Climate Change Impacts and Implications for New Zealand to 2100

Synthesis Report RA2
Lowland case study

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HIGHLIGHTS

- In the Bay of Plenty, there will be a likely increase in mean air temperature and number of hot days and dry days, increasing the risk of drought.

- There is likely to be more rain in summer and less in winter and spring.

- Sea level rise will affect the coastal zone around the Kaituna catchment, with 5,500 ha likely to be regularly inundated every couple of weeks during high tide (1.8 m above mean sea level) affecting the dairy industry and maize cropping.

- Change in pasture production is positive under all scenarios for both sheep and dairy pasture. The magnitude of the change is larger for dairy than for sheep. Total annual pasture growth increases by 1–5 % around mid-century and by 2–7.5% by 2100. Seasonal average growth rates show consistent, large increases in winter and spring, as expected under warmer conditions and an extended growing season.

- For forestry, simulations with constant CO_2, there were reductions in productivity of 4–20% for both 2055 and 2085 depending on the Representative Concentration Pathway (RCP) scenario. For simulations with increasing CO_2, growth increased by about 10–15% by 2055. The between-site variability was higher for the simulations with constant CO_2 than for those with increasing CO_2, with standard deviations by 2085 ranging from 3 to 7% for simulations under constant CO_2, which reduced to 2–3% under increasing CO_2. It is consistent with the general tendency for increasing CO_2 to have greater beneficial effects for plants growing under otherwise more stressful conditions.

- For maize silage, the impact of climate change yields was assessed considering model runs with or without adaptation of crop genotype and sowing dates. Model results indicate a higher risk of yield losses when sowing dates are not adapted. For these conditions, yield loss estimates increase from mid-century (5%) to the end of the century (12%). In contrast, by adapting sowing dates to a warmer climate (i.e. sowing early), yield losses were minimised and yield gains occurred for specific locations. Climate change impacts on silage yield were uneven across the catchment. More negative impacts were estimated in the northern lowlands, currently the most suitable area for arable cropping.

- Hayward kiwifruit production viability for the Te Puke area is projected to decrease steadily over time and becomes consistently marginal by the 2050s and non-viable by the end of the century. The key reason for this is the loss of sufficient winter chilling as the climate warms. However, other inland North Island regions and many parts of the South Island (particularly Canterbury) show an increase in viability (based purely on temperature) for this crop variety over the century.

- Land-use change in the catchment could be significant over the next century, and is projected to be affected by both the socio-economic pathways and climate change. The Shared Socio-Economic Pathway scenario chosen (SSP3) is projecting high log and sheep & beef prices compared with dairy prices. By comparing two land-use change models, we found that there is generally a shift from sheep & beef farming to forestry by the end of the century. High log prices cause forestry to increase beyond baseline levels in both models. However, discrepancies in model assumptions and structure meant that there were differences in dairy changes (opposite directions) and magnitude. Regardless, the consistent result of an increase in afforestation in the Kaituna by 2100 across all scenarios suggests environmental outputs such as GHG emissions and freshwater contaminant loads could be reduced over the next century, even if there is some intensification in the catchment.

- For the remaining swamps in the Kaituna, increased precipitation may induce a change in wetland type to a permanently wet state (e.g. ephemeral to swamp); a higher nutrient system (e.g. fen to swamp), or a more aquatic system (shallow water, pond or lake). Lower rainfall would increase pressure on obligate wetland plants and therefore vegetation types dominated by these species. Changes in rainfall periodicity or intensity will also have an impact, as it may increase the extent of wetland margins and thus favour facultative dryland species, many of which are alien weeds.

- An integrated assessment provided an overview of potential future impacts of both climate change and socio-economic changes. In the scenario that was investigated (high Representative Concentration Pathways (RCP), fragmented world), there is almost no attempt to curtail climate change on a global scale and only very limited, reactive local efforts. Costs of production would generally increase due to a need for increased environmental management for pest control and water shortages, with a higher risk for a decline in commodity prices due to increased global competition.

1 INTRODUCTION AND BACKGROUND

1.1 The CCII project

The "Climate Changes, Impacts and Implications" (CCII) project is a 4-year project (October 2012 – September 2016) designed to address the following question:

> *What are the predicted climatic conditions and assessed/ potential impacts and implications of climate variability and trends on New Zealand and its regional biophysical environment, the economy and society, at projected critical temporal steps up to 2100?*

The CCII project brings together a strong research team with knowledge and modelling capabilities in climate, ecosystems, land and water use, economics, and sociocultural research to address the environment sector investment plan priority of "stronger prediction and modelling systems".

The project is based on five inter-related Research Aims (RAs) that will ultimately provide new climate change projections and advancements in understanding their impacts and implications for New Zealand's environment, economy and society. The five RAs are:

Research Aim 1: *Improved Climate Projections*

Research Aim 2: *Understanding Pressure Points, Critical Steps and Potential Responses*

Research Aim 3: *Identifying Feedbacks, Understanding Cumulative Impacts and Recognising Limits*

Research Aim 4: *Enhancing Capacity and Increasing Coordination to Support Decision-making*

Research Aim 5: *Exploring Options for New Zealand in Different Changing Global Climates*

The overall purpose of RA2 is to: Perform five case studies on the potential impacts of climate change and other key drivers on alpine, hill & high country, lowland, coasts & estuaries, and marine environments. This synthesis report presents the results of the lowland case study.

1.2 Lowland case study description

Climate change will impact primary sectors such as dairy, horticulture, and arable cropping, as well as ecological functioning of native ecosystems, particularly wetlands. Expected increases in land-use competition and intensification will compound these impacts. The lowland case study was established to explore climate change impacts on primary productivity, the resulting land use changes and social impacts, as well as extent and condition of native ecosystems, and potential biosecurity issues.

1.3 Projected climate changes for the Bay of Plenty region

A complete assessment of updated climate change projections for New Zealand, based on data described in the CCII RA1 Synthesis Report, has recently been performed by NIWA for the Ministry for the Environment (MfE 2016). [1]This report includes projections for the middle and end of the century, incorporating results from multiple climate models and four "Representative Concentration Pathways" or RCPs. The RCPs represent estimated changes in radiative forcing resulting from greenhouse gas (GHG) concentration trajectories under different

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[1] http://www.mfe.govt.nz/publications/climate-change/climate-change-projections-new-zealand

socio-economic assumptions. The RCPs describe four potential climate futures (see Appendix 9.1); RCP2.6 represents a low-emission mitigation pathway, requiring removal to achieve a decline in atmospheric CO_2 by 2050, whereas RCP8.5 is the high emission scenario. The two middle pathways (RCP4.5 and 6.0) require stabilisation of emissions at different time points during the 21st Century.

For the Bay of Plenty region, the following "snapshot" of future climate changes by the end of the century (compared with the present-day) is based only on RCP8.5 and the average of several climate models (Tait et al, 2016). Here then the list of climate changes.

- Increase in the mean air temperate (°C):
  Summer 3.3; Autumn 3.2; Winter 3.1; Spring 2.8

- Change in the mean precipitation at Tauranga (%)[2]:
  Summer +7; Autumn +3; Winter –1; Spring –11

- Increase in the number of "hot days" (Tmax ≥ 25°C):
  Present-day 16.3 days/yr; End of century 75.6 days/yr

- Decrease in the number of "cold nights"
  (Tmin ≤ 0°C): Present-day 17.3 nights/yr;
  End of century 2.3 nights/yr

- Increase in the number of "dry days"
  (Precipitation <1mm/day) by 5-10 days/yr

- Increase in the 99th percentile rainfall amount (approximately equal to the heaviest 24-hour rainfall each year) by 5–10%

- Decrease in the 99th percentile wind speed (approximately equal to the third highest average daily wind speed each year) by 0–5%

- Increase in drought intensity/duration, as indicated by an increase in Potential Evapotranspiration Deficit (amount of water needed for irrigation) by 50–100 mm/yr (an approximately 25–35% increase from present-day)

For more detailed information, the reader is directed to the MfE report (2008).

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[2] Note, there is a large range of projected changes, depending upon the climate model.

2 STAKEHOLDER ENGAGEMENT AND CASE STUDY SELECTION

2.1 Case study selection criteria

In order to identify potential case study areas, the research team compiled a nation-wide short list of options that were assessed against several key criteria: access to existing scientific data and models; potential significance of climate change impacts; wide range of land use present; wide range of natural vegetation types present; and current relationships with local stakeholders. As the Bay of Plenty region contained several of the preferred potential locations, a meeting with the Regional Council was convened in November 2013 to jointly select the case study area. Through this discussion, the Kaituna catchment (including a coastal zone around Papamoa beach) was identified and an initial research plan was constructed. This area is likely to be affected by both drought and flood related climate issues. This area is subject to a community development strategy developed by the Regional Council that includes the development of a vision for the future. Pressing issues include pressures from increased population growth and land-use intensification. Iwi within this area have had a treaty settlement and are about to enter into a co-governance relationship with the regional council.

2.2 Lowland case study description

The Kaituna River is the outflow from Lake Rotorua, controlled by a dam at the Okere Falls. The catchment is about 63,000 ha and represents a typical lowland environment in New Zealand, with a mixture of natural ecosystems (freshwater wetlands and native forests) and a wide range of primary production (maize cropping, kiwifruit horticulture, forestry, dairy, sheep & beef farming). Because of the controlled aspect of the river flow upstream of Okere falls, we decided to focus our project on the lower Kaituna River.

The share of land comprises mainly grassland (25,600 ha) used for dairy in the lowland areas and sheep & beef farming in the hill country (Fig. 1). Exotic forestry and indigenous forest is present in the upper part of the catchment, while the lower part is covered by the kiwifruit industry (6,000 ha near te Puke) (see Table 1).

Figure 1: Map of the land covers in the lower Kaituna catchment.

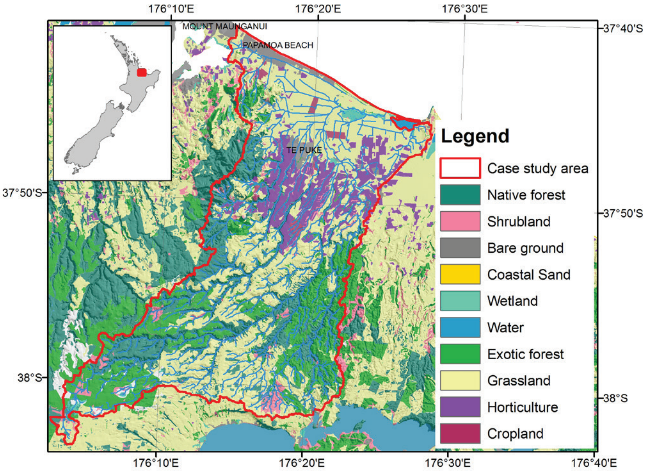

Table 1: Land cover derived from LCDB3 (Landcare Research, 2012) in the lower Kaituna catchment

Land cover (LCDB3)	**Area (ha)**
Cropland	555
Grassland	25,608
Indigenous forest	14,696
Exotic forest	12,040
Orchard	5,855
Wetland	202
Shrubland	2,429
Other	1,809
Total	**63,194**

2.3 Issues raised

A workshop in Te Puke on 9 September 2014 brought together organisations and agencies whose interests and activities could be affected by climate change in the case study area.

Participants included representatives from local iwi/hapu (active groups and trusts) Zespri, Dairy NZ, Fonterra, Beef + Lamb, the forestry sector, the horticultural sector, Bay of Plenty Regional Council (including a Councillor), Western Bay District Council, Department of Conservation , New Zealand Landcare Trust, Federated Farmers, Rural Women's Network, Maketu Ongatoro Wetland Society, and several local environmental consultants.

The purpose was to introduce the proposed research, refine the proposal based on what was important to the stakeholders, identify complementary sources of data or models, and spatially locate the potential wider impacts and implications of climate change using large aerial photos.

During the workshop, a number of additional climate-related issues were identified. Given the local significance of the issue, the research team incorporated a sea-level rise component. However, given the lack of scientific knowledge and uncertainties about future projections, it was not possible to deal with all of them. Certain issues were acknowledged and flagged for future research needs or addressed in other case studies (see Table 2). Some questions could be partly answered by a modelling exercise with the CCII team.

A post-event evaluation illustrated the success of the workshop and a desire for on-going interactions to learn more about the potential impacts of climate changes on the catchment.

Table 2: Issues raised by stakeholders in the Kaituna catchment.

Domain	Issue raised within scope of CCII	Issue raised for future research
Coastal	How will sea level rise impact the lower portion of the catchment (including farmland, urban areas)?	What will be the flooding frequency and how will it impact on coastal inundation and salinization? What impact could salinization of ground water have on low lying communities and farms? How will coastal erosion evolve and to what extent will it affect properties? What would be the economic cost of continued drainage compared to managed retreated wetlands?
Freshwater		How can clean water and healthy estuaries be maintained? How will erosion, sedimentation, nutrient load (nitrogen and phosphorus) impact on water quality? Cost of the stock banks which protect the farmland may become prohibitive over time – Is there a point where stop-banks are no longer a good choice, what would happen then?
Natural systems	What are the threats on the freshwater wetlands?	What will be the future of the perched wetland in the catchment (Kaituna Reserve)? Can we identify future wetland restoration sites for added biodiversity benefits?
Natural risks	What new pests might migrate to the area?	What will be the likely changes in fire risk? What will be the likelihood of more frequent extreme events and what would be their magnitude?
Primary production	How will kiwifruit industry be impacted by climate change?	
Land-use change	How would climate change exacerbate or counteract current land-use change trends?	What would be the suitability of land use for a range of future crops? How can we best manage river water quality and fisheries in face of future land-use changes? What should the land be managed for? Can we locate vulnerable land and vulnerable land uses (that is areas where the risks are high)?
Infrastructure capacity		What will be the impact of climate change on infrastructures?
Social & cultural issues		What will be the impacts of climate change on Māori land? What is the timescale for environmental impacts (short, medium or long-term)? How will resilience to change be affected? How do we best communicate uncertainty of results? What future local livelihoods are possible? How may climate change affect the local wetland and estuary, including social and cultural values such as the food basket?
Climate change planning		How can we integrate climate change information into future planning?

