural Business Behaviours Model (McDonald et al., 2025) determines the cashflows of individual farms (current and capital, income and expenditures) over time following a natural hazard event. Several studies have been undertaken which apply these interfacing modules alongside the Dynamic Economic model (e.g. McDonald et al. (2018), Smith et al. (2019b), Brown et al. (2023))

For the interfacing modules mentioned thus far, the focus is largely on the modelling the recovery of businesses and industries to their pre-impacted states, and calculating the losses occurring during disruption and recovery. Given, however, the climate change context of this study, we now need to develop a new module that focuses on changes in farm systems in response to permanent changes in the natural environment (e.g. increasing mean high water springs and increased frequency of inundation).

2 Natural Capital and Inundation Module

2.1 Overview

The Natural Capital and Inundation Module (NCIM) simulates annual farm financials, over a 50-year period, considering impacts on farms from sea level rise. The model includes consideration of:

1. Losses in productive capacity of farms due to land inundation, both permanent (i.e. rising mean high water springs) and occasional (i.e. increasing height of extreme sea level under storm events). This can be viewed as losses in the delivery of the ecosystem service 'provisioning service' and thus effectively a loss in the natural capital of farms.
2. The risks and realisation of damages to key farm capital, which may have implications for the way in which farmers and landowners continue to operate their farm.
3. Increasing costs of drainage and defence under future SLR, including for those farms that use this as a mitigation to (1).

To create realistic future simulations, the farm model also incorporates potential landowner behaviour. Specifically, it models decisions landowners might make to change to an alternative farm type, and/or give up on farm drainage and defence, in response to changing financial conditions.

The NCIM only considers farms that are at risk under sea level rise, and each farm, subscript i, can only have one farm type (land use), subscript f, at a time (see also Appendix A.1). The Module recognises that land use change, specifically switching between farm types, is a potential response of farmers and landowners to SLR and the resulting impacts on financial conditions.

A stock and flow structure is used to keep track of the farm type allocated to each farm, and whether it has drainage and defence or not, through time. Here the stock $\textbf{LanduseWD}_{i,f}$ is set to 1 to indicate that farm i has defence and drainage and is assigned farm type f. Similarly a value of 1 for $\textbf{LanduseND}_{i,f}$ indicates that farm i has no defence and is assigned farm type f. While a value of zero indicates that farm type f is not the selected farm type. Each farm, i, must have a single farm type f at any time, and can either have defence or not, in other words:

$$\sum_{f}\left(\textbf{LanduseND}_{i,f} + \textbf{LanduseWD}_{i,f}\right) \equiv 1.$$

At each time step (Δt), for each farm, i, the Natural Capital and Inundation Module calculates:

- the current farm performance, which depends on the type of farm system or land use in operation, the extent of any land inundated and whether they have drainage and defence in place,

- the costs and benefits of drainage and defence.

Based on these calculations, as well as additional information about the timing of capital renewals, any capital damage from SLR, and insurance retreat, the model calculates whether any farms would undergo a change in farm type or would give up on their drainage and defence for the next time step Δt (where $\Delta t \ll 1$ year).

2.2 Farm Performance

2.2.1 Measuring Farm Profitability (with and without defence)

Ignoring for the time being the costs of drainage that farms might face, the module uses a standard measure of farm profitability $EBITDA_i$ (Earnings Before Interest, Taxes, Depreciation and Amortization) for each farm (subscript i). Where the overall farm performance for farm i ($EBITDA_i$) will depend on what the current 'landuse' or 'farm type' is (denoted by subscript f; only one farm type per farm at any one time) and whether there is a defence and drainage system.

We capture this in our model using:

$$EBITDA_i(t) = \sum_f \Big(EBITDA\_ND_{i,f}(t) \times \mathbf{LanduseND}_{i,f}(t) + EBITDA\_WD_{i,f}(t) \times \mathbf{LanduseWD}_{i,f}(t) \Big) \tag{2.1}$$

where $EBITDA\_ND_{i,f}$ is $EBITDA$ for farm i and farm type f **with no defence**, while $EBITDA\_WD_{i,f}$ is the $EBITDA$ for farm i and farm type f **with defence**.

Simplifying equation (2.1), we see that if there is no drainage or defence in place, and the farm is in farm type f:

$$EBITDA_i = EBITDA\_ND_{i,f}$$

while if there is drainage and defence, and the farm is in farm type f:

$$EBITDA_i = EBITDA\_WD_{i,f}$$

To calculate $EBITDA\_WD_{i,f}$ we determine the value of base production for each farm i and farm type f ($baseprod_{i,f}$) and then subtract off the costs:

$$EBITDA\_WD_{i,f}(t) = baseprod_{i,f}(t) - \Big[fixedcosts_{i,f}(t) + prodcosts_{i,f}(t) + landcosts_{i,f}(t) \Big] \tag{2.2}$$

where $fixedcosts_{i,f}$ is the sum of all expenses for farm type f and farm i that stay fixed regardless of the production levels or land area farmed, $prodcosts_{i,f}$ is the the sum of the costs that vary depending on production levels, and $landcosts_{i,f}$ is the sum of the costs that vary with land natural capital (e.g. the land area farmed and land quality).

Considering Equation (2.2) for $EBITDA\_WD_{i,f}$, we see that SLR does not impact farm $EBITDA$ where there is defence in place, except with respect to changing costs for defence and drainage itself (see Section 2.4). This implies continuous upgrading of defence systems in response to SLR so that the overall risks to each farm remain constant with base conditions. This was a simplifying assumption used in this initial study, and reflected the nature of the data available (see also Section 4.4). Other situations could also be considered by adding additional complexity to the model.

When there is no defence in place, $EBITDA\_ND_{i,f}$ varies according to the equation:

$$\begin{aligned} EBITDA\_ND_{i,f}(t) =& baseprod_{i,f}(t) \times relativeprod\_ND_{i,f}(t) \\ & - \Big[fixedcosts_{i,f}(t) \\ & \quad + prodcosts_{i,f}(t) \times relativeprod\_ND_{i,f}(t) \\ & \quad + landcosts_{i,f}(t) \times relativeNC\_ND_{i}(t) \Big], \end{aligned} \tag{2.3}$$

where $relativeprod\_ND_{i,f}(t)$ is a scalar that varies through time and represents the impact on farm production costs due to SLR, and $relativeNC\_ND_{i}(t)$ is a scalar that varies through time representing the impact of SLR on natural capital costs.

2.2.2 Farm Production

Under SLR, the natural capital available to coastal farms may be reduced both through permanent inundation (i.e. increasing areas of land below mean high water springs) and from episodic inundation during storm events.[1]

In terms of episodic inundation, hydrological events, or hazards, are typically quantified in terms of annual probabilities or return periods. Anticipating the data available, we have therefore chosen to quantify relative changes in farm production as relative changes in 'expected' farm production, where production is influenced by the available land or natural capital. To calculate this, we first define the expected farm production relative to the base, for a given return period or probability threshold, p, as $expprod\_RP_{i,f,p}$. The expected overall relative production, $relativeprod\_ND_{i,f}$, is the integral of a curve defining the relative production level that is anticipated to be equalled or exceeded, for a given probability threshold. As an example, assume that we have a set of return periods of: 1 in 10 years; 1 in 50 years; 1 in 100 years; and 1 in 200 years (i.e. $p = [10, 50, 100, 200]$), these correspond to the set of annual probabilities of 0.1, 0.02, 0.01, 0.005 respectively. In this example, the expected production relative to the base can be approximated as:

$$\begin{aligned} relativeprod\_ND_{i,f} =& 0.5(expprod\_RP_{i,f,p\leq 1} + expprod\_RP_{i,f,p=10}) \times (1 - 0.1) \\ & + 0.5(expprod\_RP_{i,f,p=10} + expprod\_RP_{i,f,p=50}) \times (0.1 - 0.02) \\ & + 0.5(expprod\_RP_{i,f,p=50} + expprod\_RP_{i,f,p=100}) \times (0.02 - 0.01) \qquad (2.4) \\ & + 0.5(expprod\_RP_{i,f,p=100} + expprod\_RP_{i,f,p=200}) \times (0.01 - 0.005). \qquad (2.5) \end{aligned}$$

Economic models of firm production typically recognise that there are different forms of resources available to be used for production ("factors of production"), being both different forms of capital (e.g. natural capital, built capital) as well as other resources such as labour. Such models also typically recognise an ability to substitute one factor of production for another while maintaining the same level of output. The elasticity of substitution concept measures the ease by which one

[1] Rising groundwater, including salinated groundwater, is an additional and related issue for farms. This topic is not covered by this initial national study due to data availability constraints.

input can be substituted for another, and can also help quantify the impacts on production of a drop in the supply of a factor, where other factors are held constant.

In this module we have relied specifically on the commonly used constant elasticity of substitution (CES) functional form to model firm production accounting for losses in the availability of natural capital over time. Under this formulation:

$$rprod_{i,f,p} = \gamma_{i,f} \left[\delta_{i,f}^{nc} (NC_{i,f,p})^{\eta_{i,f}} + \delta_{i,f}^{of} (OF_{i,f,p})^{\eta_{i,f}} \right]^{\frac{1}{\eta_{i,f}}}, \tag{2.6}$$

where $NC_{i,f,p}$ and $OF_{i,f,p}$ are, respectively, the relative quantity of natural capital and other factors for production at farm i and for farm type j, under return period p, and $\gamma_{i,f}$ is the scale parameter. The input share coefficients for input types $NC_{i,f,p}$ and $OF_{i,f,p}$ are $\delta_{i,f}^{nc}$ and $\delta_{i,f}^{of}$, where $0 \leq \delta_{i,f} \leq 1$ and $\delta_{i,f}^{nc} + \delta_{i,f}^{of} = 1$. Furthermore, η_i is a parameter defined by the elasticity of substitution, $\epsilon_{i,f}$ between inputs $NC_{i,f,p}$ and $OF_{i,f,p}$:

$$\eta_{i,f} = \frac{\epsilon_{i,f} - 1}{\epsilon_{i,f}}, \qquad \eta_{i,f} \leq 1. \tag{2.7}$$

The smaller the elasticity parameter, $\epsilon_{i,f}$, the greater the effect of losses in natural capital on farm production. The outcome of Equation (2.6) is also that, while all other conditions remain constant, each incremental loss in the availability of natural capital will have a greater impact on farm production than the last increment. This can be justified on the basis that the more significant the loss of farm natural capital, the less ability to make up for these losses through strategies and the application of other farm resources (e.g. using labour to feed out stock).

It is worth noting that there may be special farm types where the relationship of increasingly greater production losses from losses in natural capital may not occur, and instead for the purposes of modelling these farm types it could be assumed that production will decline simply in proportion to the hectares lost (e.g. when farm output is the revenue from leasing hectares to a large horticulture operation and lease payments are on a per hectare basis). Such special cases can be modelled simply by setting the share parameter for natural capital, $\delta_{i,f}^{nc}$, to 1, and applying a very high elasticity of substitution, $\epsilon_{i,f}$.

In order to determine the quantity of natural capital available for a given return period, we can begin by noting that for the special case where the return period is less than one year ($p \leq 1$) the natural capital available on a farm ($NC_{i,f,p\leq 1}$) will exclude land that is permanently lost to farming through SLR. We deem this to include both land under mean high water springs, as well as land inundated at least annually, as the latter may be generally impractical for farming purposes. As we are calculating here natural capital *without* drainage and defence, we also assume that any land that is subject to drainage and defence at the outset, will not be useful natural capital for farming, should defence and drainage not be available [2].

When estimating farm natural capital for return periods greater than 1 ($NC_{i,f,p\geq 1}$), we exclude the natural capital contained in land subject to permanent inundation or orginally under drainage,

[2] For some case studies it is possible that land contained within existing defence and drainage schemes will have some usefulness even without drainage. The hydrological data we have available for our case study does not allow for such nuanced considerations.

as well as any additional land that would be inundated at the given return period. For this latter land we take into consideration that such land may not be inundated for an entire year, so a scalar is applied representing the proportion of the year lost.

2.3 Land Use Change

For tracking the change in $\mathbf{LanduseND}_{i,f}$, a flow out of the stock ($changeoutND_{i,f}$) represents a change out of that farm type, while a flow into the stock ($changeinND_{i,f}$) is a change into that farm type:

$$\mathbf{LanduseND}_{i,f}(t + \Delta t) = changeinND_{i,f}(t) - changeoutND_{i,f}(t) \tag{2.8}$$

and similarly,

$$\mathbf{LanduseWD}_{i,f}(t + \Delta t) = changeinWD_{i,f}(t) - changeoutWD_{i,f}(t) \tag{2.9}$$

In this section we describe the equations related to land use change for farms without defence and drainage in place. Because the incentives for different land uses may be different depending on whether the defence and drainage is in place, and a farm may currently have drainage, the module also keeps track of changes in land use with defence, $\mathbf{LanduseWD}_{i,f}$. The equations used for the case with defence are the same as used with no defence.