3 METHODOLOGY

3.1 Future concentration scenarios

Climate outcomes based on RCPs are modelled via the Coupled Model Inter-comparison Project (CMIP5) through numerous Earth System Models or General Circulation Models (GCM). We used six GCMs (BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES, and NorESM1-M) to update and improve regional-scale projections of New Zealand climate trends and variability to 2100. The output variables were precipitation, maximum and minimum air temperature, relative humidity, vapour pressure, solar radiation, and wind speed. Each variable was calculated on a regular grid (0.05°, approximately 5 km) using the Virtual Climate Stations (VCS) from NIWA (Tait & Turner 2005) at a daily, monthly, and annual temporal resolution for the 1971–2100 period.

3.2 Quantitative modelling

We reviewed available models that could be applied to the Kaituna catchment and help answer some or part of the questions raised during the workshop (Table 2). A series of models was available to quantify some elements of resources (water and land), demographics, economic development (trends in commodity prices, primary production changes, land-use suitability, and land-use change patterns) and environmental factors (vulnerability to natural ecosystems, pests and disease) (Table 3). Details on the parameterisation and methods for each model are available in Appendix 9.2.

3.3 Integrated assessment

One of the objectives for the project was to provide an integrated view of how the different parts of the landscape interact with each other, utilising as much as possible the models given in Table 3. To achieve this, models were linked to each other and tested through future scenarios to better understand interactions and feedbacks.

Research Aim 5 provided the scenarios that were to be tested (see RA5 synthesis report). The architecture of these scenarios adopts two global elements from a global scenario toolkit (Ebi et al. 2013) plus one national-scale element. These are global RCP (see section 3.1), global Shared Socio-economic Pathways (SSP) and New Zealand-specific Shared climate Policy Assumptions (SPA). Unlike earlier assessments,

Table 3: Models used for the Kaituna catchment.

Domain	Model	Indicator
Population	Population model (Cameron 2013)	Demographic
Land	Sea level rise calculator (Stephens & Bell 2015)	Area at risk of sea level rise and storm surge
Economic development	Climat-DGE (Fernandez & Daigneault 2015)	Commodity prices downscaled to New Zealand
Primary production	CenW (forestry) (Kirschbaum et al. 2012) APSIM (maize) (Holzworth et al. 2014) BiomeBGC (pasture) (Keller et al. 2014) Suitability index (kiwifruit) (Tait et al. in prep)	Yield change Yield change Yield change Suitability index
Land-use change	NZFARM (Daigneault et al. 2014) LURNZ (Olssen & Kerr 2013)	Change in land use area and spatial allocation
Natural ecosystem	Vulnerability model (wetlands) (Bodmin et al. 2016)	Change in water supply per wetland type
Erosion	NZeem (Dymond et al. 2010)	Sediment loss due to land cover changes
Pests and disease	CLIMEX (Sutherst et al. 1999)	Suitability index for pests/diseases

the 5th IPCC assessment Report (AR5) scenarios for climate change decoupled the climate model outputs expressed through RCPs, from their socio-economic drivers expressed through the concept of SSPs. Shared socio-economic pathways describe plausible trends in the evolution of society and global economy. Van Vuuren and Carter (2013) introduced a framework to illustrate combinations of RCPs and SSPs. These new scenarios can be compared with the old IPCC AR4 scenarios. The Shared climate Policy Assumptions (SPAs) are specific to New Zealand. SPAs describe potential climate change mitigation and/or adaptation policies not specified in the SSPs. They provide a third axis to the scenario matrix and allow national-level development choices that may reinforce global trends or actively go against them.

To help assess plausible scenarios, O'Neill et al. (2013) suggested outlining several elements that are relevant for defining both challenges to mitigation and adaptation (Table 4). They were evaluated quantitatively via modelling where possible, and complemented with narratives from the CCII research team.

Each element from Table 4 was assessed on the basis of an example scenario. In our case, we tested the combination RCP8.5/SSP3/SPA-A. RCP8.5 is the highest greenhouse gas concentration trajectory adopted by IPCC AR5 pathway. SSP3 corresponds to high socio-economic challenges for both mitigation and adaptation. In our example scenario, we hypothesised that New Zealand is lagging relative to global efforts to mitigate, with incremental and reactive adaptation on a piecemeal basis, which we refer to as SPA-A.

The models from Table 3 operate at different scales (sector-based scale and landscape scale) (Fig. 3) and have as inputs either the RCP scenario only (primary production, wetlands) or a combination of RCP and SSP assumptions (for example the land-use change models). We assessed a scenario based on climate scenarios for RCP8.5 up to 2100 and assumptions according to SSP3 and SPA-A. The arrows represent soft-coupling between models. Information flows from the scenario assumptions into the trade and growth model climat-DGE. The RCP projections are used as inputs to the primary production models (cenW, biomeBGC and APSIM). Outputs from these models are then used for the land-use change models (LURNZ and NZFARM), in particular through the commodity prices and the yield change projections.

Table 4: Elements of scenario analysis (adapted from O'Neill et al. 2013).

Categories	**Elements**
Demographics	Total population and age structure, urban vs. rural populations, and urban forms
Economic Development	Global and regional GDP, trends in productivity, sectoral structure of national economies (share of agricultural land)
Environmental Factors	Air, water, soil quality, ecosystem functioning
Resources	Fossil fuel resources and renewable energy potentials, fresh water, land
Welfare	Human development, educational attainment, health
Institutions and Governance	Existence, type and effectiveness of national/regional/global institutions
Technological Development	Type (e.g. slow, rapid, transformational) and direction (e.g. environmental, efficiency, productivity) of progress
Broader Societal Factors	Attitudes to the environment/sustainability/equity and world views, life styles, societal tension and conflict levels
Policies	Non-climate policies

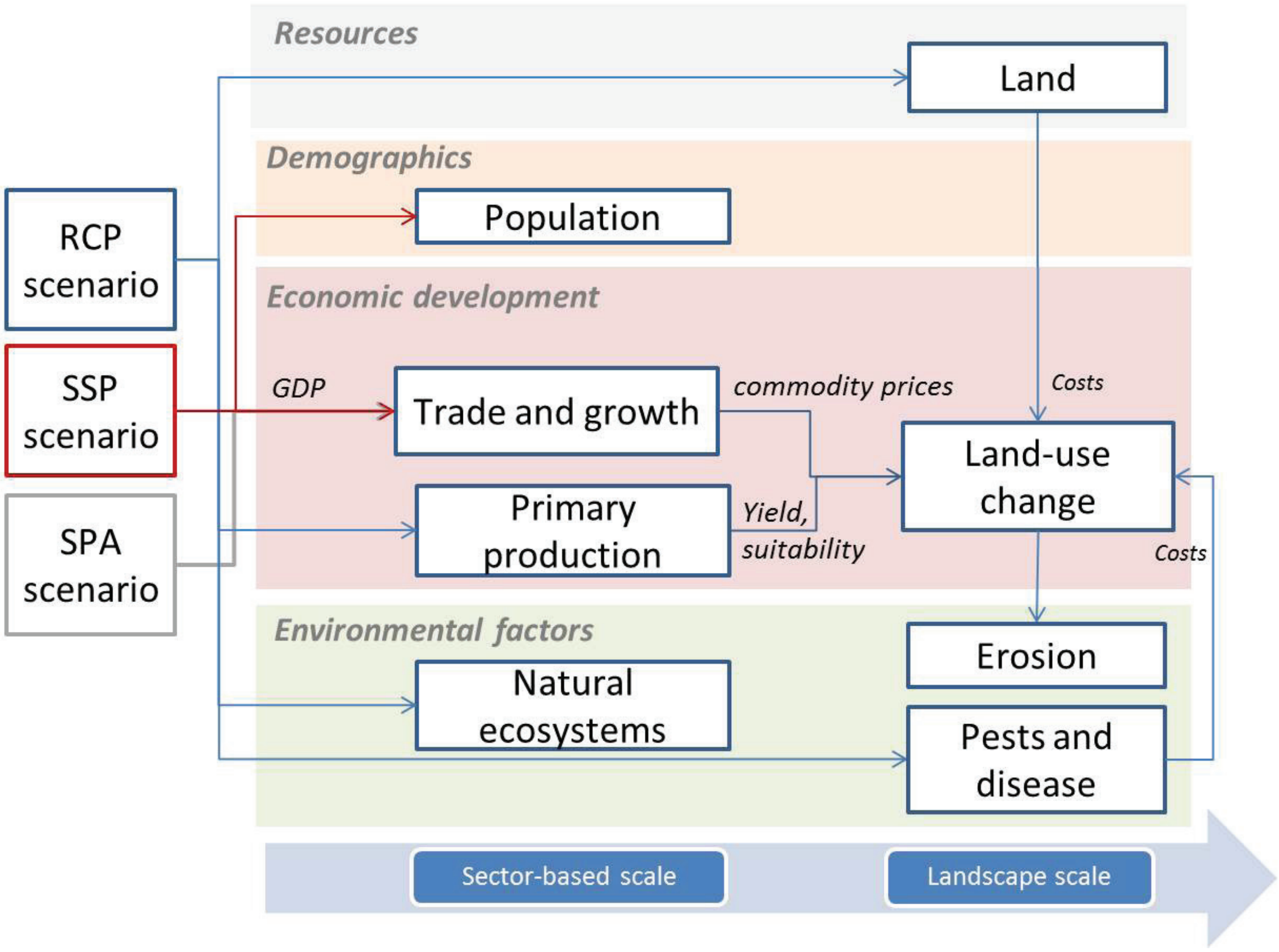

Figure 2: Framework for quantitative modelling of the integrated assessment.

4 RESULTS AND DISCUSSION

4.1 Quantitative modelling

This section describes the outputs from each individual model from Table 3.

4.1.1 Demographics

The population model projected the population (by age and sex) for each of the sixteen regions of New Zealand for the integrated scenario RCP 8.5/SSP3/SPA-A, up to 2100 on an annual basis. However, the model does not explicitly separate urban from rural populations, as the spatial resolution is at the regional level.

In this scenario, the total population of New Zealand is projected to increase from 4.44 million in 2013 to a peak of 5.04 million in 2043, before declining to 3.85 million by 2100. However, the total projected population is sensitive to assumptions about future international migration. Different assumptions about international migration trends will result in different projected future populations. Moreover, the calculations of the sixteen regions differ substantially over the projected period, with some (e.g. Auckland, Waikato) increasing consistently over the entire projection period, while others (e.g. West Coast, Southland) are mostly expected to show population decline. This is in line with other projections and expectations about population decline in rural and peripheral New Zealand more generally (Jackson & Cameron 2015).

Focusing on the results for the Bay of Plenty region, the total population in this scenario is projected to increase from 279,700 in 2013 to a peak of 332,600 in 2054, before declining to 281,600 in 2100. The most striking feature of the population change over this period is the substantial ageing of the population. The population aged 65 years and over is projected to increase from 48,200 in 2013 to a peak of 104,200 in 2084 before declining to 100,200 in 2100. As a percentage, this older population is projected to increase from 17.2% of the population in 2013 to 35.6% of the population in 2100. Moreover, the population aged 85 years and over is projected to increase from 5700 in 2013 (2.0% of total population) to a peak of 35,400 in 2098 (12.3% of total population) before declining to 34,400 in 2100 (12.2% of total population).

Implications – The New Zealand population for scenario RCP8.5 and SSP3 is projected to increase to a peak in 2043 then decrease to 3.85 millions by 2100. For the Bay of Plenty, this also implies an aging population.

4.1.2 Sea level rise

4.1.2.1 Global sea level rise

In the modern era, global sea level began to rise around the latter half of the 1800s, and steadily increased at a rate within the range 1.4–1.9 mm/year during the 20th century.

Across New Zealand, the average relative (local) sea-level rise from 1900 to 2015 is 1.78 ± 0.21 mm/yr and, since 1961, is 2.14 ± 0.47 mm/yr (Ministry for the Environment 2016); results that are very similar to those given in Church and White (2011) for global averages. This means projections for global sea-level rise can generally be adopted, provided allowances are made for regional and local differences.

In the satellite era (since 1993), global mean sea level has risen by 3.3 mm/yr, attributable partly to natural climate variability and partly to an acceleration in sea-level rise due to warming of the atmosphere and oceans.

Key drivers of the rise in sea level are:

- Thermal expansion from warming ocean waters
- Additional water mass added to the ocean from glaciers, ice sheets and net freshwater runoff
- Vertical land movement can substantially alter the local sea-level rise, with any land subsidence compounding the ocean rise.

Locally, it is the local or relative sea-level rise that needs to be adapted to – not the global average rate. However, projections of future sea-level rise are usually based on global projections. For New Zealand, therefore, offsets need to be applied to projections for differences in the regional-ocean response for the SW Pacific (e.g. a modest additional 0.05 m by the 2090s, Ackerley et al. 2013) and local vertical land movement (which can be measured by continuous GPS recorders).

IPCC projections (5th Assessment Report, Working Group I, Chapter 13, Church et al. 2013) of global sea-level rise by 2100 cover a range of around 0.4–1 m, depending on the Representative Concentration Pathway (RCP) climate scenario used, which includes future emissions, population growth and other socio-economic factors. The range in sea-level rise projections is much narrower in the near-term to 2060 (0.3–0.4 m). However, beyond 2100, the spectre of runaway instabilities of polar ice sheets in West Antarctica and Greenland, if global temperatures exceed a threshold of ~2°C above pre-industrial levels (Golledge et al. 2015), considerably increases the range of possible future sea-level trajectories to consider in planning and design.

Small increases of the order of 1–5% in wave height and storm surges from climate change effects are also likely by 2090 (NIWA WASP project, unpublished).

4.1.2.2 Defining the land-sea boundary

Tide is the main cause of sea-level variability in New Zealand. The tides result from the gravitational pull of both the moon and sun on the Earth's oceans. The changing orientation between the moon, the sun, and the Earth causes the tide heights to cycle between higher spring tides and lower neap tides, with the spring peaks separated in time by about 2 weeks. In areas that are sheltered from waves, the land-sea boundary tends to occur at the location reached by the spring tides, and this elevation is known as mean high-water springs (MHWS). The definition of the MHWS elevation is important in New Zealand because it defines the legal landward boundary of the coastal marine area, i.e. what is considered to be on land, and what is considered to be in the sea. On wave-exposed coastlines the MHWS boundary occurs on the beach; in sheltered estuaries it marks the boundary between estuarine sediment and saltmarsh vegetation.
The MHWS elevation is 1.0 m above Moturiki Vertical Datum 1953 (MVD–53), at present-day mean sea level (MSL).

4.1.2.3 Coastal-storm inundation

Storm-tides occur when storms (which can raise the sea-level by up to 0.6 m along the Bay of Plenty coastline) coincide with high spring tides. Storm tides are higher than tides alone, and cause coastal-storm inundation, where the sea encroaches onto land. At the open coast, waves can also contribute to coastal erosion and inundation. NIWA calculated the elevations that storm-tides and waves could reach to along the Bay of Plenty coastline (Goodhue et al. 2015). At present-day MSL, there is a 39% chance, per year, that coastal-storm inundation (storm-tide + wave setup) will reach 2.8 m MVD–53. As this elevation can be expected to be reached every 2 years on average, the area inundated is likely to resemble a salt-tolerant coastal wetland.

4.1.2.4 Mapping sea-level rise effects on coastal inundation

We mapped a future SLR of 0.8 m by 2100. A 0.8 m SLR was added to both the MHWS and the 2-year average recurrence interval sea-level elevations.

Areas below the MHWS + 0.8 m SLR value (1.8 m above MVD-53) will effectively become "sea" – regularly inundated every couple of weeks during high tide. This will represent a large change in exposure to the sea for these areas.

Areas flooded once every 2 years (on average) after 0.8 m SLR (3.6 m above MVD-53) could represent the extent of new wetland on the coastal fringe (Fig. 3). The affected area (about 5,500 ha) is currently composed of about 60% dairy farming.

Implications – Coastal inundation due to sea level rise (under a 0.8-m scenario) is projected to affect about 5,500 ha of land that could become regularly inundated every couple of years during high tides. This land, currently under dairying, is projected to become wetland.

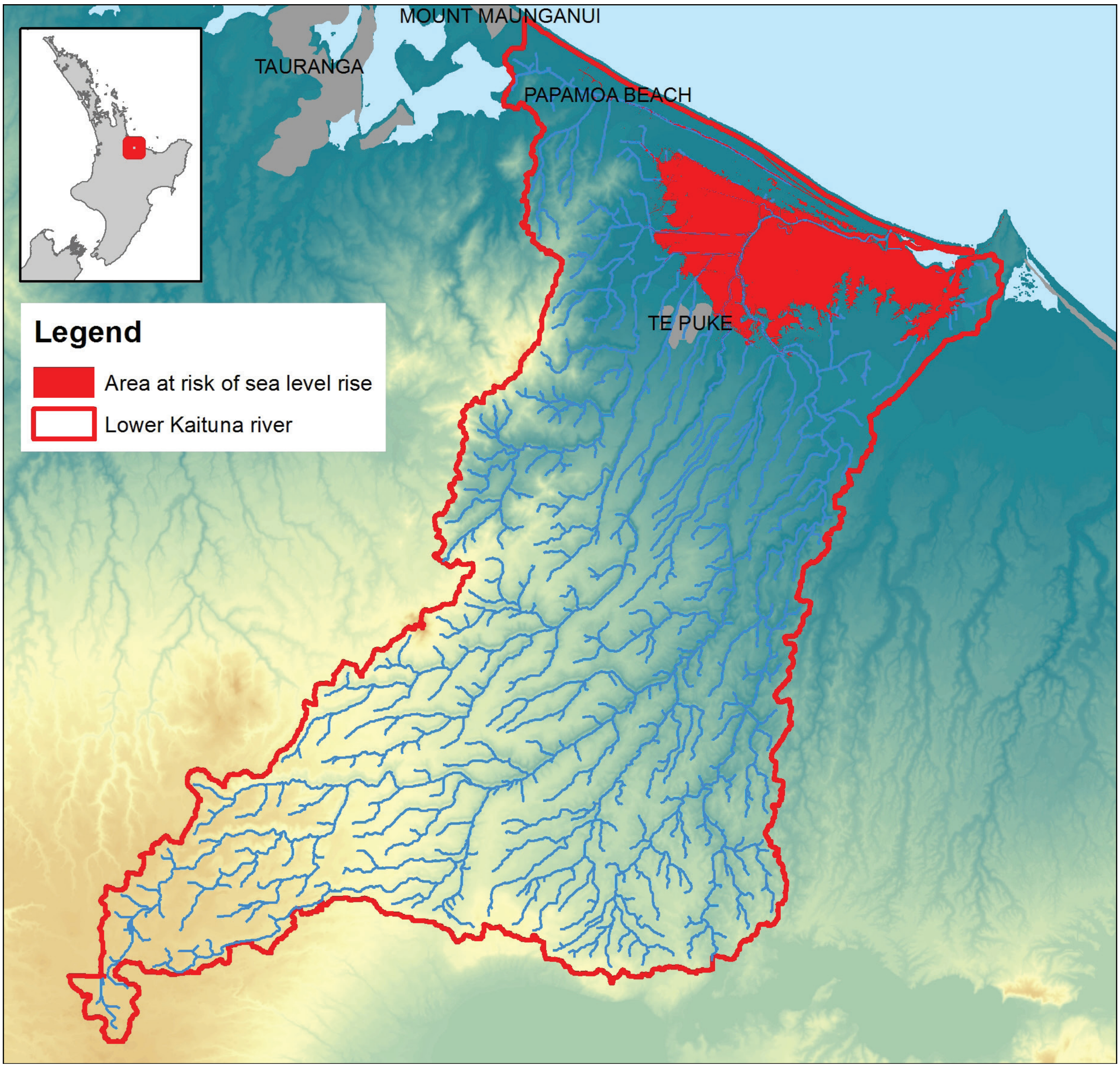

Figure 3: Map of the area at risk of sea level rise for areas flooded every 2 years on average after 0.8 m SLR.

4.1.3 Primary production

4.1.3.1 Pasture production

Results are reported as a model ensemble mean, formed by averaging the pasture production from all 6 individual GCMs for each scenario. Future scenarios are compared with the RCP past baseline to give the relative amount of change in pasture production. 20-year averages are calculated at two time slices: mid-century (2046–2065) and end-of-century (2081–2100). Figure 4 contains model ensemble averages of total annual pasture production for RCPs 4.5 and 8.5, in terms of percentage change from the baseline (RCP past). Table 5 and Table 6 show annual totals and seasonal growth rates for all four scenarios, averaged spatially over the entire Kaituna region.

Overall, the change in pasture production is positive under all scenarios for both sheep and dairy pasture. The magnitude of the change is larger for dairy than for sheep. Total annual pasture growth, averaged spatially over the entire Kaituna region, increases by 1–5% around mid-century and by 2–7.5% by 2100 (Tables 5 and 6). The increase is largely attributable to the CO_2 fertilization effect, as the amount of increase in production follows the trends in CO_2 atmospheric concentrations from each RCP. The increase in production is largest in RCP 8.5 at 2100, in which the CO_2 atmospheric concentration is highest (~850 ppm). This effect is more than enough to offset any adverse climate effects on production.

Seasonal average growth rates show consistent, large increases in winter (JJA) and spring (SON), as expected under warmer conditions and an extended growing season. Autumn (MAM) shows small increases in the majority of scenarios, while hotter, drier summers (DJF) result in a decline in growth, which is quite large at mid-century in the high-emissions scenarios. Despite the net positive gain in total annual production, the seasonal feed gap from losses in summer could be significant at a farm level and deserves attention in planning for future change.

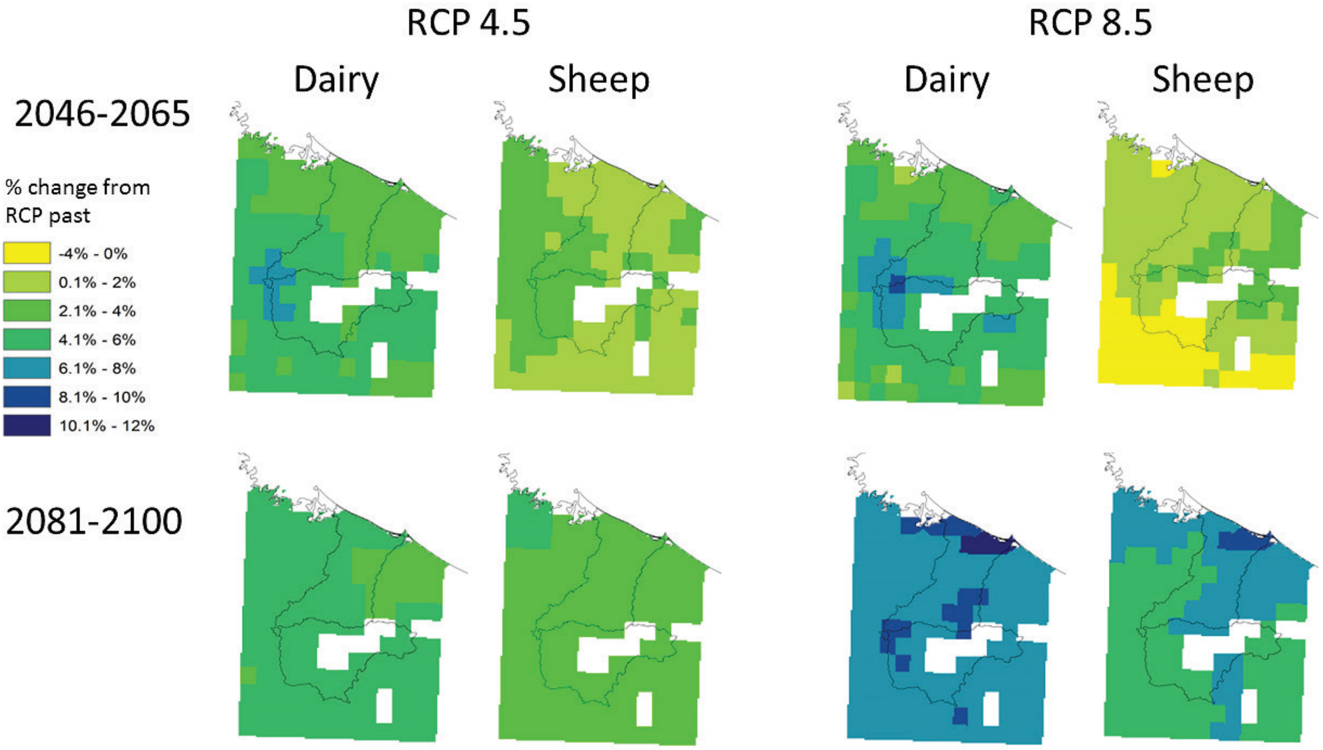

Figure 4: Maps of model ensemble-mean average total annual pasture production in the Kaituna Lowlands catchment under RCP 4.5 (low emissions) and RCP 8.5 (high emissions), for dairy (left) and sheep (right) pasture systems, in percent change from baseline (RCP past). Urban areas and major bodies of water are excluded. All remaining land is modelled as if it were available for pasture, regardless of actual land use. Mid-century projections (2046–2065) appear on the top row and end-of-century (2081–2100) appear on the bottom.

Table 5: Dairy model ensemble pasture production results for all RCPs, averaged over the entire Kaituna region, for the time periods 2046–2065 and 2081–2100. Columns contain average annual total in kilograms of dry matter (DM) per hectare and seasonal average daily production in kilograms of DM per hectare per day. The right column in each block is the percentage change from the baseline RCP past.

1985–2005	**annual**		**SON**		**DJF**		**MAM**		**JJA**	
RCP	total kg DM/ha	% change	kg DM/ha/day	% change	kg DM/ha/day	% change	kg DM/ha/day	% change	kg DM/ha/day	% change
past	12967	–	49.81	–	52.36	–	30.04	–	10.42	–
2046–2065 RCP										
2.6	13296	2.5%	52.31	5.0%	52.39	0.1%	30.09	0.1%	11.45	9.9%
4.5	13526	4.3%	54.72	9.9%	50.69	-3.2%	30.73	2.3%	12.57	20.7%
6	13549	4.5%	55.43	11.3%	50.04	-4.4%	30.56	1.7%	12.93	24.2%
8.5	13560	4.6%	57.71	15.9%	45.69	-12.7%	31.23	3.9%	14.62	40.4%
2081–2100 RCP										
2.6	13269	2.3%	52.01	4.4%	52.58	0.4%	30.14	0.3%	11.20	7.6%
4.5	13548	4.5%	53.84	8.1%	52.49	0.3%	30.84	2.7%	11.82	13.5%
6	13727	5.9%	54.44	9.3%	53.16	1.5%	31.18	3.8%	12.17	16.9%
8.5	13935	7.5%	55.80	12.0%	52.65	0.6%	31.89	6.1%	12.89	23.7%

Table 6: Sheep model ensemble pasture production results for all RCPs, averaged over the entire Kaituna region, for the time periods 2046–2065 and 2081–2100. Columns contain average annual total in kilograms of dry matter (DM) per hectare and seasonal average daily production in kilograms of DM per hectare per day. The right column in each block is the percentage change from the baseline RCP past.