For each farm, land use change will occur as a discrete event rather than, say, a gradual change over time. Thus, it is necessary to specify thresholds and/or events that may initiate a switch between farm types. Four sets of conditions initiating a change out of a land use are recognised in the module, $LUCoutND_{i,f,k}$ for $k = \{1, \ldots, 4\}$ where $LUCoutND_{i,f,k} = 1$ when a condition is met. The change out of a farm type will occur when any of these conditions are met:

$$changeoutND_{i,f} = \begin{cases} 1 & \text{if} \quad \left(\sum_k LUCoutND_{i,f,k}\right) \geq 1 \\ 0 & \text{if} \quad \left(\sum_k LUCoutND_{i,f,k}\right) < 1. \end{cases} \tag{2.10}$$

Each of the land use change initiation conditions are discussed further in the following sections. The four sets of conditions relate to:

1. changes in the relative profitability of different farm types,
2. costly capital items coming up for renewal,
3. insurance retreat, and
4. damage to critical capital from inundation events

Whenever one of the sets of conditions is satisfied, and thus a change out of the current land use/farm type occurs, there must be a corresponding change into another land use/farm type. The corresponding changes into a land use are respectively denoted $LUCinND_{i,f,k}$, with

$$changeinND_{i,f} = \begin{cases} 1 & \text{if} \quad \sum_k \left(LUCinND_{i,f,k}\right) \geq 1 \\ 0 & \text{if} \quad \sum_k \left(LUCinND_{i,f,k}\right) < 1. \end{cases} \tag{2.11}$$

2.3.1 Changing relative profitability of farm types, condition $k = 1$

Land use change occurs (i.e.$LUCoutND_{i,f,k=1} \geq 1$) when there is at least one more profitable farm type in terms of $EBITDA$ than the current farm type, and the farm can feasibly change to one of these more profitable farm types (there are no environmental barriers to entry or large capital investments required). Note that the module only allows for this type of land use change to be initiated when large capital items are not up for renewal ($CCupgrading_{i,f} \neq 1$), as under these situations, different financial incentives will need to be considered.

Consequently, $LUCoutND_{i,f,k=1}$ is defined as:

$$LUCoutND_{i,f,k=1} = \begin{cases} 0 & \text{if} \quad CCupgrading_{i,f} = 1 \\ 1 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) > EBITDA_i \end{cases} \tag{2.12}$$

where $EBITDA\_NDavail_{i,f}$ is a matrix of the $EBITDA$ for all farm types ***available*** for land use change out of the current farm type.

$$EBITDA\_NDavail_{i,f} = \left(\mathbf{LanduseND}_{i,f} * \mathcal{A}\right) \times EBITDA\_ND_{i,f}$$

This is calculated using the $f \times f$ allowed land use transition matrix, $\mathcal{A}$ (which has zeros on the diagonal), matrix multiplied by $\mathbf{LanduseND}_{i,f}$ to get a matrix of ones and zeros indicating the available farm type transitions from the current farm type for each farm i. This is then multiplied the $EBITDA\_ND$ to get the potential $EBITDA$ for each available farm type that the current farm could transition into.

By allowing for land use change when there is a change in relative farm type profitability, the module is inherently assuming that land follows the most profitable farm type.[3] There are, of course, a variety of reasons why this may not occur, such as lack of know-how for undertaking alternative farm operations, poor information available on relative farm profitability, and simply inertia to change. For the purposes of many applications, this will nevertheless be a useful scenario or assumption to consider.

Associated with a change out of the current farm type there must be an equivalent change into another farm type. This model chooses the farm type f to transition into is based on relative profitability $EBITDA$ of the available options:

$$LUCinND_{i,f,k=1} = \begin{cases} 0 & \text{if} \quad \sum_f LUCoutND_{i,f,k=1} < 1 \\ 1 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) \leq 0 \text{ and } f = V \\ 1 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) > 0 \text{ and } \max(EBITDA\_NDavail_{i,f}) = EBITDA\_ND_{i,f} \\ 0 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) > 0 \text{ and } \max(EBITDA\_NDavail_{i,f}) \neq EBITDA\_ND_{i,f} \\ & \quad\quad \text{and } f \neq V \end{cases} \tag{2.13}$$

[3] In real world contexts, there will often be situations where land will persist in a farm type that is not the most profitable, as measured by $EBITDA$, because there are significant investment costs in transitioning to an alternative farm type. In creating this module it has been assumed that, within the context of land subject to future SLR, there will be a reluctance to transition to new farm types that require significant capital investment, and land use change will generally follow a de-intensification path, whereby significant capital investments will not be required for transitioning from one land use to the next land use. This assumption is encoded into the farm types available for transition to, as defined by set $\mathcal{A}$, and is carried forward through the calculation of $EBITDA$ for the available farm types, $EBITDA\_NDavail_{i,f}$. In the context of this approach, $EBITDA$ is a valid metric for identifying land use change thresholds. It is acknowledged that more complex land use transitions might also need to be considered for special applications, which involve new capital investment considerations. In such cases, the threshold criteria would need to be reconsidered.

In equation 2.13, it is assumed that one of the farm type options under consideration will always be a vacant or abandoned farm (i.e. $f = V$). Should no other farm type be profitable, $EBITDA\_NDavail_{i,f} > 0$, this will end up as the choice for the new farm type.

2.3.2 Capital up for renewal, condition $k = 2$

When $EBITDA$ is used as a metric to determine the relative profitability of farm types, the relative costs of capital to operate those farm types are effectively ignored. When, however, a large capital item comes up for renewal (e.g., a dairy shed is due for replacement), the need to include capital costs in the assessment of relative farm profitability will be greater, as farmers will wish to consider whether those new capital investments are worthwhile. The module therefore allows for land use change to also occur (i.e. $\sum_f LUCoutND2_{i,f} \geq 1$) when there is a change in the relative performance of $EBIT$ between farm types. The $EBIT$ metric is the same as $EBITDA$, except that in the $EBIT$ metric, capital depreciation and amortisation costs are included as expenses that reduce farm profitability. So, if we denote the set of $EBIT$ for all farm types available for land use change out of the current farm type with no defence as $EBIT\_avail_{i,f}$,

$$EBIT\_avail_{i,f} = \left(\mathbf{LanduseND}_{i,f} * \mathcal{B}\right) \times EBIT_{i,f}$$

where $\mathcal{B}$ is similar to the transition matrix $\mathcal{A}$, but with the possible transitions for the situation of capital being up for renewal. Then $LUCoutND2_{if}$ is defined as:

$$LUCoutND_{i,f,k=2} = \begin{cases} 1 & \text{if} \quad \max(EBIT\_avail_{i,f}) > EBIT_{i,f} \text{ and } CCupgrading_{i,f} = 1 \\ 0 & \text{otherwise,} \end{cases} \tag{2.14}$$

where $CCupgrading_{i,f}$ is equal to one when critial capital is up for renewal.

Associated with the change out of a farm type due to capital up for renewal, there must be a change into a new farm type. Here we assume:

$$LUCinND_{i,f,k=2} = \begin{cases} 0 & \text{if} \quad \sum_f LUCoutND_{i,f,k=2} \neq 1 \\ 1 & \text{if} \quad \max(EBIT\_avail_{i,f}) < 0 \text{ and } f = V \\ 1 & \text{if} \quad \max(EBIT\_avail_{i,f}) \geq 0, \text{ and } \max(EBIT\_avail_{i,f}) = EBIT_{i,f} \text{ and } f \neq V \\ 0 & \text{if} \quad \max(EBIT\_avail_{i,f}) \geq 0, \text{ and } \max(EBIT\_avail_{i,f}) \neq EBIT_{i,f} \text{ and } f \neq V \end{cases} \tag{2.15}$$

i.e. that a farm changes to the most profitable available alternative, and that a farm changes to vacant land use $f = V$ if none of the alternative land uses have $EBIT > 0$.

2.3.3 Insurance retreat, condition $k = 3$

Should insurance cover no longer be available for costly capital items due to increasing risk from SLR, this will discourage farmers from undertaking activities dependent on these investments. Nevertheless, should such capital already be in place, it is unlikely that farmers will cease operations until such time as the capital item(s) come up for renewal and/or the capital item(s) have been damaged (e.g. by an inundation event), and thus face repair or replacement.

The module therefore allows for possible land use change ($LUCoutND_{i,f,k=3} \geq 1$) according to the equation:

$$LUCoutND_{i,f,k=3} = \begin{cases} 1 & \text{if} \quad CCupgrading_{i,f} = 1 \text{ and } inretreat_{i,f} = 1, \\ 0 & \text{otherwise} \end{cases} \tag{2.16}$$

where $inretreat_{i,f}$ indicates that for the farm type f on farm i, there are critical and costly capital items for which insurance is not practically available. For the purposes of the modelling it is assumed that insurance retreat will occur should the annual probability of damage for critical natural capital ($CCprobdamage_{i,f}$) exceed the insurance retreat threshold $INTHRESHOLD_f$ for that farm type:

$$inretreat_{i,f} = \begin{cases} 1 & \text{if} \quad CCprobdamage_{i,f} > INTHRESHOLD_f \\ 0 & \text{otherwise} \end{cases} \tag{2.17}$$

As with the other possible situations for land use change, it is also necessary to identify a new farm type for the farm after land use change. Here we use relative profitability of different farm types to determine the new farm type following the land use change:

$$LUCinND_{i,f,k=3} = \begin{cases} 0 & \text{if} \quad \sum_f LUCoutND_{i,f,k=3} \neq 1 \\ \text{else} & \\ 0 & \text{if} \quad inretreat_{i,f} = 1 \\ 1 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) > 0 \text{ and } \max(EBITDA\_NDavail_{i,f}) = EBITDA\_ND_{i,f} \\ 0 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) > 0 \text{ and } \max(EBITDA\_NDavail_{i,f}) \neq EBITDA\_ND_{i,f} \\ 1 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) \leq 0, f = V \\ 0 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) \leq 0, f \neq V \end{cases} \tag{2.18}$$

We assume that farms transition to vacant land use $f = V$ if none of the alternative farm types are profitable and insurable (if there is critical capital involved in the farming activity).

2.3.4 Damage to critical capital, condition $k = 4$

Finally, a fourth category of land use change occurs ($LUCoutND_{i,f,k=4} \geq 1$) according to the equation:

$$LUCoutND_{i,f,k=4} = \begin{cases} 1 & \text{if} \quad CCdamage_{i,f} = 1 \text{ and } inretreat_{i,f} = 1 \\ 0 & \text{else} \end{cases} \tag{2.19}$$

where $CCdamage_{i,f} = 1$ if there is critical costly capital on the farm that has been significantly damaged.

As in condition $k = 3$ (insurance retreat), we use the relative profitability of different farm types to determine the new farm type:

$$LUCinND_{i,f,k=4} = \begin{cases} 0 & \text{if} \quad \sum_f LUCoutND_{i,f,k=4} \neq 1 \\ \text{else} & \\ 0 & \text{if} \quad inretreat_{i,f} = 1 \\ 1 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) > 0 \text{ and } \max(EBITDA\_NDavail_{i,f}) = EBITDA\_ND_{i,f} \\ 0 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) > 0 \text{ and } \max(EBITDA\_NDavail_{i,f}) \neq EBITDA\_ND_{i,f} \\ 1 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) \leq 0 \text{ and } f = V \\ 0 & \text{if} \quad \max(EBITDA\_NDavail_{i,f}) \leq 0 \text{ and } f \neq V \end{cases} \tag{2.20}$$

We assume that farms transition to vacant land use $f = V$ if none of the alternative farm types are profitable and insurable [4].

[4] Technically these equations could set $LUCinND_{i,f,k} = 1$ for more than one farm type f, for a given farm i if the $EBITDA\_ND$ (or $EBIT$ for $k = 2$) is exactly equal for two different farm types on the same farm i. The possibility of this is vanishingly small, however in the code for the model we add in a condition to deal with this edge case.

2.4 Drainage and Defence

The Natural Capital and Inundation module keeps track of the financial costs farmers incur for defence and drainage systems, and how these costs could change over time as a result of SLR. It is furthermore recognised that there is a choice to be made by landowners as to whether these systems continue to be maintained and upgraded. The module therefore also keeps track of the benefits of these systems, and a comparison between the estimated benefits and costs is the basis for determining whether the systems persist.

2.4.1 Costs of drainage and defence

For the purposes of creating an operational module, we have endeavoured to create a method for quantifying drainage costs that will estimate both base costs for all case study farms and potential cost changes under SLR. However, we note that drainage costs are likely difficult to define in a generic manner for a national level study - the base data is patchy and administered/set by a range of different organisations, each with different approaches to cost recovery. Another complication is that it is difficult to separate drainage/defence necessary because of the relationship between farms and the nearby sea, and drainage necessary for other hydrological factors (e.g. high groundwater, poorly draining soils, river flooding), and that there are also interrelationships between these hydrological influences on drainage. We note further that in the future, drainage needs will be influenced not only by SLR but also other aspects of climate change, for example increased intensity of rainfall events.

For now, it is assumed that the drainage and defence costs of a farm will be directly related to the area of land served by drainage / defence, as well as a measure of the severity or intensity of drainage / defence required. In terms of the latter, we have used the drainage elevation, the difference in elevation between the drained land and the recipient location of the drained water, to measure the severity of drainage / defence (i.e. higher severity with lower drainage elevation). Furthermore, since our case study is concerned with coastal farms, we will assume that the recipient location for all farms is sea level (which will rise under SLR).

The annual levy for drainage and defence for farm i, $levyDD_i$, is defined by the function F:

$$levyDD_i = F(drainagearea_i, drainagelevation_i), \tag{2.21}$$

where

$$F(drainagearea_i, drainagelevation_i) = \ldots(drainagelevation_i - sealevel(t)) \tag{2.22}$$

The stream of discounted future costs over all n years (n =[1,2,3,...,N]), $DDcosts_i$, is subsequently calculated as:

$$DDcosts_i = \frac{levyDD_i}{(1+r)^0} + \frac{levyDD_i}{(1+r)^1} + \frac{levyDD_i}{(1+r)^2} + \ldots + \frac{levyDD_i}{(1+r)^N}. \tag{2.23}$$

2.4.2 Benefits of drainage and defence

The ability to fully assess the benefits of maintaining drainage and defence will be limited due to uncertainty in the future. In this module, we have taken a pragmatic approach to the benefit assessment.