1985–2005	**annual**		**SON**		**DJF**		**MAM**		**JJA**	
RCP	total kg DM/ha	% change	kg DM/ha/day	% change	kg DM/ha/day	% change	kg DM/ha/day	% change	kg DM/ha/day	% change
past	8542	–	37.15	–	32.97	–	16.82	–	7.03	–
2046–2065 RCP										
2.6	8656	1.3%	39.01	5.0%	32.06	-2.7%	16.62	-1.2%	7.52	7.0%
4.5	8704	1.9%	40.48	9.0%	30.01	-9.0%	17.08	1.5%	8.13	15.7%
6	8663	1.4%	40.93	10.2%	28.74	-12.8%	17.25	2.6%	8.31	18.2%
8.5	8602	0.7%	41.97	13.0%	25.58	-22.4%	17.83	6.0%	9.14	30.0%
2081–2100 RCP										
2.6	8711	2.0%	38.87	4.6%	32.55	-1.3%	16.92	0.6%	7.47	6.3%
4.5	8841	3.5%	40.01	7.7%	32.33	-1.9%	17.16	2.0%	7.72	9.9%
6	8935	4.6%	40.48	8.9%	32.94	-0.1%	17.01	1.1%	7.85	11.7%
8.5	9050	5.9%	41.33	11.3%	32.27	-2.1%	17.73	5.4%	8.18	16.4%

4.1.3.2 Forestry

Figure 5 compares the 2055 and 2085 growth response to climate change under different RCPs with constant CO_2 with the response averaged for the simulations of all six GCMs. There are similar growth responses under RCP4.5 and 8.5. Growth reductions averaged about 5–10%, and generally increased somewhat in a direction from south-west to north-east. The most notable feature was a growth reduction by about 20% in the north-eastern coastal zone, probably as a result of stronger water limitations, especially where sites had poor water-holding capacities. By 2085, the pattern of growth reductions noted for the 2055 simulations became noticeably stronger, especially under the higher emission RCP (RCP8.5). The high-producing south-west still remained fairly unaffected by climate change, but the north-eastern half, showed greater vulnerability, especially the northern coastal strip. So, while in the south-west, growth reductions even under RCP 8.5 were limited to about 10%, growth reductions in the north-east were about 25% and exceeded 30% on the eastern coastal strip.

The negative growth responses to climate change under constant CO_2 turned into general positive growth responses when increasing CO_2 was factored in as well. This difference was most pronounced for simulations under RCP 8.5, with simulations under the lower-emission RCP4.5 showing both less extreme negative responses for simulations under constant CO_2 and less positive response with increasing CO_2.

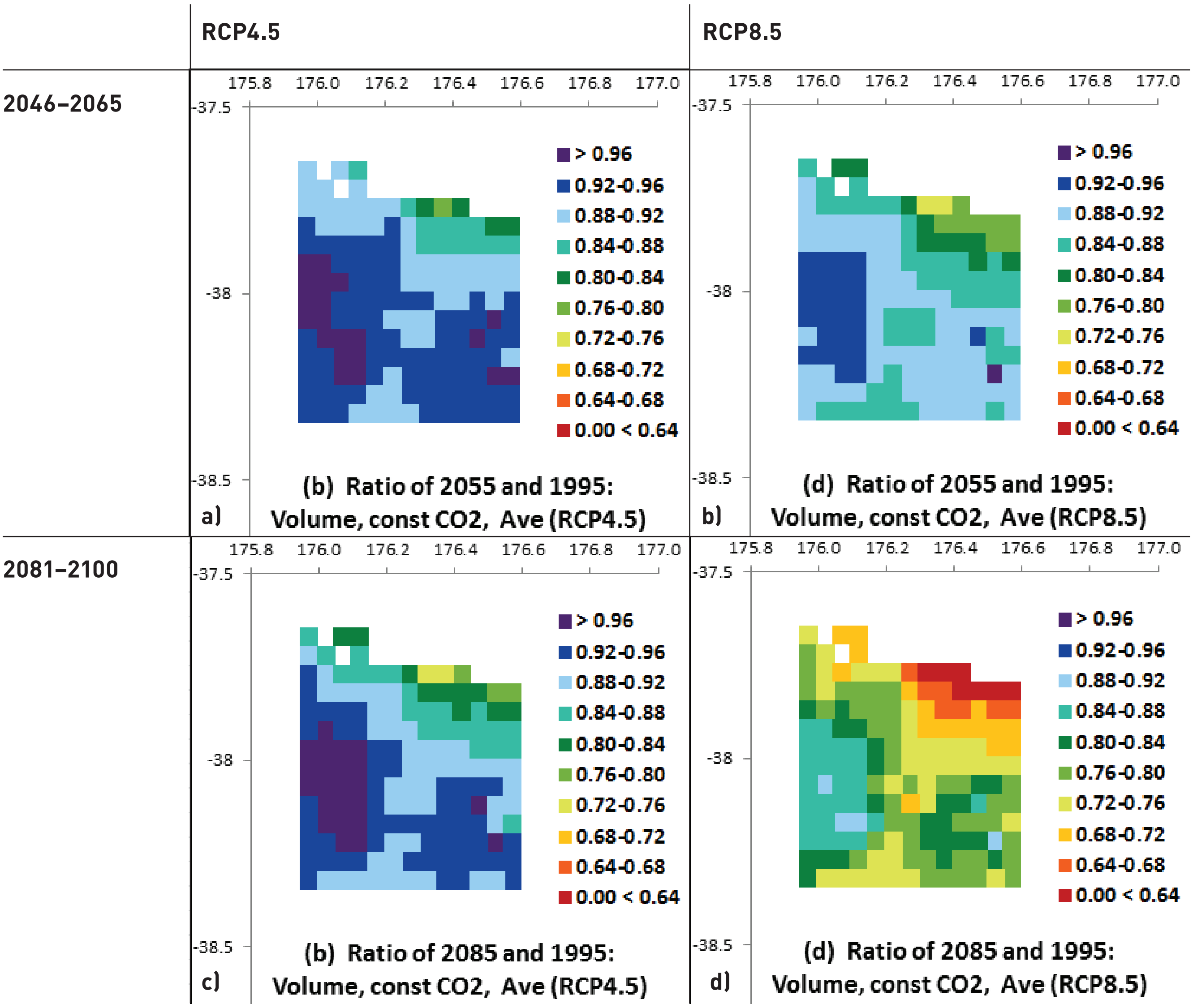

Figure 5: Ratio of 2055 to 1995 and 2085 to 1995 productivity, modelled with constant CO_2 under RCP4.5 and 8.5, and for the average response of the six different GCMs.

By 2055, there were general growth enhancements by about 5–10% under the three lower-emissions RCPs and growth responses of 15–20% under RCP 8.5 (Fig. 6). Increasing CO$_2$ somewhat evened out the regional differences, but there was still a tendency for growth responses to be slightly greater in the south-west than the north and north-east.

These patterns strengthened for the 2085 simulations. Under RCP 4.5, there was a positive growth response by an average of about 15%, with a greater response in the south-west and a lesser response in the north-east. The growth responses were even greater under RCP 8.5, but the regional differences largely disappeared (Fig. 6).

Interestingly, the vulnerability of the northern coastal strip that was most apparent in the RCP 8.5 simulations (Fig. 5d) completely disappeared and transformed into a region with the most positive growth responses (Fig. 6b, d). This pattern was indicative of the central role played by water relations and enhanced water-use efficiency under elevated CO$_2$. Under constant CO$_2$, these regions suffer growth reductions through increased evaporative demand, with sites with low water-holding capacity particularly vulnerable. With increasing CO$_2$, however, water-use efficiency increased greatly so that these sites become less rather than more sensitive to water stress, hence resulting in a change from the most negative to the most positive growth responses.

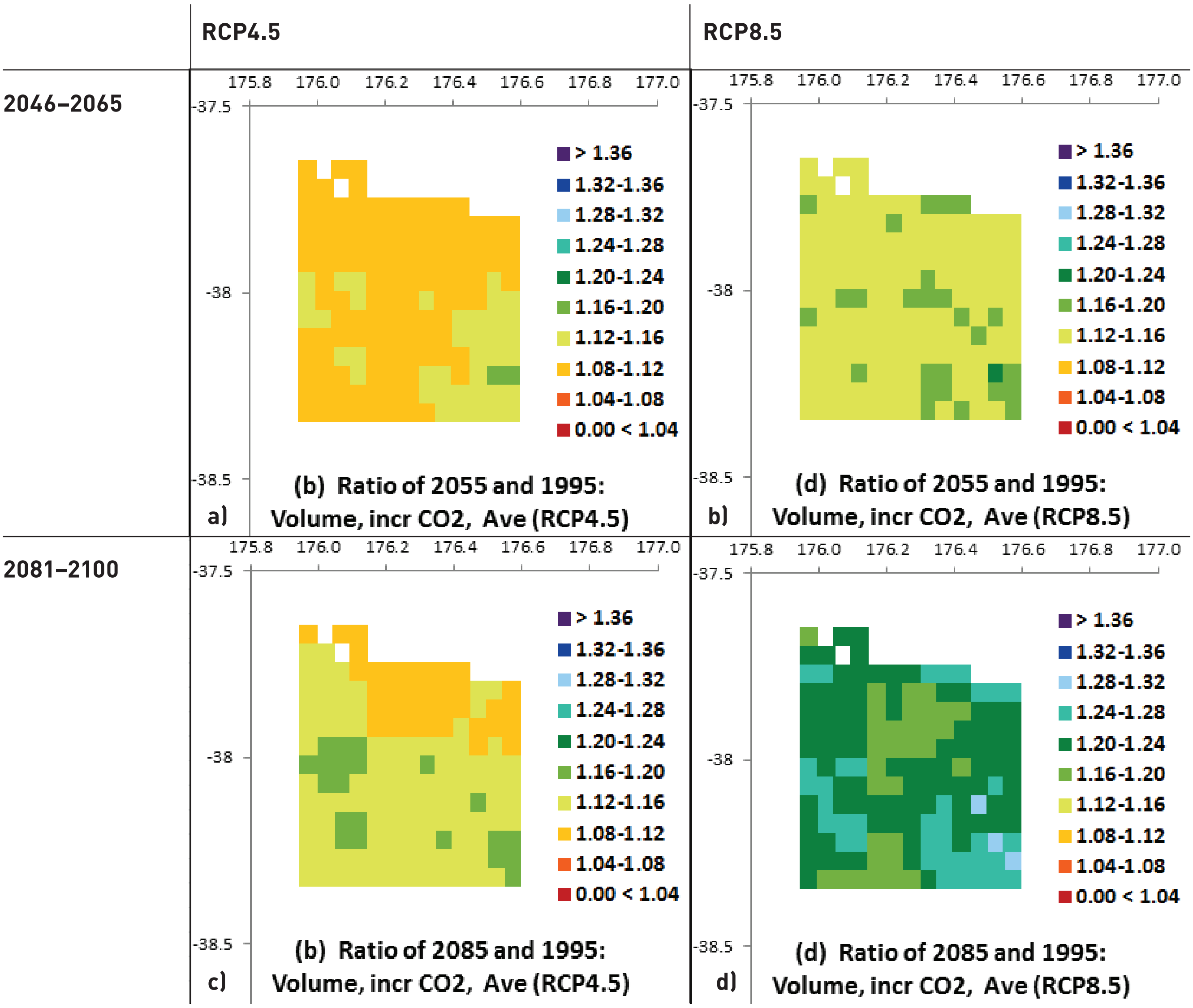

Figure 6: Ratio of 2055–1995 and 2085–1995 productivity, modelled with increasing CO$_2$ under RCP4.5 and 8.5, and for the average response of the six different GCMs.

Overall results have been summarised in Table 7. Under RCP 2.6, and for simulations with constant CO_2, there were only minor reductions in productivity of 4% for both 2055 and 2085. Under the other RCPs, there was a growth reduction of about 10% by 2055, with little difference in the simulations under different RCPs. Differences between RCPs emerged by 2085, with productivity under RCP 4.5 having a similar 9% growth reduction as in 2055, but for RCP 6.0, the growth reduction increased from 8 to 13%, and for RCP 8.5 from 12 to 23%.

For simulations with increasing CO_2, growth increased by about 10% by 2055 under the three lower-emissions RCP2 and by 15% under RCP 8.5. By 2085, the growth increased actually reduced from 8 to 6% under RCP 2.6, but increased for the three higher-emissions scenarios. As shown previously in the comparison between different GCMs, the between-site variability was higher for the simulations with constant CO_2 than those with increasing CO_2, with standard deviations by 2085 ranging from 3 to 7% for simulations under constant CO_2, which reduced to 2–3% under increasing CO_2. This is consistent with the general tendency for increasing CO_2 to have greater beneficial effects for plants growing under otherwise more stressful conditions.

Table 7: Ratio of future to 1995 productivity under different RCPs. Data for 2055 and 2085 give the ratio of future-year productivity relative to that in 1995. Data show means +/- SD for the 150 individual sites of the Bay of Plenty region.

	2055	**2085**	**2055**	**2085**
	Constant CO_2		Constant CO_2	
RCP 2.6	0.96 +/- 0.02	0.96 +/- 0.03	1.08 +/- 0.01	1.06 +/- 0.02
RCP 4.5	0.92 +/- 0.04	0.91 +/- 0.05	1.11 +/- 0.01	1.14 +/- 0.02
RCP 6.0	0.92 +/- 0.03	0.87 +/- 0.05	1.11 +/- 0.02	1.18 +/- 0.02
RCP 8.5	0.88 +/- 0.04	0.77 +/- 0.07	1.15 +/- 0.01	1.22 +/- 0.03

4.1.3.3 Cropping

To assess spatial changes to potential crop yield under rain-fed conditions, the growth of silage maize was simulated across the entire catchment without considering assumptions about current or future land-use suitability. For the historical climate, average silage yields were estimated to range from 12 to 26 t/ha, depending on the location and the hybrid maturity type used (Fig. 7). Higher silage yields were projected for long-maturity hybrids grown in the more coastal northern lowland areas. These spatial patterns were in agreement with expert opinion and surveyed data for the region.

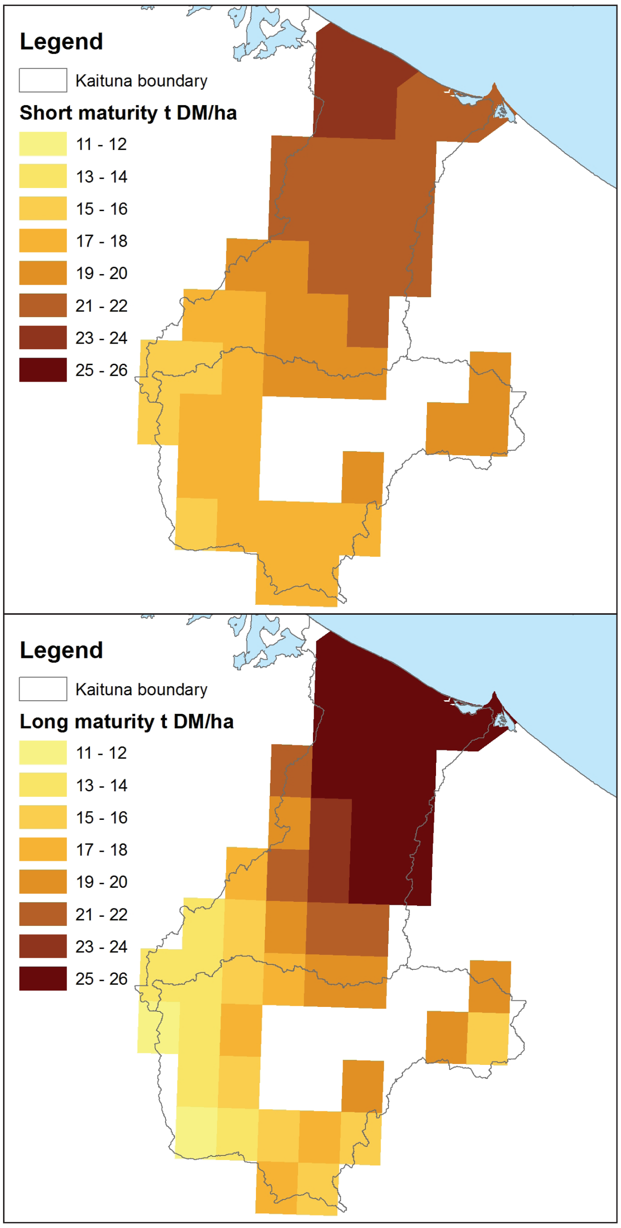

Figure 7: Estimated average silage yields for 20-year historical climate runs under rain-fed conditions.

The impact of climate change on maize silage yields was assessed by considering model runs with or without adaptation of crop genotype (short- and long-maturity hybrids) and sowing dates (i.e. sowing earlier in response to warmer temperatures). These two key independent tactical adaption options are used by farmers to adjust to year-by-year weather variability (Teixeira et al. 2016) and are expected to play an important role under climate change.

Model results indicate a higher risk of yield losses when sowing dates are not adapted, particularly for short-maturity hybrids (Fig. 8). For these conditions, median yield loss estimates increase from mid-century (5%) to the end of the century (14%) mainly because the crop cycle is shortened due to faster crop development. In contrast, by adapting sowing dates to a warmer climate (i.e. sowing early), yield losses were minimised and yield gains occurred for specific locations, particularly when using long-maturity hybrids. These results highlight that current sowing dates are unlikely to maintain yields under the warmer future assumed in the simulations.

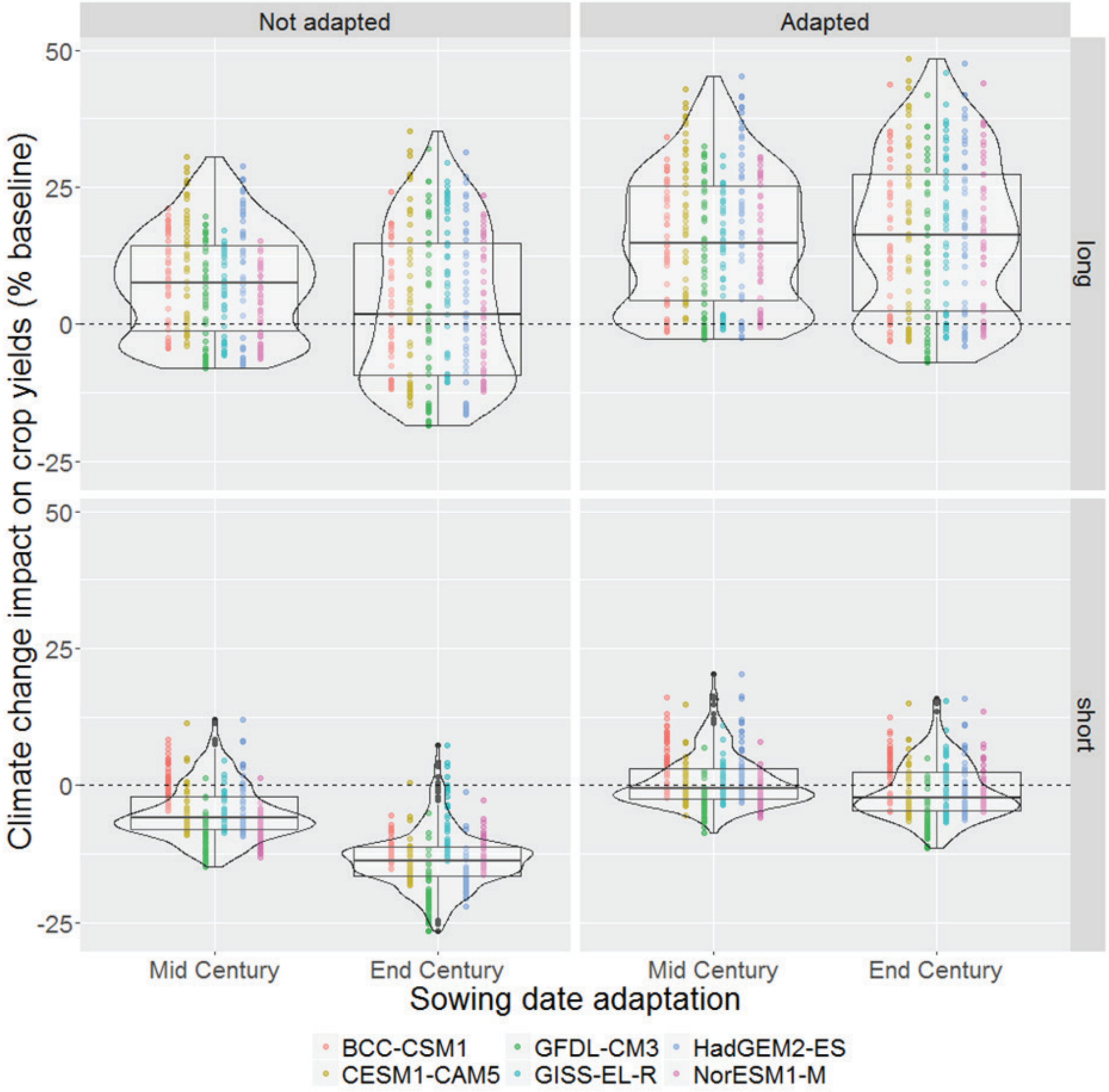

Figure 8: Simulated average change in silage maize yield (% of baseline) for 47 grid-cells (points), six climate models (colour legends) and two time-slices (mid- and end-century). Simulations considered adaptation of crop genotypes (short- and long-maturity hybrids) and sowing dates (not adapted or adapted) to climate change.

Climate change impacts on silage yield were uneven across the Kaituna catchment. More negative impacts were estimated in the northern lowlands, currently the most suitable area for arable cropping, as illustrated for the two GCMs that gave the most contrasting results (Fig. 9).

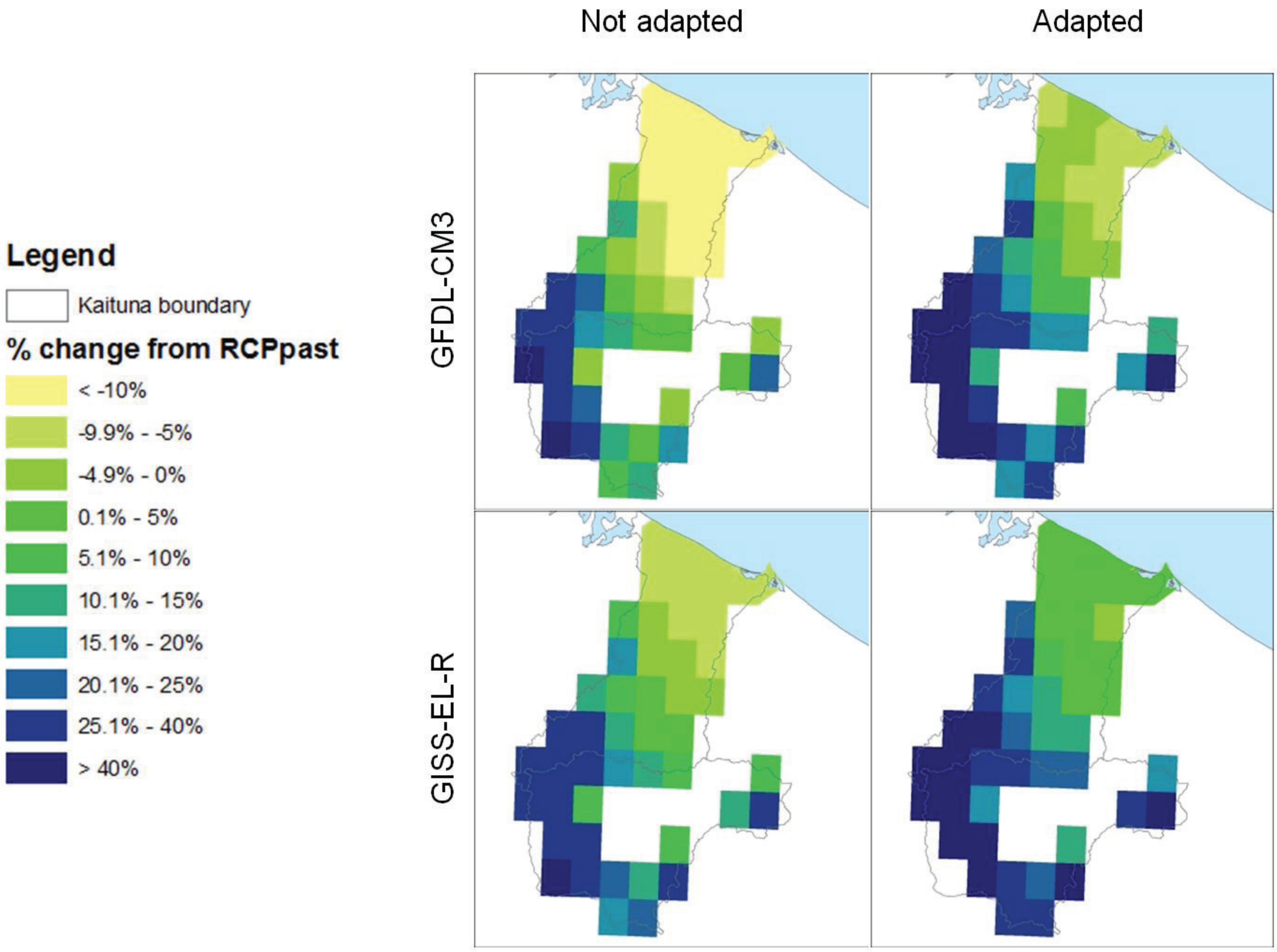

Figure 9: Average yield changes for end-century (2080–2100) for the two climate models with most contrasting results (GFDL-CM3, GISS-EL-R). Note: Simulations consider both adapted and not adapted sowing dates for a "long-maturity hybrid" and a soil with "high water holding capacity".

In contrast, the more positive yield responses due to climate change were estimated for the south-western areas of the catchment. Under current climate, maize yields in these higher altitude areas are limited by low temperatures. The uncertainty due to GCM climate projections is illustrated by relating yield changes to the average elevation in each grid-cell in Figure 10.