Clearly, a potential benefit of drainage and defence is the increase in annual EBITDA that is possible without being subject to permanent and periodic loss of natural capital. As described above, the model tracks EBITDA for a farm with defence in place, and also tracks EBITDA without defence in place. Thus, the benefits of defence in these respects, $\mathit{natcapEBITDAbenefit\_DD}_i$ can be calculated simply as:

$$\mathit{natcapEBITDAbenefit\_DD}_i = \sum_f \Big[\mathit{EBITDA\_WD}_{i,f} \times \mathbf{LanduseWD}_{i,f} - \mathit{EBITDA\_ND}_{i,f} \times \mathbf{LanduseND}_{i,f}\Big] \tag{2.24}$$

In a similar manner, the benefits of drainage and defence can also be assessed in terms of EBIT for the current land use, i.e.,

$$\mathit{natcapEBITbenefit\_DD}_i = \sum_f \Big[\mathit{EBIT\_WD}_{i,f} \times \mathbf{LanduseWD}_{i,f} - \mathit{EBIT\_ND}_{i,f} \times \mathbf{LanduseND}_{i,f}\Big] \tag{2.25}$$

In the future it may be the case that without drainage and defence in place, a farm may also face significant risks to its critical capital, and this would lead to a de-intensification of the farm, or at least reliance on a farming approach that does not depend on and put costly capital at risk. We therefore assume that among the land use options available for each farm will be a 'back stop' farm type g ($g \in \mathcal{A}$ and $g \in \mathcal{B}$) which provides farmers with an income stream from the land, without significant financial risks (e.g. cut and carry operation, leased grazing). The potential benefits of drainage and defence in terms of avoiding a change to a low capital land use can be considered with reference to this back stop farm type, both in terms of EBITDA and EBIT:

$$\mathit{deintEBITDAbenefit\_DD}_i = \mathbf{max}\left[\sum_f \left(\mathit{EBITDA\_WD}_{i,f} \times \mathbf{LanduseWD}_{i,f} - \mathit{EBITDA\_ND}_{i,f=g}\right),\ 0\right], \tag{2.26}$$

and

$$\mathit{deintEBITbenefit\_DD}_i = \mathbf{max}\left[\sum_f \left(\mathit{EBITWD}_{i,f} \times \mathbf{LanduseWD}_{i,f} - \mathit{EBITND}_{i,f=g}\right),\ 0\right]. \tag{2.27}$$

Based on the probability of critical capital damage, $\mathit{probCCdamage}_{i,f}$, we can derive the probability of land use change, $\mathit{probLUC}_i$, simply as

$$\mathit{probLUC}_i = \begin{cases} 0 & \text{if } \sum_f(\mathit{probCCdamange}_{i,f} \times \mathbf{LanduseWD}_{i,f}) < \mathit{INTHRESHOLD}_f \\ \sum_f(\mathit{probCCdamange}_{i,f} \times \mathbf{LanduseWD}_{i,f}) & \text{otherwise} \end{cases} \tag{2.28}$$

We can then create an estimate of the expected future benefits of drainage and defence, taking into account both the possibility of natural capital losses through inundation, and land changing to the less risky, low capital farm type. In *EBITDA* terms, the discounted benefits are defined across all future years considered as,

$$EBITDAbenefits\_DD_i = \sum_{n=1}^{N}\left[\frac{deintEBITDAbenefit\_DD_i \times [1-(1-probLUC_i)^n]}{(1+r)^n} + \frac{natcapEBITDAbenefit\_DD_i \times (1-probLUC_i)^n}{(1+r)^n}\right] \quad (2.29)$$

Similarly, in *EBIT* terms, the gross benefits over all years considered is,

$$EBITbenefits\_DD_i = \sum_{n=1}^{N}\left[\frac{deintEBITbenefit\_DD_i \times [1-(1-probLUC_i)^n}{(1+r)^n} + \frac{natcapEBITbenefit\_DD_i \times (1-probLUC_i)^n}{(1+r)^n}\right] \quad (2.30)$$

2.4.3 Decision to retain drainage and defence

For each farm i, the net benefit of retaining drainage and defence, respectively in *EBITDA* and *EBIT* terms, is simply:

$$netEBITDAbenefit\_DD_i = EBITDAbenefits\_DD_i - DDcosts_i, \quad (2.31)$$

and

$$netEBITbenefit\_DD_i = EBITbenefits\_DD_i - DDcosts_i. \quad (2.32)$$

We then define whether it is worthwhile for an individual farm to remove defence and drainage ($removedrainagef_i = 1$) according to the requirements:

$$removedrainagef_i = \begin{cases} 1 & \text{if} \quad netEBITDAbenefit\_DD_i < 0 \\ 1 & \text{if} \quad netEBITbenefit\_DD_i < 0 \text{ and } \sum_f (CCupgrading_{i,f} \times \mathbf{LandUse\_ND}_{i,f}) = 1 \\ 0 & \text{otherwise} \end{cases} \quad (2.33)$$

Since drainage and defence is typically operated as a scheme, to which several farms belong, we cannot determine whether a drainage and defence scheme is maintained for a farm simply by looking at the benefits and costs of that individual farm. The module deals with this problem by assuming that a drainage scheme is removed should more than half of the farms in the scheme determine that the costs outweigh the benefits, i.e.

$$removedrainage_d = \begin{cases} 1 & \text{if} \quad \sum_i (removedrainagef_i \times farmbyscheme_{i,d}) > (0.5 \times \sum_i farmbyscheme_{i,d}) \\ 0 & otherwise \end{cases} \quad (2.34)$$

We use the subscript d to denote the drainage scheme to which a farm potentially belongs ($d = [1, 2, 3, ..., D]$) and the auxiliary $farmbyscheme_{i,d} = 1$ when farm i belongs to a group in drainage scheme d. If the stock $\mathbf{Defence}_d = 1$ indicates that the particular scheme d is being maintained, it can be defined as:

$$\frac{d}{dt}(\mathbf{Defence}_d) = \frac{1}{\tau}(removedrainage_d), \quad (2.35)$$

where τ is again set as the time step of the model.

3 Connecting to the MERIT Dynamic Economic Model

As explained above, the MERIT Dynamic Economic Model (DEM), is a multisectoral and multi-regional dynamic economic model. It operates at the industry-level for New Zealand and traces how changes in one or more sectors flow through the economy due to inter-industry relationships as well as changes in income flows and the way in which factors of production are allocated in the economy.

The new Natural Capital and Inundation Module is used to calculate the direct changes, at the farm level, resulting from sea level rise. In order to estimate the economy-wide implications, the DEM is first run under its baseline conditions (see (Vergara et al., 2019)), over a 50-year simulation. The results from the Natural Capital and Inundation Module (NCIM) are then used to adjust the DEM and a subsequent 50-year simulation is conducted. Outputs from the two simulations are compared to create metrics of the impacts of sea level rise.

Although the MERIT Dynamic Economic Model (DEM) provides a wide coverage of the economic system, it does not contain the level of detail around different types of farm systems as contained within the NCIM - there is just an aggregate activity representing each economic industry (dairy cattle farms in our case study come under the 'dairy cattle farming' industry and all other farms in our case study come under the 'sheep, beef, grain and other farming' industry). The DEM must therefore model changes to the directly impacted farms in a more coarse manner than the NCIM. Nevertheless, the DEM provides a useful indication of the sale of impacts at the national level, and the way in which impacts will flow through the economic system dye to complex economic interrelationships.

To connect the NCIM to the DEM, we have essentially used the NCIM to ascertain the extent to which production of goods and services will change from impacted farms, relative to the resources available to those farms at the outset. This is used to generate an 'operability shock' applied to each of the two directly impacted farming industries. For more details of applying such shocks, please refer to Smith et al. (2019a).

4 Case Study Overview

The preceding sections have detailed the theoretical framework and mechanics of the new Natural Capital and Inundation Module. To demonstrate the module's capabilities and quantify the potential economic impacts of sea-level rise (SLR) on a key sector, this framework is now applied to a national-level case study of New Zealand's agriculture.

This case study serves two primary purposes: first, to generate the specific biophysical and financial inputs required to simulate farm-level responses to SLR, including adaptation decisions and changes in land use; and second, to provide these direct impacts as inputs into the MERIT Dynamic Economic Model, enabling an assessment of the flow-on consequences for the wider New Zealand economy. The following subsections provide a detailed overview of the case study's scope, scenarios, and data sources.

Our case study focuses on the vulnerability of New Zealand's rural coastal lowlands to sea-level rise. This area supports primary production, including high-value agricultural industries such as sheep, beef and grain farming, as well as dairy farming and horticulture. All farm types are sensitive to changes in land area available for farming, and the frequency and extent of inundation events. For the purposes of this case study, however, we concentrate specifically on pastoral farming (ie horticulture is excluded).

4.1 Spatial Area

To define the spatial area of farms potentially impacted by coastal inundation, a multi-step geospatial process was undertaken.

First, a maximum potential inundation zone was delineated. To ensure all potentially affected properties were included, a conservative, long-term scenario was used: the inundation extent of a 1-in-1,000-year return interval coastal inundation event under a 2-metre sea-level rise assumption, as modelled in the national inundation dataset (Paulik et al., 2023).

This broad inundation zone was then refined to isolate the study's focus on rural land. The zone was spatially intersected with the official Statistics New Zealand Urban/Rural classification boundaries (Stats NZ, 2023), and all areas classified as 'urban' were excluded.

Finally, to ensure compatibility with the subsequent farm generation methodology, which operates at the SA1 statistical area level, the final case study area was defined by selecting all SA1s that intersected with the resulting "rural inundation zone". This approach ensures that any farm that is partially within the potential impact zone is fully included in the analysis. The resulting spatial area is illustrated in Figure 4.1.

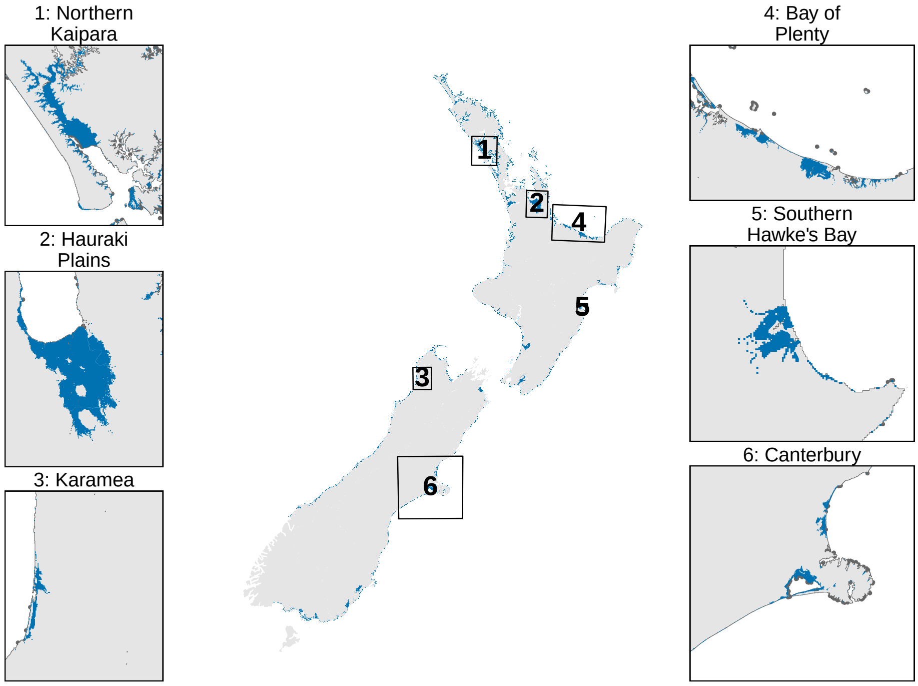

Figure 4.1 Map illustrating the geographical distribution of the case study areas. The main map provides a national overview, while the numbered inset maps (1-6) offer a magnified view of selected areas.

4.2 Sea Level Rise Scenarios considered

To assess a range of potential futures, the analysis incorporates SLR projections from the SeaRise programme, which integrate IPCC estimates with local vertical land movement (Naish et al., 2024). Three distinct scenarios were defined, as detailed in Table 4.1, to capture outcomes from moderate mitigation efforts to a high-emission future. The spatial variation in these projections is illustrated in Figure 4.2.

Table 4.1 Sea-Level Rise Scenarios based on NZ SeaRise Programme Projections.

Scenario	Year	Sea Level Rise (m)	SLR Projection Percentile
Optimistic (RCP 4.5)	2020	0	50^{th}
	2050	0.3	50^{th}
	2100	0.7	50^{th}
Moderate (RCP 7.0)	2020	0	50^{th}
	2050	0.3	50^{th}
	2100	0.8	50^{th}
Pessimistic (RCP 8.5)	2020	0	50^{th}
	2050	0.3	50^{th}
	2100	0.9	50^{th}

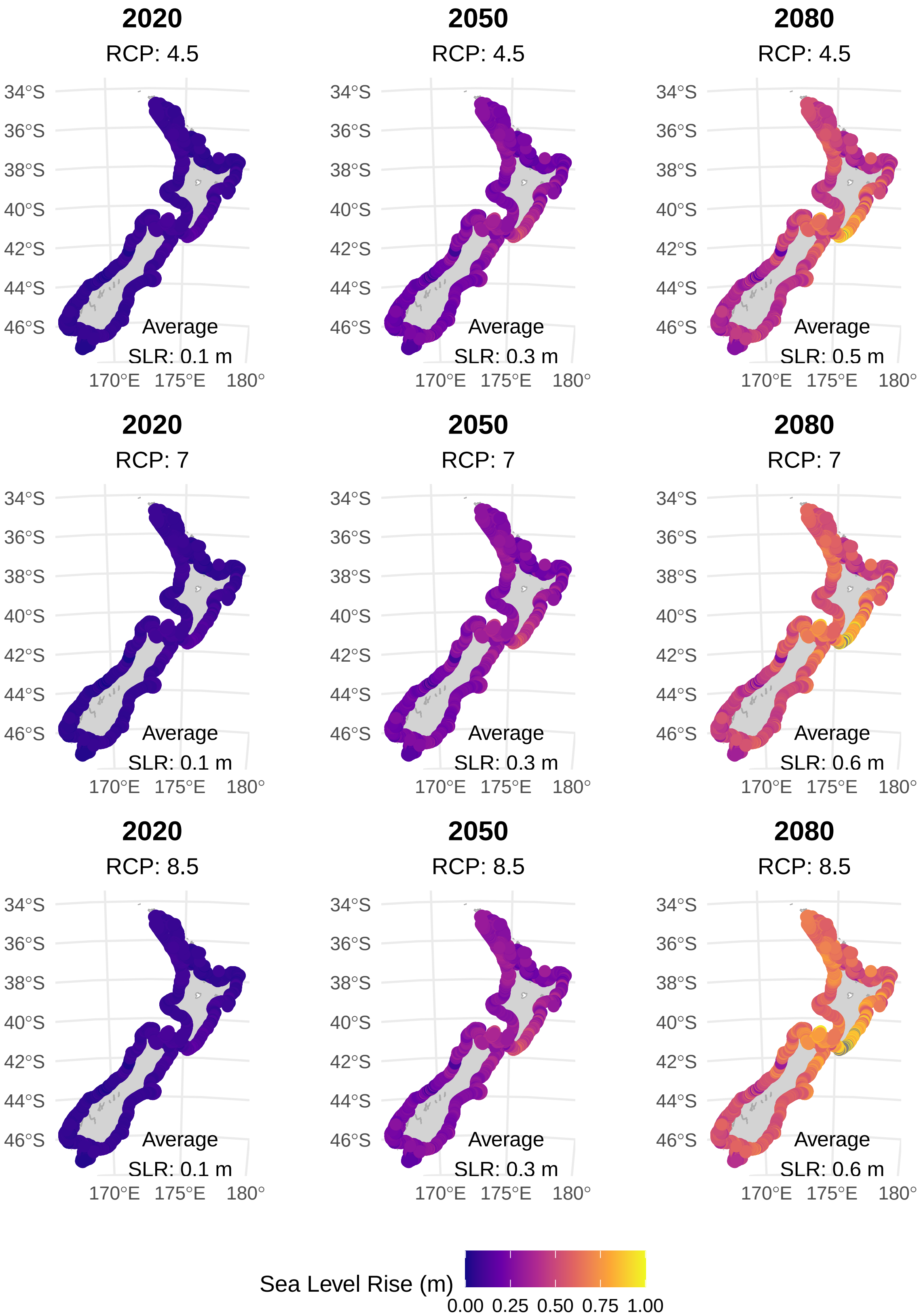

Figure 4.2 Map illustrating the spatial variation of projected sea-level rise across New Zealand for the selected scenarios, based on NZ SeaRise data.

4.3 Farm Types

For this national-level case study, we have focused on pastoral farms. These farms are aggregated into two broad farm types, (1) dairy cattle farming and (2) sheep and beef farming - this is consistent with national accounts data and MERIT industry definitions. We have considered it important to also include an additional farm type, with low fixed capital investment, to cover off the potential ways in which land might be managed under increasing risk of inundation. So we have costed a 'cut and carry' farming operation.

4.4 Data Sources and Limitations

Populating the new Natural Capital and Inundation module with suitable data has been one of the most challenging aspects of undertaking the national level case study. We have, nevertheless, endeavoured to identify practical solutions to enable the national-level assessment of SLR on rural activities to be undertaken:

- *Farm level data* - no national dataset of farm locations and boundaries exists, let along data on individual farm financial information. The solution has been to generate a synthetic dataset of farm properties, along with generation of synthetic financial data for each farm and alternative land use options.
- *Drainage schemes* - drainage scheme information is patchy, inconsistently defined, and must be sourced from numerous authorities and organisations. Given that there has been a limit on the time that can be expended on bringing this information together, we have sought a pragmatic approach to estimating the farms that are currently operating under drainage and defence schemes (refer to Section 5.1.6.1).
- *Inundation mapping* - the areas of land inundated under various sea level rise increments and return periods has been taken from a national study quantifying New Zealand's land area exposed to unundation from extreme sea-levels and relative sea level rise (Paulik et al., 2023). The authors note that topographic elevation data utilised in such analyses often lacks sufficient resolution to enable capture of the effects of mitigation structures (e.g. defence walls, stop banks) on inundation. The inundation mapping therefore included a process of adding in structures from the New Zealand Inventory of Stopbanks (Crawford-Flett et al., 2022). With these adjustments included in the inundation mapping it was nevertheless found that there is a relatively large numbers of farms, and associated capital items, subject to severe inundation risk, even at the present time. For the most part we believe that this likely represents incomplete coverage of defense structures in the national inventory, rather than farms operating presently under high risk. In order to avoid the new NCIM overestimating land use change in the immediate to near future due to this high inundation risk to certain farms, the pragmatic approach has been to simply assume that farms located within drainage scheme areas (see preceding bullet point) will not be subject to significant damage to capital assets from inundation, nor will these farms suffer insurance retreat (see Section 2.3.3). In reality, the design level of individual structures will vary, and some inundation events may well overwhelm certain defence structures. We have, however, been unable to take into consideration these potential outcomes, nor the increasing severity of such outcomes under SLR, in this case study, given the nature of the data available.

5 Developing Model Inputs

5.1 Generation of representative farms

Our new Natural Capital and Inundation module operates on the farm scale. As no existing national data set describes all farm boundaries, a representative data set was generated to provide a synthetic yet sufficiently realistic and spatially explicit representation of agricultural businesses for analysis.

5.1.1 Generation of Representative Farm Properties (boundaries and land use)

The creation of representative farms was a multi-step process designed to aggregate individual land parcels into coherent farm units that align with official regional business statistics. The primary input datasets included LINZ property titles (Land Information New Zealand, 2024), LUCAS land use data (Ministry for the Environment, 2024), Statistics New Zealand SA1 statistical boundaries (Stats NZ, 2024a), and corresponding business demography data (ANZSIC business counts) (Stats NZ, 2024b).

The process began by assigning a predominant land use to each individual LINZ property title by sampling the most common value from the LUCAS land use raster within its boundary. These parcels were then linked to their corresponding SA1 area and assigned an ANZSIC industry code, connecting them to official business counts. The central challenge was reconciling the number of land parcels with these business statistics. The analysis leveraged a key feature of the Stats NZ data, which provides counts of business locations (Geographic Units or 'GEOs') rather than unique enterprises. This aligns with the model's approach of creating farms that do not span SA1 boundaries, as a single enterprise with multiple locations is already counted in each SA1. To group the parcels into farms, k-means clustering was applied. For example, in an SA1 with 20 dairy-classified parcels but only 5 official business locations, the algorithm grouped the geographic centroids of the 20 parcels into 5 distinct spatial clusters.

For the technical specifications of the clustering, the base R `kmeans` function (Hartigan-Wong algorithm) was used, with the number of clusters (k) set dynamically to the official business count for the relevant ANZSIC-SA1 pairing. The clustering relied on the Euclidean distance metric and, by default, employed only one random start and a maximum of ten iterations for each run.

To ensure all productive agricultural land was accounted for, a final rule was applied: if a land use was present within an SA1 but no business count was recorded, a single representative business was assumed to exist. The result of this process was the assignment of a unique farm ID to each parcel, with the collection of all parcels sharing the same ID constituting the boundary of one representative farm.

5.1.2 Selection of farms for case study

The national dataset of representative farms was then filtered to include only those properties relevant to the case study of rural coastal lowlands. This was achieved by applying a spatial filter to select farms intersecting with a "processing corridor" defined by combining all land below a 30-metre elevation contour with a 500-metre buffer inland from the current coastline. This ensures the analysis is constrained to the most vulnerable agricultural areas.

5.1.3 Farm natural capital

As described in Section 2.2.2, losses of land contained within farms due to both rising seas and episodic inundation are considered when calculating future farm production and earnings/EBITDA. Recognising that not all land is equal, and that some land within a farm will be more or less productive than other land, we have generated a proxy metric of natural capital per ha that is used when assessing a farm's relative loss in production capacity over time.

The per ha proxy measures of natural capital are generated by first intersecting the farm polygons with a national Land Use Capability (LUC) dataset (Manaaki Whenua, 2024). The LUC dataset defines the land's inherent **capability** based on physical characteristics. A specific pasture productivity rate (in tonnes of dry matter per hectare), derived from the modelling work described by Amies et al. (2021), was assigned to each subdivided parcel based on its farm ID and LUC class using the national dataset from Manaaki Whenua (2024b). The total baseline pasture production for each farm was then calculated by multiplying its partitioned sub-areas by the respective pasture production rate. The proxy measures assigned to each of the land areas within farms also provide the basis for quantifying future net losses in farm natural capital upon sea level rise and coastal inundation.

5.1.4 Farm transition potentials

As described above, the modelling represents a simplified version of reality with just four farm types possible for each farm, listed in order of land use intensity: (1) dairy cattle farming, (2) sheep and beef farming, (3) cut and carry farming and (4) abandoned land. Although it is possible for sheep and beef farms to chose to transition to higher intensity farms, it is not a focus of this study to consider increasing land use intensity. We also note that in the real world there are certain barriers that may exist, particularly in terms of policies to avoid increasing greenhouse gas emissions and freshwater contaminants. We have therefore assumed that no farm can transition to dairy cattle farming, or in other words, the only dairy cattle farms are those that exist at t=0. It is assumed, however, that dairy cattle farms can transition to any of the other three land types. Sheep and beef farms can transition to either cut and carry farms or abandoned land. Similarly, cut and carry farms can transition to sheep and beef farms or abandoned land.

See also Appendix A.2 for a mathematical description of the transition potential matrices.

5.1.5 Farm financial accounts

For each synthetic farm , financial accounts were developed for the two farm types - sheep and beef farming and cut and carry farming. In addition, for farms that commence as dairy cattle farms, financial accounts were also developed for the dairy cattle farming operation. For each farm type, the financial accounts are created to be consistent with the income and expenditure definitions in the latest national accounts supply and use tables (e.g. 199 commodity definitions - see Stats NZ (2021)).

- *Dairy cattle farms*: Market Economics Ltd has developed supply and use tables for each region in New Zealand for the year ending March 2020 (see methodology in Smith et al. (2015)). These accounts cover 109 industries, with dairy cattle farming being amoung the individual industries. The process of developing financial accounts for dairy cattle farms in the case study involved disaggregating the respective regional supply and use account for dairy cattle farms. For each region, the industry accounts were split first into farms in the case study versus farms outside the case study, based on the number of farms in the case study compared to the total count of farms in the region (Stats NZ, 2024). The financial income and expenditure accounts where then disaggregated further to the farm scale by assuming simply that the income and expenditure per ha is uniform across all case study farms located in the same region.

- *Sheep and beef farms*: Sheep and beef farms span a greater range of land types than dairy cattle farms and can vary quite substantially in terms of operation. For example, large and extensive high country farms are likely to have quite substantially different income and expenditure accounts from smaller low-lying farms. A different approach has therefore been taken to the generation of farm financials for the synthetic sheep and beef farms. The Sheep & Beef Farm Survey (Beef + Lamb, 2025) produces example farms for eight different farm classes, the estimated number of commercial sheep and beef farms in each class, along with a description of the classes contained within each New Zealand (aggregated) region. Each farm in the study area is allocated to one of the eight farm classes. To do this, we use the size of the farm, and the relative distribution of the classes in the region in which the farm is located to estimate a probability that a synthetic farm is contained within each farm class. Random number generation is then used to finalise the selection of the farm class for each farm.

  Once a synthetic farm is assigned a farm class, it is simply assumed that the per hectare costs and revenues for the example farm of that relevant class applies to the synthetic farm.

  Finally, the costs and revenues are translated to the categories used in the national supply and use tables.

- *Cut and carry farms*: The purpose of this farm type is to include a land use that allows for revenue to continue to be generated, without substantial risks to expensive capital items. There are likely to be a variety of options that could be tested. We have chosen to look at a cut and carry operation being informed by previous projects investigating freshwater policy options. In this previous work, land use options mooted by experts for land set aside as flood plains had included cut and carry operations. As part of a recently completed Endeavour Programme investigating no-stock land use options for volcanic locations, an example set of per hectare financial accounts was developed for maize silage operations that involve an annual rotation each of maize and grass silage (Perrin Ag , 2023). We have relied on these per hectare accounts to generate the income and expenditure accounts for cut and carry operations. Since, however, maize is generally not suitable to coastal locations (MPI, Plant and Food Research, Manaaki Whenua, 2023) we have simply assumed two rotations of grass for the cut and carry operations.

  It is unlikely that entire farms will be suited to cut and carry operations. We have simply assumed that the area of a farm able to grow grass silage is the equal to the hectares within the farm that is high producing land (LUC class 1-3) or 20% of the farm area, whichever is greater.

The final step in the generation of the farm financial account is to interrogate each expenditure line item and assign a proportion of that expenditure that is fixed versus likely to vary with either changing farmed area or production levels. The breakdown of expenditure in this way is necessary to track changes in future farm financials (see Section 2.2.1).

5.1.6 Farm critical capital and risks to that capital

The need to renew or replace expensive capital items, which we term here 'critical capital' is an important consideration in the modelling in that it may trigger land use change (see Sections 2.3.2 and 2.3.3). Below is a description of the way in which critical capital items were identified for each of the farm types.