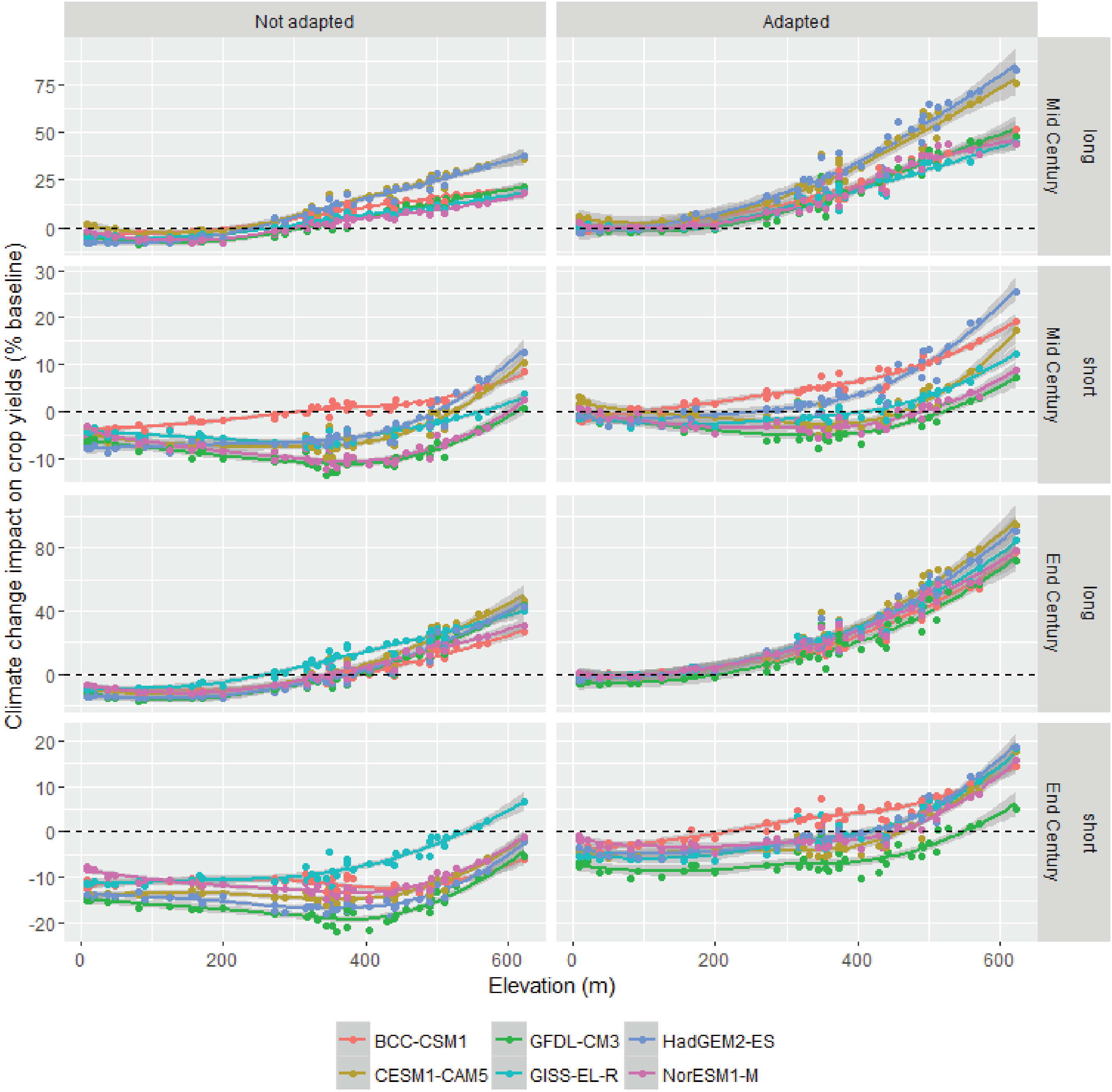

Figure 10: Simulated climate change impact on silage maize yields across the gradient of elevations in the Kaituna catchment for six climate models, two time-slices and two hybrid types (short- and long maturity) with and without considering adaptation of sowing dates.

These results suggest that another possible alternative adaptation to climate change is to expand silage maize production to higher lands. However, the occurrence of other limitations to arable cropping (e.g. terrain, land-use suitability, and soil characteristics) and environmental constraints may limit the degree of adaptability (Fig. 11).

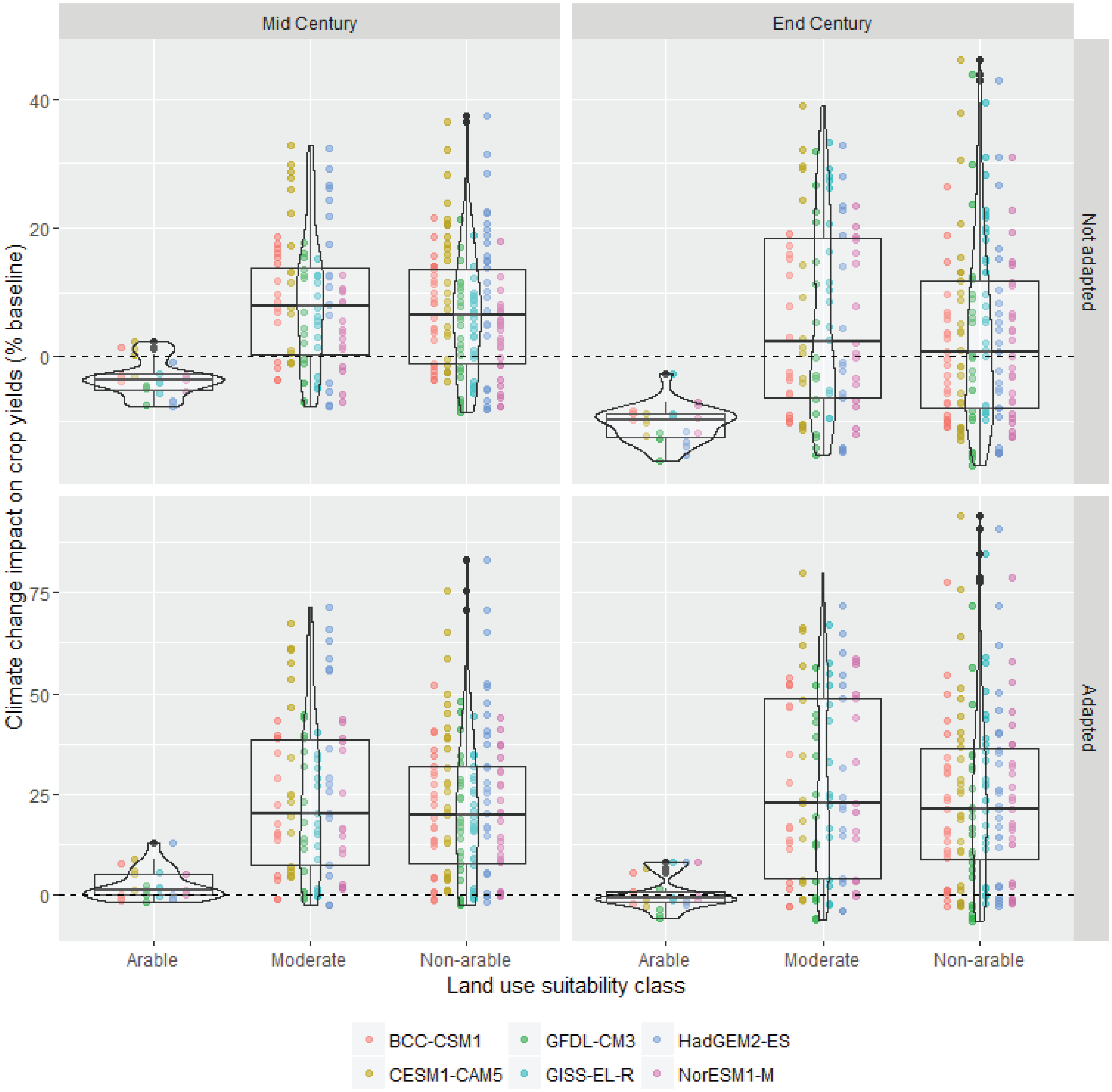

Figure 11: Simulated average climate change impact on silage maize yields within individual grid-cells for six GCMs (colour legends). Distribution pooled across all GCMs and grid-cells (boxplots) for two time-slices (mid- and end-century), with and without adaptation of sowing dates. Note: Simulations for a long-maturity hybrid on a high water holding capacity soil.

The key insights from this analysis refer to quantifying the value of adaptive options available for arable cropping. First, in the case of maize silage, the use of long-maturity genotypes might help minimise negative impacts of climate change. This occurs because warmer temperatures shorten the growth cycle of arable crops, reducing the time available to capture solar radiation for photosynthesis. The use of long-maturity hybrids, which may include introducing genotypes not yet commercially available in New Zealand, could partially counteract the acceleration of crop development caused by high temperatures. Second, results indicate that maintaining current sowing dates will not achieve the same yields under a warmer climate. Earlier sowing dates are necessary to maintain or increase yields. Although the change of sowing dates is a common practice in the management of arable crops, it is important to consider trade-offs with other aspects of the agricultural system not fully accounted in this study, such as the harvest time of previous crops in rotation (Teixeira et al. 2016) and higher risk of frost damage. Third, the possibility of expansion of cropping to higher altitude areas depends on other limitations (e.g. terrain relief and soil characteristics) and on the absolute yields being above thresholds sufficiently high for profitable production. Finally, it is important to notice that this modelling study does not account for all factors that may become important under a warmer climate. This includes, for example, the risk of increase in crop damage by biotic stresses (pests, pathogens, and weeds) and extreme events (floods, heat waves, and storms).

4.1.3.4 Kiwifruit viability

Perhaps the most critical temperature-related time of the year for kiwifruit production is the three-month period May to July. The 'coldness' of this period has a very strong influence on both the quantity and quality of kiwifruit flowers, as well as the timing of flowering. This in turn has a direct influence on the number of buds, the timing of bud-break, and hence the number and quality of fruit produced by the vine. Sufficient 'winter chilling' is therefore vital for kiwifruit production viability. As temperatures increase due to global warming, the risk of insufficient winter chilling also increases, as does the risk of poor kiwifruit crops.

A simple temperature threshold-based empirical model has been developed for assessing current and future (based on six GCMs and four RCPs, out to the year 2100) Hayward kiwifruit viability for the Te Puke area (Tait et al. in prep). The model includes the effects of applying, or not applying, hydrogen cyanimide (a chemical spray that can artificially enhance the winter chilling effect). The model is further used to look at potential future Hayward kiwifruit viability over the entire country.

The output of the Hayward kiwifruit production viability model is a categorisation of each year (from 1971 to 2100, under six GCMs and four RCPs) as either 'good' (i.e. requiring little vine management intervention), 'marginal' (i.e. requiring significant vine management intervention including the possible application of hydrogen cyanimide), or 'poor' (i.e. when climatic conditions have resulted in a relatively poor crop, despite crop management intervention).

Figure 12 shows the decadal frequency of poor production years at Te Puke, over the period 1971–2100, for each of the six GCMs. This shows that while there is some inter-model variability, there is also a very consistent overall pattern of (for the RCP8.5 scenario) a steadily increasing frequency of poor production viability through the middle part of the century, ending with all years being poor.

Figure 13 examines the variation of poor viability for the four RCPs. Only the HadGEM2-ES model is shown to avoid cluttering the plot, but the same general pattern is present for the other five GCMs. This plot shows that RCPs 4.5, 6.0 and 8.5 have a similar profile, while the only RCP that does not yield a full 10 years in a decade with poor production viability is RCP2.6. This is the greenhouse gas concentration pathway which was designed to match the goal of limiting the global mean temperature increase to 2°C above pre-industrial levels, requiring significant reductions in global emissions (plus removal of CO_2 from the atmosphere).

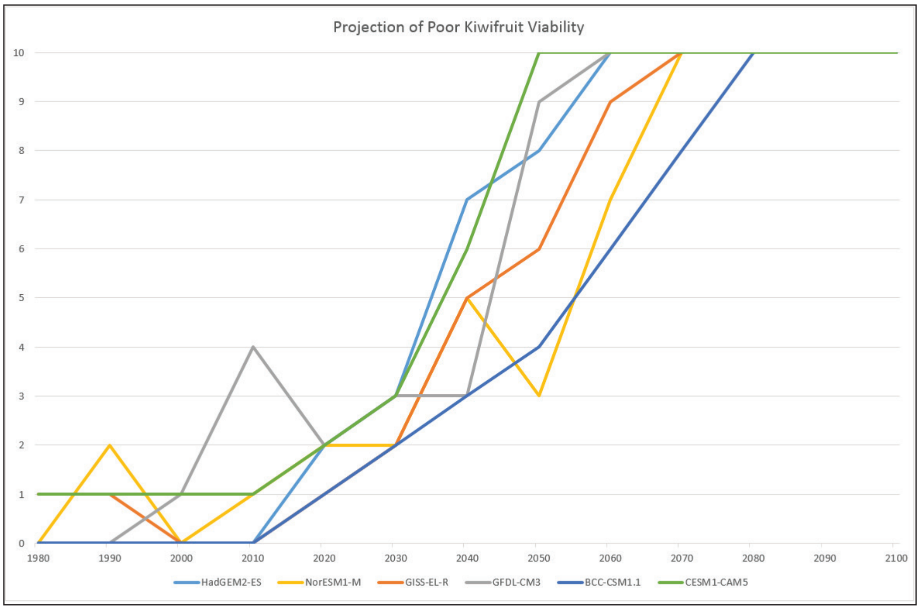

Figure 12: The number of years per decade with 'poor' production viability for Hayward kiwifruit for all six GCMs, based on RCM RCP8.5 simulated data for Te Puke and no application of hydrogen cyanimide. The year on the X-axis is the last year of the decade.