- *Sheep and beef farms*: Sheep and beef farms generally exhibit relatively low capital investment and often that investment is dispersed among many items rather than a single or few very expensive items. As such, we have not deemed there to be any specific built capital that quantifies as 'critical capital' for the modelling. We do, however, acknowledge that the stock carried on farms represents a significant portion of the assets of a farm, and if risks to stock become sufficiently large, it may induce farmers to re-evaluate their landuse. During flooding events farmers will endeavour to move stock within a farm to avoid risks to animal welfare, so risks to stock will often be quite low. We have nevertheless assumed that if a high threshold of land is subject to flood risk, then effectively 'critical capital' is at risk. An initial assumption of 80 % of land under flood is used. Given that stock will generally be of varying ages with replacement/renewal occurring continuously rather than at a discrete time we have not considered it necessary to include the time of critical capital renewal as a potential threshold for sheep and beef farms (i.e. replacement life cycle set to 1000 years).
- *Dairy cattle farms*: We have deemed dairy sheds to be critical capital items for dairy cattle farms. As there is no national data set for the location of critical farm infrastructure, a proxy method was used to identify a representative location for the dairy shed on each dairy farm. A rules-based analysis was performed to select the most probable building from a national building footprint layer based on a weighted score of size and proximity to the nearest road, focusing the search on the largest contiguous parcel within each farm. The centroid of this selected building was used as the point location for that farm's critical capital. To enable the model to simulate land use change when capital is due for renewal, the initial age of critical capital at the start of the simulation ($t = 0$) was assigned based on a set of assumptions. The average replacement lifecycle of a dairy shed was assumed to be 50 years. At the simulation start time, the existing stock of capital was assumed to have a uniform age distribution. Each representative dairy farm was therefore assigned a random capital age by sampling from a uniform distribution between 0 and 50 years. In addition to dairy sheds, we have assumed that dairy stock constitute critical capital for farms, following the same reasoning and approach as used for stock on sheep and beef farms.
- *Cut and carry farms*: The very purpose of including this farm type in the modelling was to have a land use option available that does not entail high risk of damage to costly capital items. Thus no critical capital are identified for this land use.

As described in Sections 2.3.2 and 2.3.3, if critical capital items are up for renewal or damaged by an inundation event *and* the risk to these items is no longer considered acceptable to justify rebuilding or replacing, then this may induce change to another land use. Although the phrase 'insurance retreat' is used above to denote the threshold where insurance is no longer available, we can also think of this threshold as more generally identifying the probability threshold where risk is no longer deemed acceptable. So while farmers may not necessarily insure stock, and some farmers may not even insure dairy sheds, the threshold is still deemed relevant in terms of representing a threshold of unacceptable risk.

In the real world, the probability of damage where risk is unacceptable will depend on individual land owners and insurers and their risk appetites. For the purposes of this national study, however, we have simply looked for a general probability threshold to apply in a uniform manner across all farms. We note that previously an annual return probability of 2 % (or greater) has been applied as a general assumption regarding when insurance may start to be unavailable for capital items (Eaves, 2022; Reguero et al., 2020), and so this has also been applied in this study as a starting point for farms outside of drainage and defence schemes. No insurance retreat is assumed for farms within drainage and defence schemes (see Section 4.4).

5.1.6.1 Farms subject to drainage and defence schemes

To enable the model to simulate the collective nature of drainage management, a set of hypothetical drainage schemes was defined through a multi-step geospatial process. This process ensures that farms are grouped into logical, hydrologically-defined units where the economic viability of drainage can be assessed collectively.

1. **Delineating Susceptible Land:** The process began by creating a comprehensive 'poor drainage susceptibility' layer. The primary input for this was the national 1-in-2-year Annual Recurrence Interval (ARI) coastal flood dataset. Crucially, this inundation modelling already incorporates stopbank data from the New Zealand Inventory of Stopbanks (NZIS), which protects some low-lying areas from flooding in the model (Paulik et al., 2023). While protected from direct inundation, these areas would still require drainage. To ensure these zones were captured, the ARI data was combined with all land areas situated below the modelled Mean High Water Springs (MHWS) line, which acts as a proxy for this low-lying, protected land. The methodology for modelling the inland extent of MHWS is described in Section 5.2.2. This combined layer represents all land vulnerable to either direct coastal inundation from frequent storm events or poor gravitational drainage due to low elevation relative to sea level.
2. **Defining and Assigning Hypothetical Schemes:** The resulting national susceptibility polygon was spatially clustered to isolate large, contiguous areas with a high requirement for drainage, identifying zones where communal infrastructure is most critical. A total of **49 distinct polygons** were defined from this analysis, with each polygon representing a single, hypothetical drainage scheme for the purposes of the model. Representative farms were then assigned to one of these 49 schemes based on their location. This approach treats all properties within a given scheme boundary uniformly. This simplification reflects the practical challenges faced by councils in applying highly differentiated drainage rates and is a necessary concession to the geospatial processing requirements of a national-scale analysis.

This methodology is crucial for the behavioural and economic modelling framework. By grouping farms into schemes, the model can simulate the decision to abandon drainage as a collective outcome. As detailed in Section 2.4.3, the failure of a scheme is triggered when a sufficient proportion of its member landowners find it economically unfeasible, capturing the real-world dynamic where the loss of communal infrastructure affects all properties within its service area.

5.2 Methodology for quantifying direct impacts to farms from SLR

5.2.1 Quantifying land inundation

The direct physical impacts of coastal flooding were quantified by processing raw inundation raster data from NIWA (Paulik et al., 2023), which was provided in two tiers based on the underlying elevation data: high-precision LiDAR-based data and lower-precision SRTM-based data. The analysis was conducted for a range of Annual Recurrence Intervals (ARIs), including 2, 5, 10, 20, 50, 100, and 200-year events; higher return intervals available in the source data were excluded. A systematic workflow was used to convert this raw data into consistent vector flood polygons for each scenario.

1. **Mosaicking:** Individual raster tiles were stitched into seamless national layers for each scenario using Virtual Rasters (VRTs).
2. **Thresholding:** The raster depth values were converted into a binary "flood" vs. "no-flood" classification. Any area with a modelled water depth greater than 5 cm was classified as inundated. This threshold provides robustness by helping to exclude areas of minimal water depth that could be attributable to noise in the underlying elevation data, ensuring only depths of practical significance were classified as 'impacted'.
3. **Data Fusion:** The LiDAR and SRTM datasets were merged, prioritising the higher-quality LiDAR data in any areas of overlap.
4. **Vectorisation:** The final merged binary raster for each scenario was converted into a vector polygon layer, representing the dissolved inundation extent.

These final flood polygons were intersected with the representative farm layer. This process split each farm parcel into its 'impacted' and 'not impacted' components for every SLR and ARI combination, allowing for a precise calculation of lost pasture production for use in the model.

5.2.2 Coastline Retreat Modelling

To model permanent inundation from the retreat of the Mean High Water Springs (MHWS) coastline, a specific approach was developed for this study. The objective was to produce a map of the future MHWS for each climate scenario, accounting for both sea-level rise and hydrological connectivity.

The primary input datasets for the model included a high-resolution coastal DEM, constructed for the study by programmatically downloading and mosaicking the latest 1-metre LiDAR DEM tiles from the LINZ AWS S3 Open Data service (Land Information New Zealand, 2024c). Other key datasets were New Zealand's general coastline outline from the Topo50 series (Land Information New Zealand, 2024b), the detailed current MHWS coastline from LINZ (Land Information New

Zealand, 2021), and localised sea-level rise projections from the NZ SeaRise programme (Naish et al., 2024), which crucially include the effects of local Vertical Land Movement (VLM).

For each climate scenario, a target future sea level was calculated for thousands of points sampled at a 2-kilometre spacing along the current coastline. To assign a local sea-level rise projection to each of these points, a nearest neighbour spatial join was performed, linking each coastline point to the geographically closest site from the 2-kilometre resolution NZ SeaRise dataset. The final `final_water_level` was then calculated as the sum of the current MHWS elevation plus this assigned sea-level rise value.

A topography-aware cost-distance analysis was then used to propagate this water level inland. This method simulated the "path of least resistance" for water to travel across the landscape. To make this computationally feasible, the analysis was first performed on a coarse-resolution digital elevation model (500 meter) to map broad connectivity pathways, before being upscaled to a high-resolution (1 metre) grid to create a detailed final "water surface". The new coastline was then delineated by identifying all land where the ground elevation was higher than this simulated water surface. This process also resulted in small, isolated low-lying polygons (holes) within the landmass that were below the local MHWS level. A final post-processing step was therefore applied to fill these holes where they were not hydrologically connected to the main body of the sea. The resulting "dry land" polygons thus represent a continuous terrestrial landmass and were used to quantify permanent land loss for each farm. The removed low-lying holes were used in the next section as contributing to drainage costs.

5.2.3 Changing Costs for Defence and Drainage Schemes

To quantify the area on each farm requiring drainage under various sea-level rise increments, the representative farm properties likely to be in a drainage scheme were allocated to the 49 hypothetical drainage scheme polygons. To do this, a multi-step geospatial workflow was used:

1. First, an optimised query identified properties **fully contained** within a drainage zone, assigning their entire area a status of "requires drainage."
2. Next, properties **partially intersecting** a drainage zone were isolated. These properties were precisely split along the drainage boundary, creating two new components: one inside the zone ("requires drainage") and one outside ("no drainage required").
3. Finally, all properties located entirely outside the drainage zone were assigned a status of "no drainage required."

This partitioning process ensured that the specific area on each farm requiring drainage was accurately calculated. With these areas defined, the corresponding mean elevation for each parcel was derived from the national Topo50 digital elevation model (DEM). These two inputs, area and elevation, were then used to calculate the financial burden of drainage.

The cost of this drainage was calculated within the economic model using a data-driven cost function. This function was derived from a statistical analysis of drainage scheme rates from three regional councils: Bay of Plenty Regional Council (Bay of Plenty Regional Council, 2024), Environment Canterbury (Environment Canterbury, 2024), and Waikato Regional Council (Waikato Regional Council, 2024). A preliminary analysis of this data confirmed a non-linear "hockey-stick" relationship between land elevation and drainage cost. To capture this, a Non-Linear

Mixed-Effects Model was developed. While the model confirmed that most cost variation occurs at the level of the individual scheme, a generic average cost curve was derived from the model's fixed effects. For this study, the following function was used to predict the drainage rate:

$$Rate = e^{(3.16+1.36\times e^{-0.23\times \mathrm{elevation}})} \tag{5.1}$$

where the *Rate* is in dollars per hectare and the *elevation* is in metres relative to the 2016 vertical datum, as derived from Topo50 series data.

5.3 Damage to critical capital and insurance retreat

For farms located inside of drainage and defence schemes, the probability of critical capital damage is deemed to be zero (see 4.4 for explanation). For farms outside of drainage and defence schemes, the probability of inundation at the precise location of the dairy shed was determined from a spatial analysis "braketing" each shed's location between the flood zones of the most frequent event that *does* inundates it, and the most severe event that *does not*. A precise probability was then calculated by linearly interpolating based on the shed's physical distance to these two flood boundaries. This `inundation_prob` is the metric compared against the model's insurance retreat threshold.

Over the course of the model run, inundation events are also generated, with the size of these events (ie return period) generated from sampling within a uniform distribution. The size of these events, relative to the assigned inundation probability of each dairy shed, determines whether each dairy shed is damaged.

To determine whether animal stock 'critical capital' is damaged under an event, the module simply sums up the land that is inundated under the inundation event and determines whether this exceeds the 80% of the farm land area (with all land measured in biomass production units). The minimum return period that meets the 80% threshold is also used to assign the probability of critical capital damage, which is then compared with the insurance retreat threshold.

6 Results

6.0.1 Validation of the Drainage Cost Model

To validate the predictive power of the generic drainage cost function described in the methods, a group-level cross-validation was performed. The dataset, comprising numerous individual drainage schemes, was split into a training set (containing 80% of the schemes) and a testing set (containing the remaining 20% of unseen schemes). The non-linear model was trained exclusively on the training data, and its ability to predict drainage rates was then evaluated on the testing data.

The model's performance was primarily assessed using Root Mean Squared Error (RMSE), which measures the average prediction error. The validation resulted in an RMSE of $19.20 per hectare on the testing set. While the model's ability to explain variance on unseen schemes was limited due to the high variability between individual schemes (a finding consistent with the initial model fitting), the RMSE provides a practical measure of the expected prediction error. This level of error was considered acceptable for the study, given that the asymptotic model form was chosen primarily to reflect the physically-based expectation that drainage costs increase non-linearly at very low elevations. The final generic cost function curve is shown in Figure 6.1.

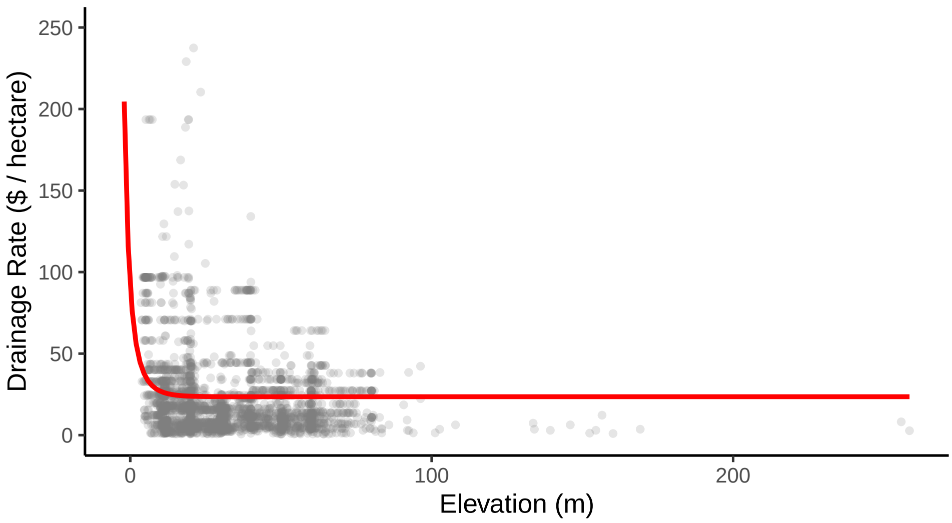

Figure 6.1 Plot of the generic drainage cost function, showing the modelled non-linear relationship between elevation and drainage rate. Elevation is measured in metres relative to the 2016 vertical datum, derived from Topo50 series data.

6.0.2 Changes in Farm Performance

The Natural Capital and Inundation Module contains some stochastic elements. In terms of impacting agriculture futures, the most important stochastic elements would appear to be the realisation of inundation events damaging critical farm capital, which then can trigger a change in land use. Due to the stochastic nature of the model, each model run will likely generate a slightly different result from previous model runs, as illustrated from ten runs of Scenario 2 (Figure 6.2). For the purposes of reporting results in the remainder of this report, we have chosen a median simulation in terms of impacts for each of the respective RCP Scenarios.

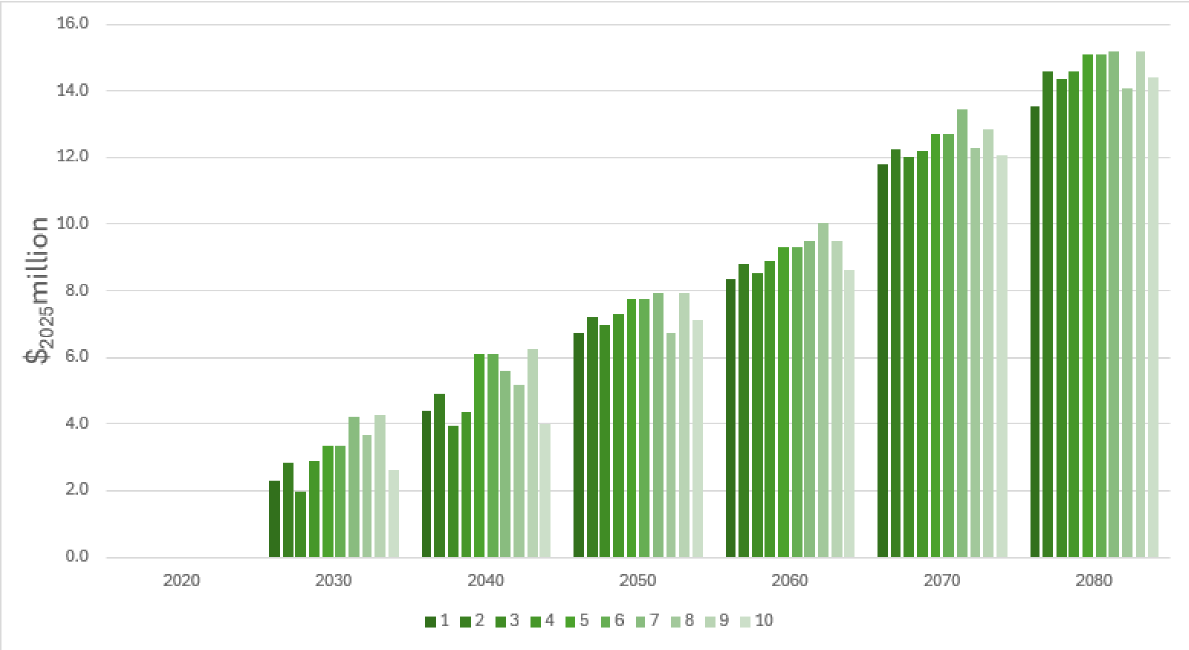

Figure 6.2 Net loss in farm performance (EBITDA) across all farms for the Moderate Scenario (RCP7.0) and under 10 model simulations

A summary of the scale of the results generated by the Natural Capital and Inundation Module, and how these results vary between the RCP scenarios is provided in Figure 6.3. Reflecting the underlying trajectories of sea level rise under the three RCP scenarios, it is only post 2050 that there is a noticeable difference between the scenarios. Even out as far as 2080, the estimated impacts at the national scale are relatively modest, being $\$_{2025}$11.7 million losses in annual EBITDA across all farms under the optimistic scenario (RCP 4.5), $\$_{2025}$14.6 million under the moderate scenario (RCP 7.0) and $\$_{2025}$19.5 million under the pessimistic scenario.

The national level results are de-compiled by aggregate region, and by aggregate industry (ie (1) sheep, beef and forage farms and (2) dairy cattle farms) in Figures 6.4 and 6.5. For these Figures we have focused just on the moderate (RCP 7.0) scenario. The regional grouping is also selected so that each aggregate region contains between 800-900 case study synthetic farms.

These figures demonstrate that the losses for dairy cattle farming are around four times as great as the losses for the sheep, beef, forage farms (e.g $\$_{2025}$16.6 compared to 4.4 million in 2080). This reflects the location of dairy cattle farms on low-lying coastal areas, as well as the generally higher starting EBITDA for these farms. It can also be noted that in some cases there is land use change out of dairy cattle farming into the other industry - hence a loss for the dairy cattle farming industry category is a gain for the other.

The largest losses, overall are in the Waikato Region (28 percent of the national impact at 2080). This region also has the greatest concentration of impacts in dairy cattle farming (e.g. 95 percent of its total impact in 2080). The Rest of North Island Region has the most even split of impacts between the two aggregated industry categories.

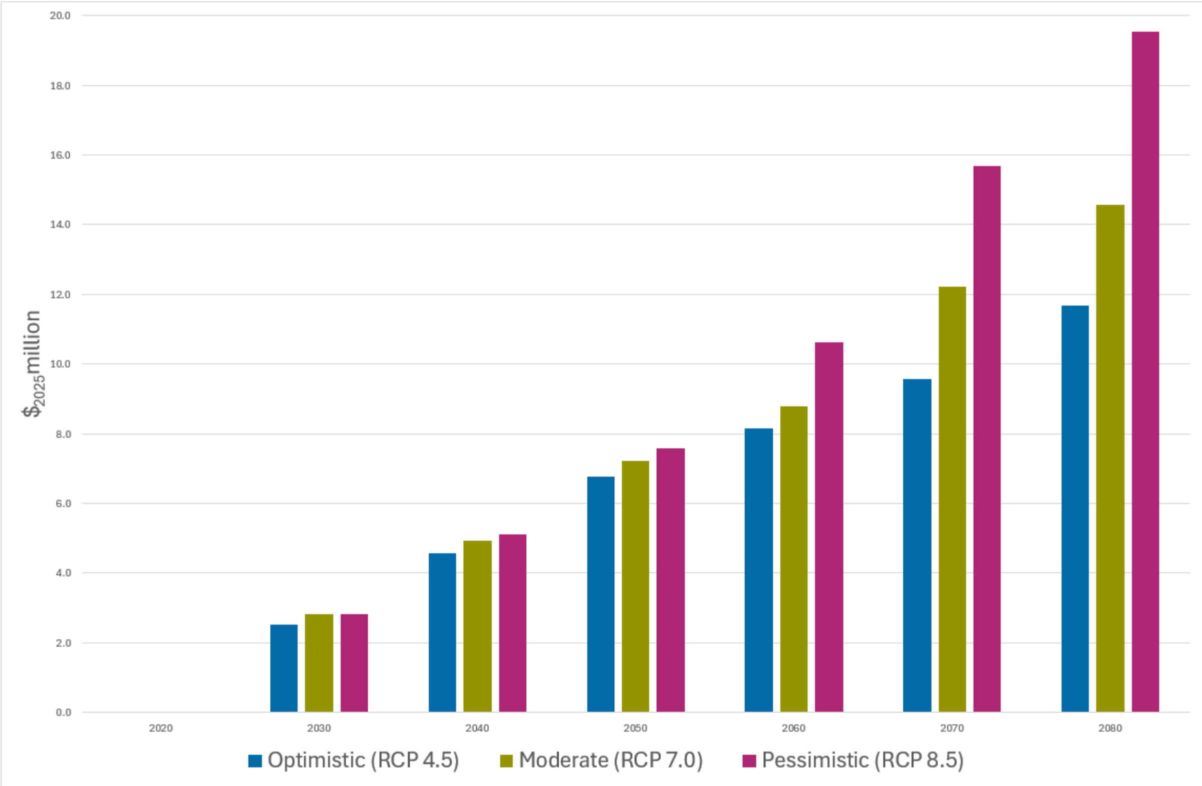

Figure 6.3 Net loss in annual farm performance (EBITDA) across all farms.

It was observed during the developing and testing of the Natural Capital and Inundation Module that there are many farms in the case study located at low elevations relative to sea level, and even during the initial years of simulation quite significant land use change (to low risk farms or even abandonment) would occur. However once account was taken of drainage and defence schemes, the occurrence of land use change during model simulations became significantly less. As shown in Table 6.1, just 3 percent of farms underwent land use change over the course of the entire simulations, with the results varying little between simulations/RCP scenarios.

Table 6.1 Farms undergoing land use change under different RCP scenarios

Region	Optimistic (RCP 4.5)	Moderate (RCP 7.0)	Pessimistic (RCP 8.5)
1 Northland	18	18	18
2 Auckland and Bay of Plenty	14	14	14
3 Waikato	26	27	28
4 Rest of North Island	49	50	51
5 Rest of South Island	31	31	31
New Zealand	138	139	142
Proportion of Case Study Farms	3%	3%	3%

A key conclusion is that much of the agricultural land subject to risks from sea level rise is likely to be already located within an existing drainage and defence scheme. Provided that these schemes are maintained and upgraded as appropriate, the extent of de-intensification of agricultural activities in response to increasing risks is likely to be relatively small at a national scale.

For land that is subject to defence and drainage, the modelling has also produced relatively

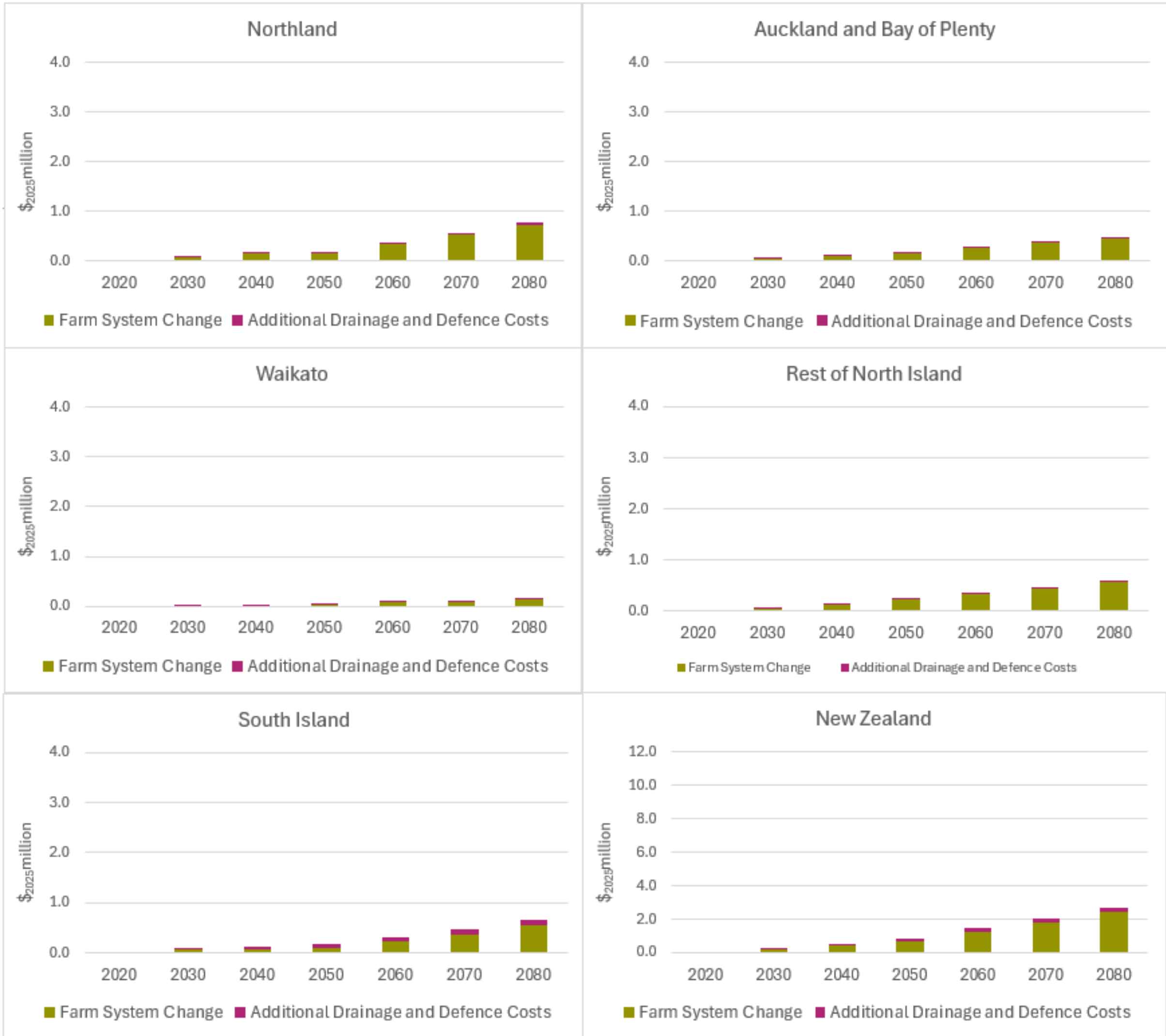

Figure 6.4 Net loss in EBITDA for sheep, beef, forage farms, by region (moderate scenario)

modest increasing drainage and defence costs over time, in response to sea level rise (refer to shaded pink bars in Figures 6.4 and 6.5). Overall these increasing costs are estimated at just an additional 200 thousand per annum at 2040, rising to an additional 0.5 million per annum in 2080. Due to these relatively modest cost increases, none of the modelled drainage schemes are abandoned under any of the simulations.