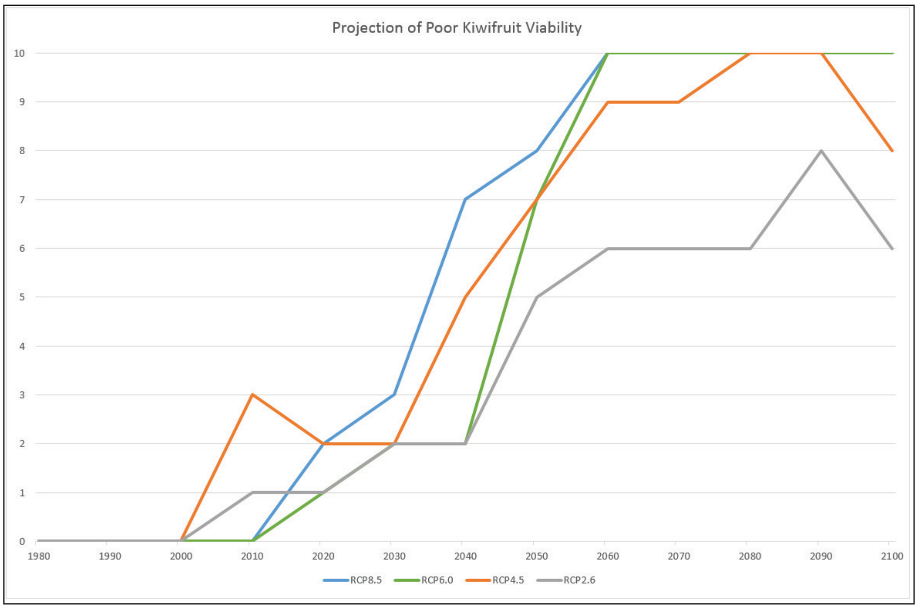

Figure 13: As for Figure 12, but showing all four RCPs for the HadGEM2-ES model.

The above results show that Hayward kiwifruit production viability for the Te Puke area is projected to decrease steadily over time and become consistently marginal by the 2050s and non-viable by the end of the century. The key reason for this is the loss of sufficient winter chilling as the climate warms. However, areas further inland in the Bay of Plenty (away from the coastal plain) as well as several other locations around the country, such as other inland North Island regions and many parts of the South Island (particularly Canterbury), show an increase in viability (based purely on temperature) for this crop variety over the century. In fact, as Figure 14 shows, many regions in New Zealand show good potential by the end of the century even without the application of hydrogen cyanimide (an important consideration, if for any reason the chemical is banned from use).

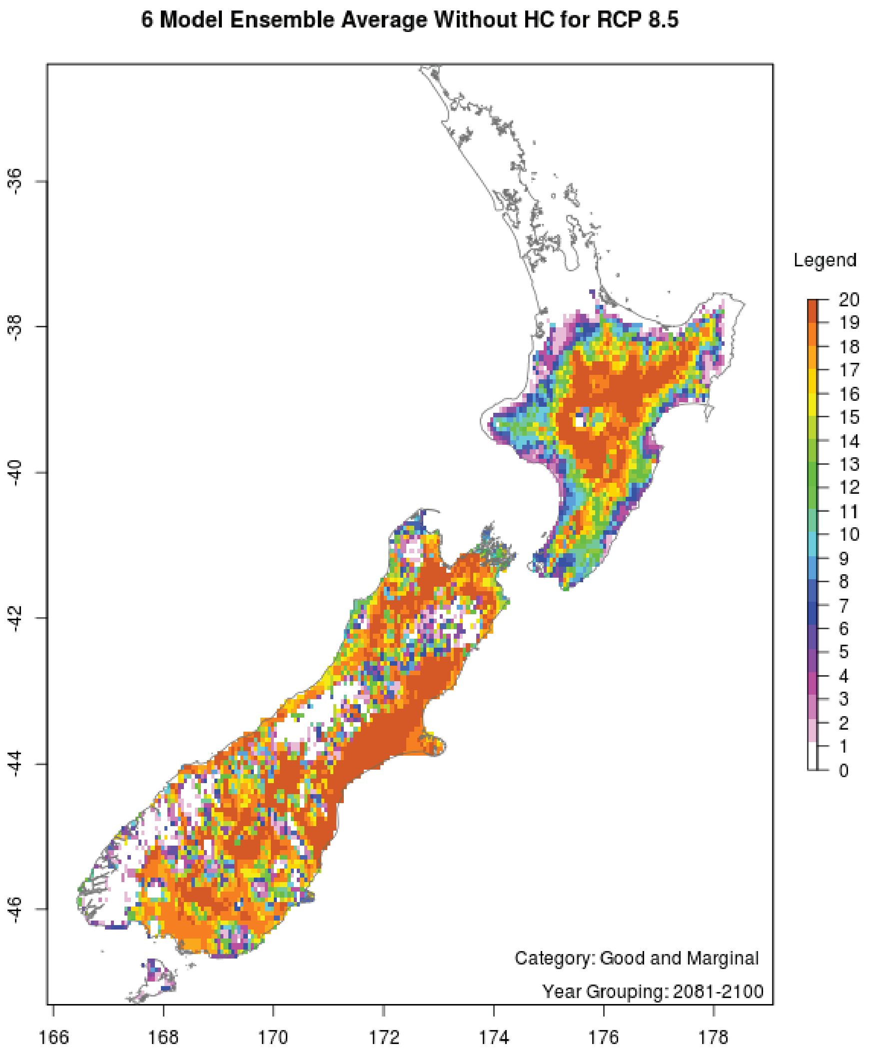

Figure 14: The number of 'good or marginal' Hayward kiwifruit viability years for the period 2081–2100, based on the average of all six GCMs and RCP8.5 (without HC).

Implications – Primary production is likely to be affected heterogeneously throughout the catchment, with winners and losers for cropping, and forestry. Pasture productivity is likely to increase more for the dairy industry than for sheep & beef. However, pasture type may change thus counteracting the productivity benefit. Besides, despite the net positive gain in total annual production, the seasonal feed gap from losses in summer could be significant at a farm level and deserves attention in planning for future change.

Hayward kiwifruit viability in Te Puke and nearby environs is very likely to become 'marginal' by the middle of the century and generally non-viable by its end, as temperatures continue to increase. Application of hydrogen cyanimide in winter greatly enhances long-term viability, but there is a risk that the chemical may be banned from use. If this happens soon, there is an urgent need to look into the viability of kiwifruit production further inland in the Bay of Plenty and in other areas of the country. Of course, detailed site-specific viability investigations, taking all production factors into account, would be required to assess the true potential for these other locations. Nevertheless, it seems clear that through good planning, the New Zealand kiwifruit industry is very likely to remain viable for many decades to come.

4.1.4 Natural ecosystems

In the Kaituna catchment, the climate projections indicate a likelihood of lower rainfall, although the range of projections is large between the models. Reduced precipitation is most likely to affect bogs and gumlands (Table 8) that are not the major wetland types in the Kaituna catchment. For the remaining swamps in the Kaituna, increased precipitation may induce a change in wetland type to a permanently wet state (e.g. ephemeral to swamp); a higher nutrient system (e.g. fen to swamp), or a more aquatic system (shallow water, pond or lake). Lower rainfall would increase pressure on obligate wetland plants (i.e. hydrophyte plants like Carex spp.) and therefore vegetation communities dominated by these species.

Changes in rainfall periodicity or intensity will also have an impact, as it may increase the extent of wetland margins and thus favour facultative dryland species, many of which are alien weeds such as blackberry *(Rubus fruticosus agg.)* and gorse *(Ulex europaeus)*.

Overall, changes in precipitation may impact wetland extent, wetland condition, community composition, or ultimately a shift in either wetland type or ecosystem. In addition, an indirect effect of climate change may be changes to land use within a catchment that subsequently increase pressure on wetland systems and reduce wetland ecological integrity.

Table 8: Likely impacts of climate change on wetland types of New Zealand (from Bodmin et al. 2016).

Wetland type	**Water source**	**Water availability change**	**Potential impacts**
Bog	Rain	Decreased rainfall	• peat growth halted or declines (decomposition) • lagg zone vegetation may change to fen/swamp/terrestrial
Fen	Rain groundwater	Increased rainfall/groundwater	• greater nutrient input from surface run off
		Decreased rainfall/groundwater	• reduction in peat formation • loss of peat
Swamp/marsh	Surface water groundwater	Increased hydrology fluctuations	• pulses of nutrients and sediments from surrounding catchment land use
		Decreased surface and/or groundwater	• wetland extent decreased • ecotone extent increase with dryland species invasion
Gumland	Rain	Decreased rainfall	• increased fire frequency and/or intensity • peat loss • invasion of dryland species • loss of extent
Pakihi	Rain	Increased rainfall	• ponding with shallow water accumulation
Ephemeral	Rain Groundwater	Increased rainfall	• shift to permanent wetland or aquatic habitat • loss of plant species adapted to wet/dry fluctuations
		Decreased rainfall	• loss or reduction in wetland extent • invasion of dryland species

Implications – Freshwater wetlands are largely dependent on the amount of rainfall and surface runoff. Future projections in the Kaituna catchment are showing a likelihood of decrease in precipitation. This might have consequences for the wetland vegetation, increasing the risk of invasive species and costs for weed control.

4.1.5 Pests and disease

New Zealand's economy is heavily reliant on primary production generating 65% of our export earnings by exploiting introduced plants and animals. Biosecurity is of critical importance to protect the production system as New Zealand's climate is highly suitable for both the species in use and the pests and diseases that impact on them. Equally important is the threat and impact that unwanted pests could have on New Zealand's native and endemic plants and animals (Kean et al. 2015). The Parliamentary Commissioner has stated that 'Introduced pests are the greatest threat by far to New Zealand's native plants and animals' (Wright 2011).

Climex (Kriticos et al. 2015) is a mechanistic species distribution model that elaborates a species response to climate; using the average maximum and minimum temperatures, rainfall and relative humidity of its current (and documented) geographic distribution and seasonal phenology, which then can be used to identify other potentially suitable locations.
A range of indices predict growth and indices that assess limiting conditions such as the survivability of periods of extreme cold, heat, wetness or drought, and combinations of these stresses, e.g. hot and wet, cold and wet (stress indices). These indices are combined into the Eco-climatic Index (EI), an overall measure of the potential of a given location to support a permanent population. EI is scaled between 0 and 100, with an EI close to 0, indicating that the location is not favourable for the long-term survival of the species. Hence, Climex enables the ability to project relative abundance and distribution of modelled species anywhere in the world (Sutherst & Maywald 1985, 2005; Baker et al. 2011; Kriticos et al. 2015).

This research is limited to species where there was an existing Climex model on the Climenz website[3] and where the model did not contain any parameter inconsistencies. No new models were developed. This updates some of the models that have been run using earlier climate change projections.

For each of the pest species the following data have been developed:

- Raster images of EI for each of the GCM X RCP X 5 year (c. 552 images/species)
- Raster images of EI for each GCM X RCP X three normal periods (2005, 2050, 2090) (72 images species)
- Raster images of MAX EI of RCP's, for each GCM X three normal periods (2005, 2050, 2090) (18 images/species)
- Raster time difference images of MAX EI of RCP's for each GCM. 2005–2050, and 2005–2090

Maps showing the EI progression of a selection of species are given below based on the normal analysis. National maps (as pdfs) will be made available via the www.ccii.org.nz website and on the climate cloud (www.climatecloud.co.nz).

The EI is the maximum value from each of the six RCM's., hence can be considered a worst case projection. EI is a climate index only, and hence assumes that there are pathways for incursion and also that the necessary habitat is present to sustain the population.

4.1.5.1 Alligator Weed

Alligator weed (*Alternanthera philoxeroides*) is one of the greatest threats to rivers, wetlands, and irrigation systems in the world. It is extremely difficult to control, as it is able to reproduce from plant fragments and grows in a wide range of climates and habitats, including terrestrial areas. In aquatic habitats alligator weed has deleterious effects on other plants and animals, water quality, aesthetics, vector populations, water flow, flooding and sedimentation. In terrestrial situations, it degrades pasture, turf, and crop production, producing massive underground lignified root system penetrating up to 50–60 cm deep. Figure 15 shows an increase of optimal areas developing from the north by 2050, as well as a smaller increase in areas from the coastline inland. It implies that incursions starting on the coast where there is appropriate land cover and are remote could become established but 'hidden' populations.

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[3] http://b3.net.nz/climenz/index.php

4.1.5.2 Pitch Canker

Pitch canker is a highly virulent pathogen damaging pines, and it is considered the most important pathogen affecting Pinus seedlings and trees globally. It can affect seedlings in nurseries and asymptomatic seedlings can be planted out. It is spread by insects, water splash, or the wind, infecting wounded trees such as those damaged by strong winds or pruning. The analysis shows that Pitch canker, which is not present in NZ, is highly suitable in the case study area. Changes in EI due to climate change projections show a continuing increase in optimal areas arising from a reduction in unsuitable locations (Fig. 16), especially over the next 20–30 yrs.

4.1.5.3 Queensland Fruit Fly

Queensland fruit fly is one of the most damaging fruit fly pests as it infests more than 100 species of fruit and vegetables. Its hosts include commercial crops such as avocado, citrus, feijoa, grape, peppers, persimmon, pipfruit, and summer fruit. The fruit fly would have serious consequences for New Zealand's horticultural industry if it were to establish in New Zealand. Queensland fruit fly, eradicated from NZ, shows an almost complete reduction in unsuitable areas, and a change from suitable to optimal areas (Fig. 17). While other species may have a narrow range of hosts, fruit flies can exploit many plants, most of which can be found in cities and gardens as well as in productive land used.