Together these two key factors underly the relatively small economic impacts that have been generated by the modelling at the national scale.

6.0.3 Sensitivity to Increasing Drainage Costs

Developing a drainage cost function for this study was challenging given the absence of a comprehensive national dataset and the great variation in drainage costs between schemes that were considered. Nevertheless, drainage costs, and the way in which these may increase over time is an important consideration for low-lying agriculture activities.

It has therefore been considered prudent to undertake some sensitivity analysis of drainage costs

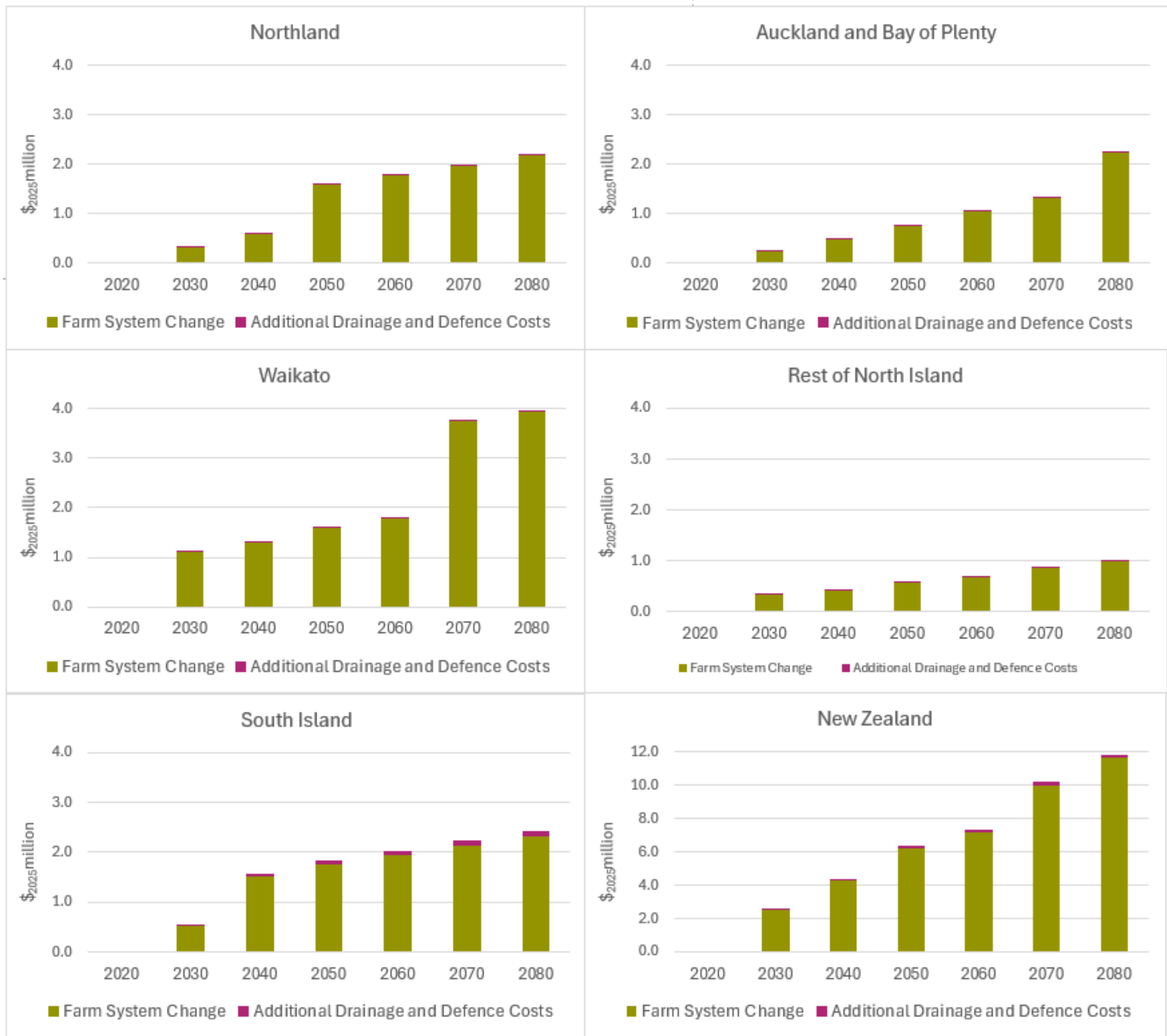

Figure 6.5 Net loss in EBITDA for dairy farms, by region (moderate scenario)

in the modelling. This has been undertaken simply by testing model simulations where the existing drainage cost function, ie as specified in Section 5.2.3, is multiplied by a factor of 2 and then 3. A comparison of the model simulations is provided in Figure 6.6. The results indicate that the drainage cost estimates would need to be significantly higher than those implemented in the model for it to generate a more than minor change in the modelling results. Even when the drainage cost function is increased by three-fold, the model produces results of only three drainage schemes being abandoned. These abandoned schemes are all located in the Rest of North Island and involve relatively few farms.

Nevertheless, it is important to note that the generic and nation-wide drainage cost function applied in this modelling is not capable of representing some of the nuances of individual drainage schemes located across the country. There will also be considerations that go beyond costs when considering the future of drainage schemes and the way in which these are repaired and upgraded over time.

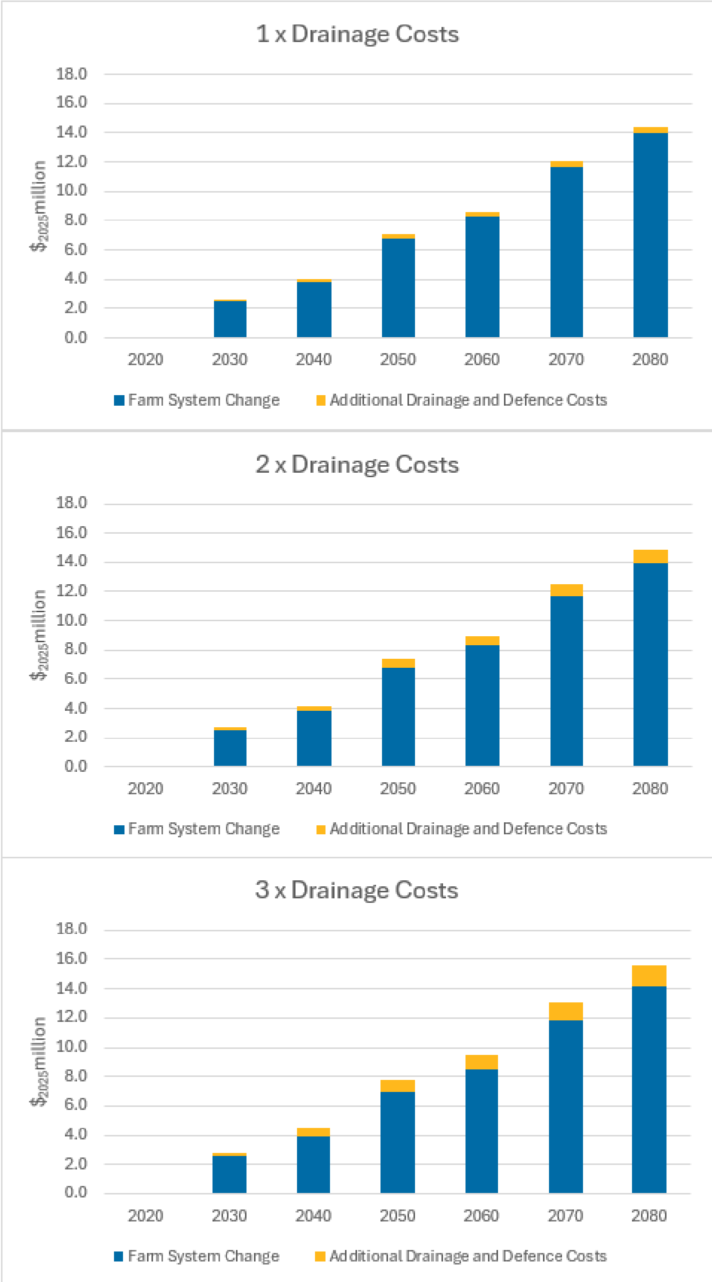

Figure 6.6 Net loss in EBITDA across all farms with differing drainage cost functions applied

6.0.4 Economy-Wide Impacts

The MERIT analysis provides an indication of the scale and distribution of impacts once flow-on effects and interrelationships in the economy are considered. The annual net changes in value added from MERIT are shown in Table 6.2 according to a ten sector categorisation. Note that the MERIT modelling extends out only to 2050 and is based on a median simulation from the moderate (RCP 7.0) scenario.

An interesting outcome of the MERIT modelling is that although the initial impacts occur in the agriculture sector (specifically dairy cattle, sheep/beef and forage farms), the internal dynamics of the model cause these impacts to be somewhat compensated by small increases in prices for agricultural products, and reallocation of capital to agriculture from other sectors, thereby enabling the agricultural sector to regain losses in value added at the coast. Some agricultural activities even experience a net gain in production due to this reallocation of capital. Thus at the sectoral level (ie not just considering the case study farms), overall changes for agriculture are small.

The results from the MERIT modelling indicate that much of the impacts from sea level rise are felt in the processing industries that depend on supply of products from impacted farms (ie meat and dairy product manufacturing). Due to the relative declining profitability of these manufacturing activities over time, alternative activities (e.g. other food manufacturing) are a little more attractive for investment and thus experience a small growth in value added (e.g. $1.1 million annual in 2050). The experience of (1) small increases in prices by consumers for agricultural products which depletes available income for other consumption, (2) losses in income from impacted farms and manufacturing activities, and (3) losses in demands for inputs to production from impacted farms and manufacturing activities, have complex flow on effects in the economy. Ultimately the model shows a loss in value added that is quite widespread across the service industries.

Table 6.2 Net changes in annual value added by sector ($\$_{2025}$million)

Sector	2020	2030	2040	2050
Agriculture	0	-0.7	0.7	-0.3
Other primary	0	0	0	-1
Meat product manufacturing	0	-0.2	-0.6	-1.1
Dairy product manufacturing	0	-1.1	-6.3	-8.3
Other food manufacturing	0	0.2	0.7	1.1
Other manufacturing	0	0	-0.1	-0.6
Utilities and construction	0	-0.7	-2.9	-7.2
Retail and hospitality	0	-0.2	-0.9	-2.2
Government, education, health	0	-0.6	-2.0	-5.0
Other services	0	-1.1	-3.5	-8.8
Total	**0**	**-4.5**	**-14.9**	**-32.4**

Table 6.3 provides similar information to Table 6.2, except that instead of reporting net changes in value added as an annual change at different points in time, the net changes are accumulated over the model simulation. In this way, the sum of all changes can be considered. Given that it is common practice to discount impacts that occur in the future, Table 6.3 repeats the results, but this time applying discount rate of 6 percent per annum. Without discounting, the cumulative net change in value added across all industries at 2050 is $329 million, and this reduces to $125 million once discounting is applied.

Table 6.3 Cumulative change in value added by sector, no discounting ($\$_{2025}$million)

Sector	2020	2020-2030	2020-2040	2020-2050
Agriculture	0	-1	-13	-13
Other primary	0	0	-1	-1
Meat product manufacturing	0	-1	-3	-11
Dairy product manufacturing	0	-2	-21	-94
Other food manufacturing	0	0	5	14
Other manufacturing	0	0	0	-4
Utilities and construction	0	-1	-19	-68
Retail and hospitality	0	0	-6	-21
Government, education, health	0	-1	-14	-47
Other services	0	-2	-26	-84
Total	**0**	**-8**	**-97**	**-329**

Table 6.4 Cumulative change in value added by sector, 6% per annum discount rate ($\$_{2025}$million)

Sector	2020	2020-2030	2020-2040	2020-2050
Agriculture	0	-1	-8	-8
Other primary	0	0	0	0
Meat product manufacturing	0	0	-2	-4
Dairy product manufacturing	0	-2	-12	-34
Other food manufacturing	0	0	3	6
Other manufacturing	0	0	0	-1
Utilities and construction	0	-1	-10	-25
Retail and hospitality	0	0	-3	-8
Government, education, health	0	-1	-7	-18
Other services	0	-1	-15	-32
Total	**0**	**-6**	**-54**	**-125**

7 Salinity

7.1 Background

A key caveat of the modelling undertaken in this study is that it is assumed that with business-as-usual practices, i.e. maintenance of drainage/defence schemes and upgrading of schemes as necessary, farm productivity can largely be maintained under rising sea levels. It is, however, worthwhile considering whether there may be issues impacting on farm productivity that are caused by sea-level rise, that cannot adequately mitigated by existing practices. In these regards, the potential of saltwater intrusion and salinisation of farms and water supplies is an important topic for consideration.

In the low elevation coastal zone, shallow groundwater frequently occurs in unconfined coastal aquifers (e.g. Bosserelle et al. (2022)). Sea-level rise can cause inland movement of the interface between fresh and saline groundwater in a process known as saltwater intrusion. For farmland where saline groundwater is close to the surface, capillary action can draw salty water up into the active root zone, leading to increased soil salinity and reduced crop yields. In the most extreme cases, previously productive farmlands may even become uneconomic and abandoned (Mondal et al. (2023)). The most obvious areas at risk from saltwater intrusion are those located at the fringe of the land-ocean interface. However the impacts potentially extend quite significantly inland (e.g. hundreds of metres) where gradual or marginal changes in productivity are difficult to detect (Su et al., 2025). Furthermore, land adjacent to water extraction/pumping and drainage infrastructure is also at risk in addition to the coastal fringes, as the saltwater/freshwater interface tends to be drawn closer to the surface at these locations (see e.g. Rasmussen). Importantly, drainage systems and groundwater extraction will often exacerbate the risks of saltwater intrusion across groundwater systems, as these lower the hydraulic pressure of freshwater, allowing denser saline water to push inland and upward into aquifers and soil (Su et al., 2025).

In addition to the direct impacts on vegetation and crops through soil salinisation, contamination of water supplies is a further important risk with sea-level rise, particularly for farms that reply on groundwater abstraction for irrigation and farm water supply. Potentially, contaminated water supplies can have impacts across wide spatial areas, extending across whole farms and also to non-farming activities.

In Aotearoa-New Zealand, and indeed globally, there is much to be learnt about these salinisation risks. Salt water intrusion will be driven by natural and anthropogenic factors that interact in complex ways that vary across space and time (Su et al., 2025). It is not yet possible to define the nature, extent and timing of salt water intrusion at fine spatial scales and under alternative sea-level rise scenarios, let alone define how these groundwater changes will impact on agricultural systems. Nevertheless, it is considered worthwhile in this study to undertake an exploratory exercise of simple what-if scenarios around salinisation to help highlight such risks and bring the topic to the forefront of conversations.

7.2 Exploratory Scenarios

For these simple, what-if scenarios we have considered just farms that are assigned to a drainage scheme under any of the simulations, ie drainage schemes as identified in Section 5.1.6.1. We have focused on land in drainage schemes mainly because these are locations of reasonably intensive agriculture and as noted above, drainage schemes are likely to intensify risks of saltwater intrusion.

As an indication of the scale or number of drainage schemes/catchments potentially impacted by saltwater intrusion, Bosserelle et al. (2026) have recently completed a national-scale assessment of near-surface unconfined coastal groundwater systems. They classified these groundwater systems as either 'head-controlled' or 'flux-controlled', with head-controlled being the most vulnerable to saltwater intrusion. They found that head-controlled systems accounted for around 36% of catchments but around 56% of coastal catchment area and are characteristic of most low-elevation coastal zones. For the purposes of this exploratory modelling it has therefore simply been assumed that 50% of drainage schemes will be impacted and these are selected simply based on random assignment.

To illustrate that salinisation impacts are unlikely to be evenly distributed across farmland in these drainage schemes, but rather more concentrated in certain areas, we have simply selected land mapped in the 2-year inundation return period at t=0 as a proxy for the most severely impacted land. This land will be low elevation and adjacent to coastlines and/or estuaries. Note that under these assumptions, and considering only 50% of the drainage schemes, the land impacted accounts for just 2.3% of the area of the coastal farms modelled.

The extent and timing of salinisation impacts are unknown. The impacts are also likely to vary across different catchments. For the purposes of these illustrative scenarios two simple options have been assessed: (1) all impacted land reaches a 20% loss of productivity by 2100 - i.e. the Lower Scenario, and (2) all impacted land reaches a 40% loss of productivity by 2100 - i.e. the Higher Scenario. The loss in productivity is assumed to gradually accrue over the next 80 years but the NCIM is only run out to 2080.

As shown by Figure 7.1, compared to the modelling without consideration of salinity scenarios, there is a substantial increase in impacts in relative terms - i.e. by 2080 under the Moderate RCP7.0 simulations the impacts are around 60% higher under the Lower Salinity scenario and 130% higher under Higher Salinity Scenario.

Although we can by no means conclude that these results are indicative of the extent of the economic impacts of salinisation - the results do demonstrate the high sensitivity of the economic outcomes to the extent and timing of potential salinisation impacts. We can note that the areas deemed impacted in these scenarios are relatively small, because (1) the number of drainage schemes identified across NZ is relatively few (with a critical clustering of low-lying land needing to be present before a 'scheme' was deemed present), and (2) because impacts for farms outside of the identified drainage scheme were not considered.[5] Yet the proportional increase in economic impacts due to salinisation are still significant.

This exercise underscores the importance of further research to assist in clarifying the nature and extent of salinisation risks for coastal lowlands. Since human activities can contribute to salt water intrusion, alongside sea level rise, it is essential to have comprehensive strategies

[5]It is also worth noting that when mapping land in the 2-year return period, if defence schemes were known this was taken into consideration in mapping the areas inundated- thus for some locations, large areas of low-lying land at the coastal fringe is not included in the mapped area

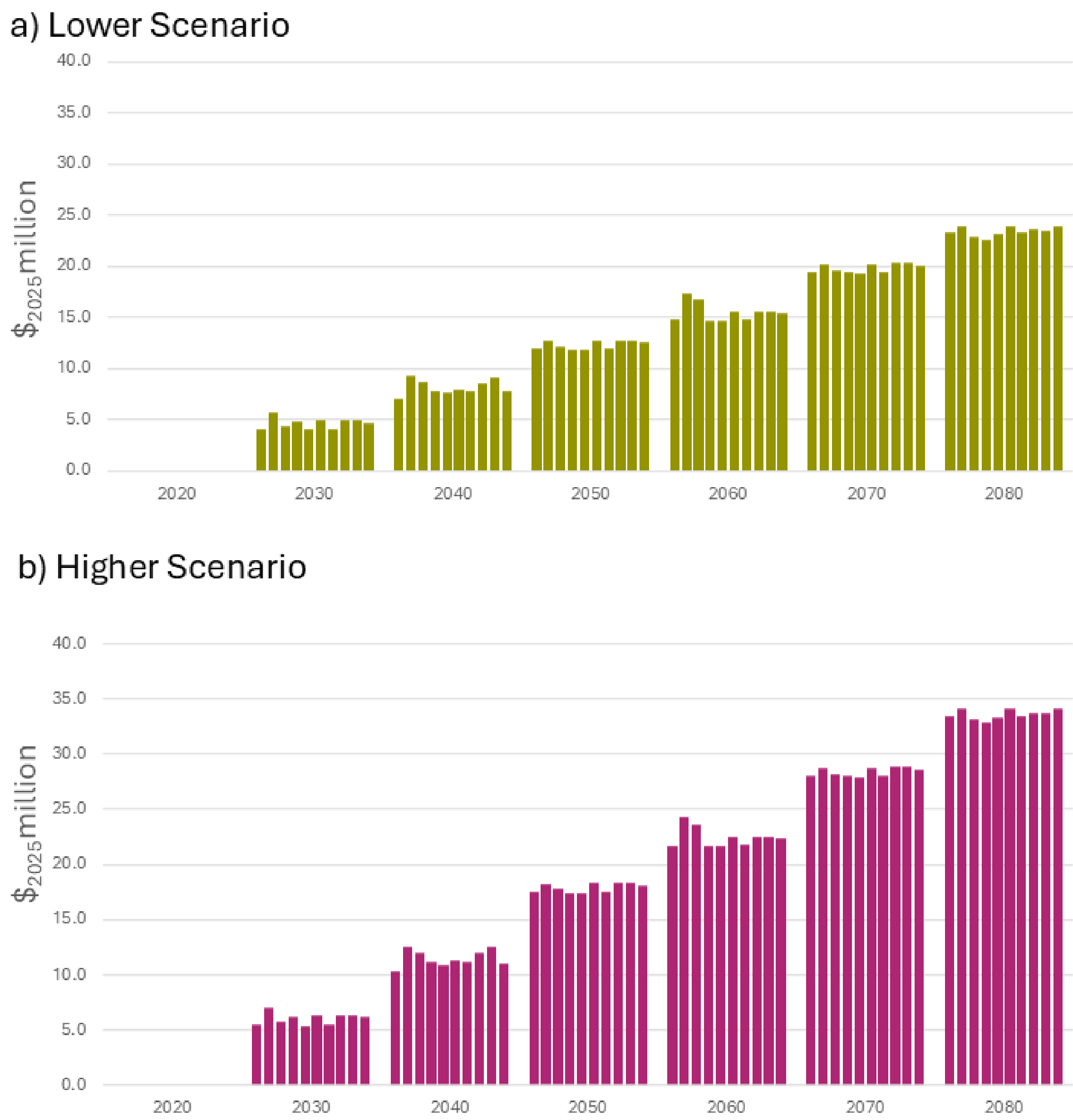

Figure 7.1 Net Loss in EBITDA for all farms under 10 simulations of a) the Lower Salinity Scenario and b) the Higher Salinity Scenario. Note: all other assumptions are as per the Moderate 7.0 Scenario.

(Su et al., 2025). Some of the mitigation options that have been suggested in the literature to address salinisation include engineering approaches to modify freshwater-saltwater interactions, application of amendments and cover crops to improve soils, through to switching to salt tolerant crops, soil-less agriculture (e.g. hydroponics) or non-agricultural uses (c.f Su et al. (2025)). Further research on the relevance of such options in the NZ context is pertinent.

8 Discussion and Conclusion

8.1 Summary

This technical study aimed to quantify the economic implications of SLR on Aotearoa New Zealand's coastal agricultural sector by integrating a New Natural Capital and Inundation Module (NCIM) with the MERIT Dynamic Economic Model. The modelling shows that, under assumptions of continued maintenance and upgrading of drainage and defence schemes, direct impacts from inundation and rising drainage costs remain moderate at the national scale.

Key findings include:

- Only a small proportion (about 3%) of farms are projected to undergo land use change over the simulation period, with much agricultural land most severely at risk from inundation and rising groundwater already protected by drainage and defence schemes.
- Economic losses in farm performance (EBITDA) are modest across all SLR scenarios, with dairy farms experiencing greater impacts due to their location and higher starting profitability.
- The largest regional impacts are concentrated in the Waikato region, primarily affecting dairy farming.
- Increases in drainage costs are projected to be manageable, and only extreme cost escalations would lead to scheme abandonment or significant land use change.
- The MERIT model shows that coastal farms bear the brunt of initial losses, at the sectoral level, price adjustments and capital reallocation mitigate these effects, resulting in moderate, distributed impacts across the wider economy.

However, the study also highlights that these results reflect only a subset of climate-related risks. Exploratory salinity scenarios—motivated by the potential for saltwater intrusion into shallow coastal aquifers—indicate that even limited areas of salinised land could substantially increase economic impacts - as the implications for farm profitability are not mitigated by business-as-usual practices. As such, further research to help clarify the nature, extent and timing of salinity risks, and the potential mitigation options, is warranted.

8.2 Limitations and Assumptions

The analysis is subject to several limitations inherent in a national scale study. The modelling excludes horticulture and other high value land uses common in coastal lowlands, meaning total economic impacts are likely underestimated. The assumption of continuous upgrading of drainage and defence schemes is a strong one; changes in funding, governance, or physical performance of these schemes could lead to more extensive de intensification than modelled.

A key limitation is the treatment of groundwater and salinity. As noted in Section 7, "it is not yet possible to define the nature, extent and timing of salt water intrusion at fine spatial scales," and the exploratory scenarios presented here are illustrative rather than predictive. Nonetheless, the magnitude of their influence on economic outcomes underscores the need for improved datasets, monitoring, and modelling of coastal groundwater systems. Salinity may represent a dominant future driver of agricultural change in some coastal catchments.

The study also focuses on long term changes in productive capacity and does not quantify losses to assets during episodic events, nor does it incorporate other climate related pressures such as extreme rainfall, drought, or emerging pests and diseases.

Overall, the findings provide a national level indication of the scale of impacts from SLR while emphasising that salinity and groundwater dynamics represent critical uncertainties. Addressing these knowledge gaps will be essential for developing robust adaptation strategies for coastal lowland agriculture.

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A Index of names and definitions

A.1 Subscripts and concordances

Most subscripts are described in Table A.1 on page 43. However, the natural capital types, and industry and commodity groupings can vary between different model applications and are described here.

Table A.1 Subscripts used in Natural Capital and Inundation Module

Subscript indices	Description
$i = [farm1, farm2, farm3....]$	Farms: each synthetic farm in the case study
$f = [farmtype1, farmtype2, ..., V]$	Farm Types: categories of farm types or land uses considered. Vacant land, V, is always included.
$p = [retper1, retper2, ...]$	Return Periods: inverse of annual probability of inundation event
$k = [luccondition1, luccondition2, ...]$	Land Use Change Conditions: the four conditions considered for determining whether a farm will change to a different farm type
$n = [1, 2, ...]$	Future Years: future years over which benefits and costs of drainage considered
$d = [d1, d2, ...D]$	Drainage Schemes: drainage schemes to which multiple farms belong

Table A.2 Farm Types

Name	Symbol	Description
$farmtype1$	d	Dairy cattle farming
$farmtype2$	sb	Sheep, beef and grain farming
$farmtype3$	g	Cut and carry operation
$farmtype4$	V	Vacant land

Table A.3 Land Use Change Conditions

Name	Description
*luccondition*1	Change in relative profitability
*luccondition*2	Capital up for renewal
*luccondition*3	Insurance retreat
*luccondition*4	Damage to critical capital

A.2 Key parameters and assumptions

The land use transition matrices, assuming a de-intensification pathway, are:

$$\mathcal{A} = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{A.1}$$

and

$$\mathcal{B} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{A.2}$$