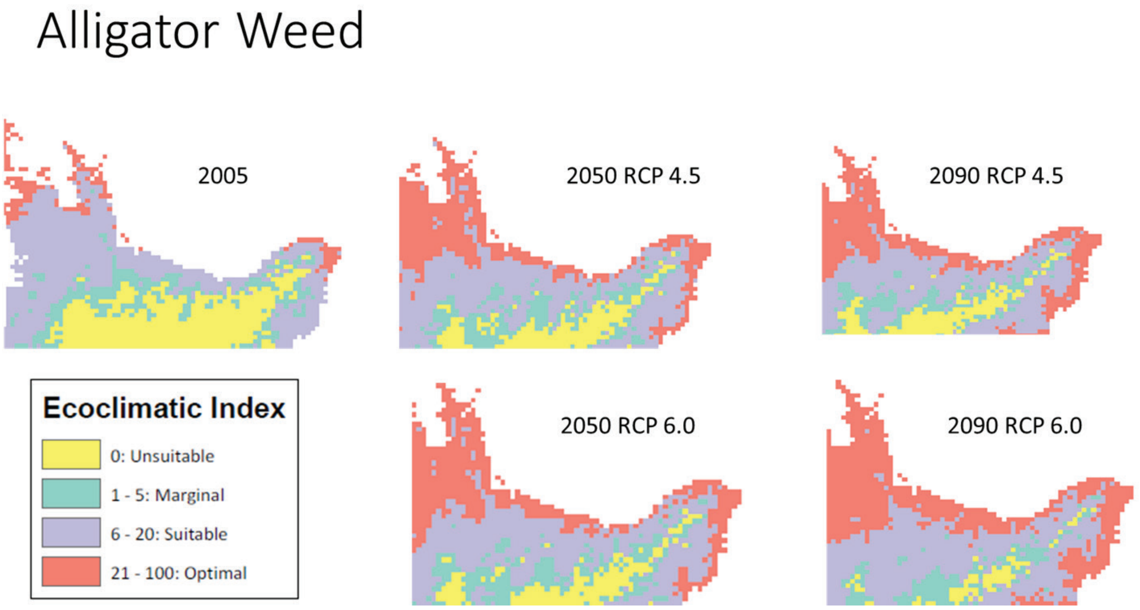

Figure 15: Maximum Ecoclimatic index of Alligator Weed under RCP 4.5 and RCP6.0. The EI is the maximum estimated for each 5 km × 5 km pixel from six regional climate models.Hence is can be interpreted as a worst case projection. EI provide an understanding of land areas that can sustain a population based on climate parameters; it does not include factors such as the incursion source or pathways and likelyhood, nor other non-climatic factors that may enable or inhibit population establishment and survival such as host availability or the presence or absence of predators.

Pitch Canker

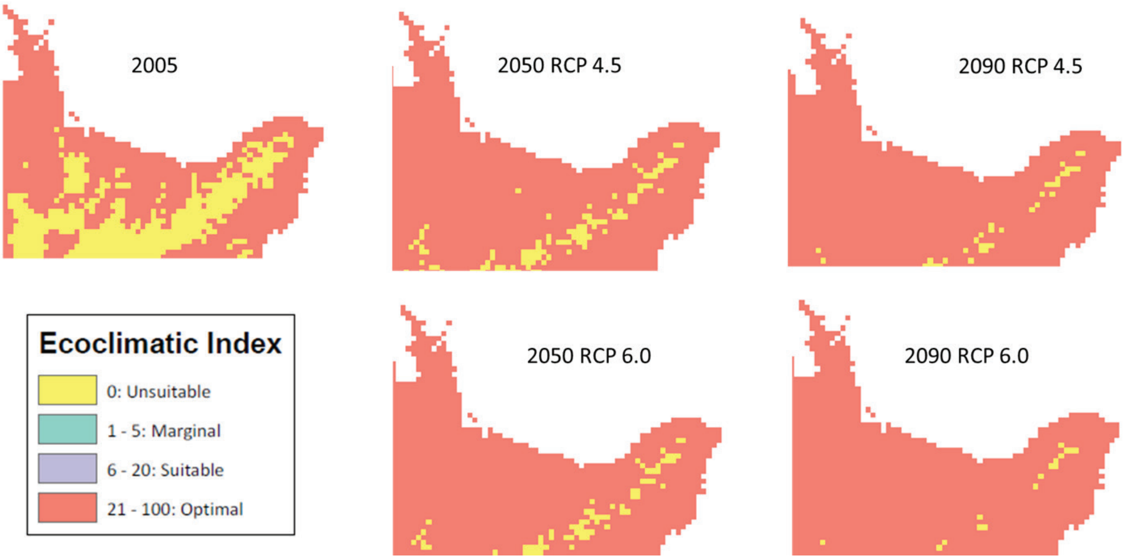

Figure 16: Maximum Ecoclimatic index of Pitch canker under RCP 4.5 and RCP6.0. The EI is the maximum estimated for each 5 km × 5 km pixel from six regional climate models.Hence is can be interpreted as a worst case projection. EI provide an understanding of land areas that can sustain a population based on climate parameters; it does not include factors such as the incursion source or pathways and likelyhood, nor other non-climatic factors that may enable or inhibit population establishment and survival such as host availability or the presence or absence of predators.

Queensland Fruit Fly

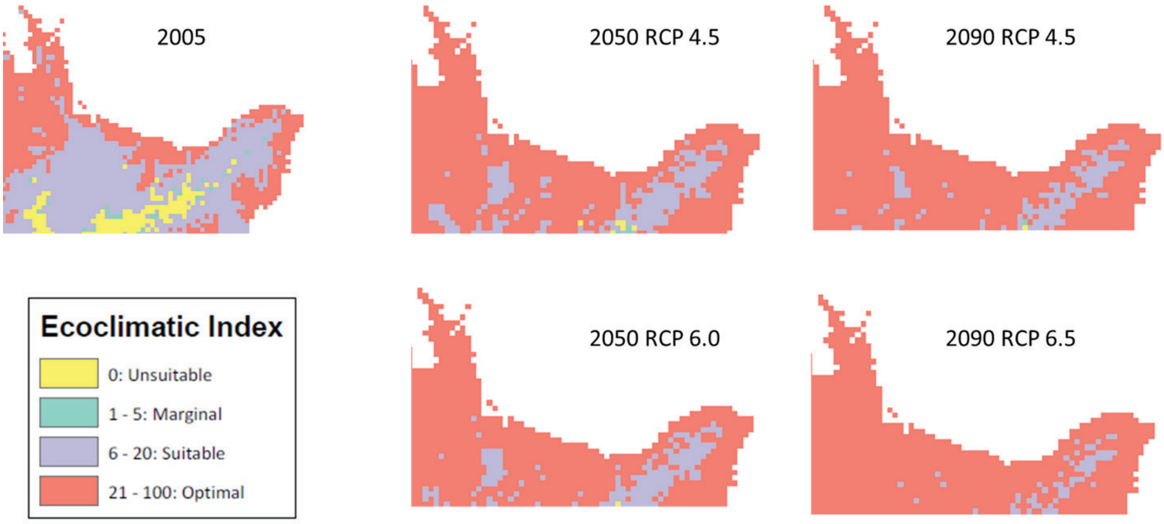

Figure 17: Maximum Ecoclimatic index of the Queensland Fruit fly under RCP 4.5 and RCP6.0. The EI is the maximum estimated for each 5 km × 5 km pixel from six regional climate models. Hence is can be interpreted as a worst case projection. EI provide an understanding of land areas that can sustain a population based on climate parameters; it does not include factors such as the incursion source or pathways and likelyhood, nor other non-climatic factors that may enable or inhibit population establishment and survival such as host availability or the presence or absence of predators.

Implications – Climate is one of the major factors limiting the distribution of plants and cold-blooded animals, hence changes in climate and climate distribution are expected to amplify the risk and impacts of pests being able to establish populations in New Zealand, with larger areas being more suitable for the establishment of current and known pests as well as becoming attractive to pests that are not currently able to establish populations in NZ. Climate change also increases the risk associated with 'sleeper' weeds, the >30,000 plants that are in gardens that could become more invasive threatening indigenous and productive ecosystems.

4.1.6 Economic modelling and land-use change

4.1.6.1 CliMAT-DGE

For this analysis CliMAT-DGE was calibrated to closely match projections published in the IIASA RCP and SSP databases (IIASA 2016). In this case, we focused on Global and New Zealand population, gross domestic product (GDP), and GHG emissions for the RCP8.5 and SSP3 scenario. Doing so facilitated the estimation of global and domestic commodity prices that could be used as inputs to other modelling used in this study, namely for the NZFARM and LURNZ Models. This scenario estimated that the largest increases in commodity prices would occur for oil, sheep & beef, forest products (logs), and milk, which could increase by 80% or more above 2012 levels by 2050 (Fig. 18). All commodity prices are estimated to increase at least slightly over time due to increases in demand associated with large global population growth.

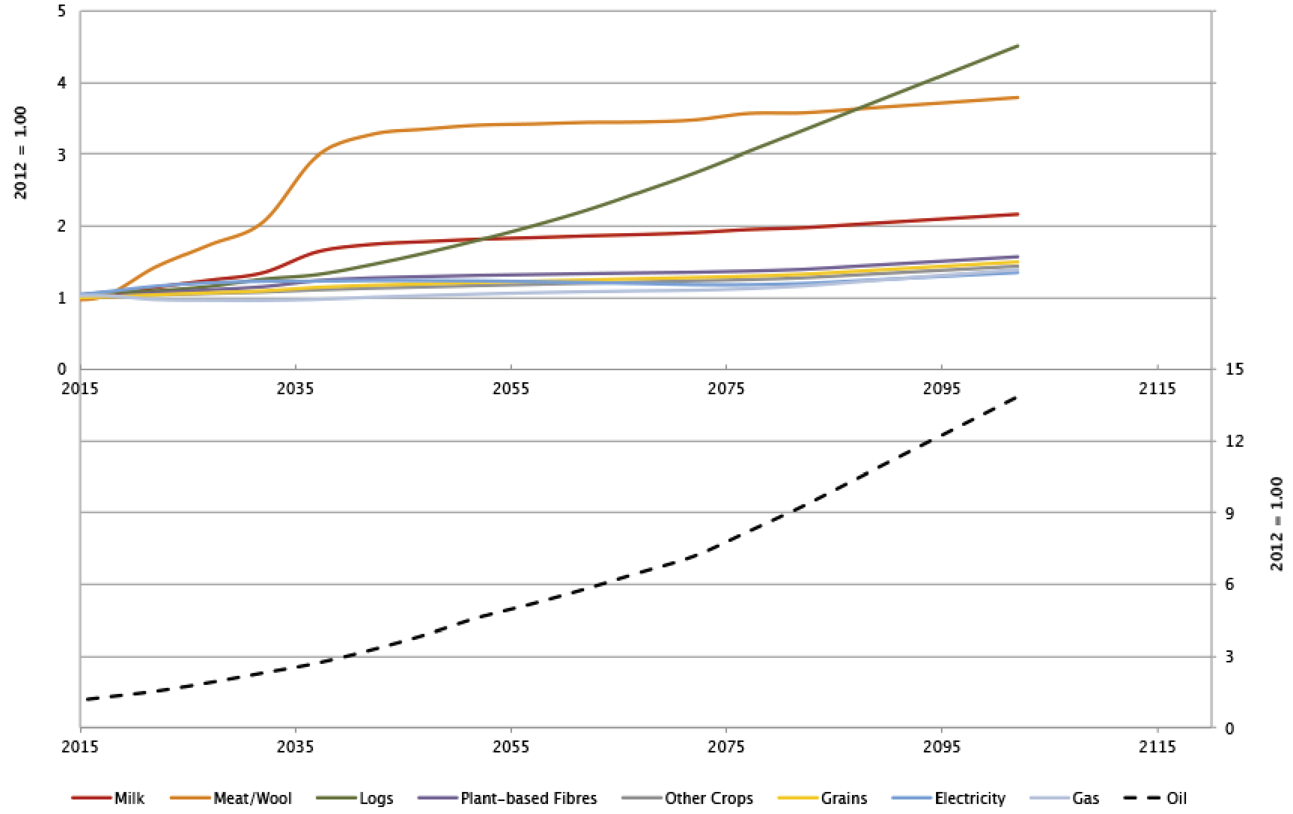

Figure 18: SSP3 agricultural commodity price index.

4.1.6.2 NZFARM

The scenario analysis focused on estimating land-use change and resulting impacts on net farm revenue and environmental outputs in 2065 and 2100 under the following conditions: (1) SSP3-only (price effect); (2) RCP8.5-only (yield effect); and (3) combined RCP8.5 and SSP3 (price and yield effect). The greatest change in land use over the different scenarios is estimated to be between forest plantations and sheep & beef farms. This is because under the RCP only scenario, forest yields are estimated to increase more than pasture or arable. However, when the effects of SSP3 are also accounted for, the large price effects estimated in CliMAT-DGE cause sheep & beef to be relatively more profitable and hence there is a large shift 'back' into that land use. The other land uses tracked in NZFARM, including arable and dairy, are not estimated to change nearly as much (Fig. 19). In addition, there is a greater change in land use relative to 2015 areas when the SSP3 impacts are accounted for in the model simulations as opposed to just accounting for potential yield changes under a RCP8.5 climate trajectory.

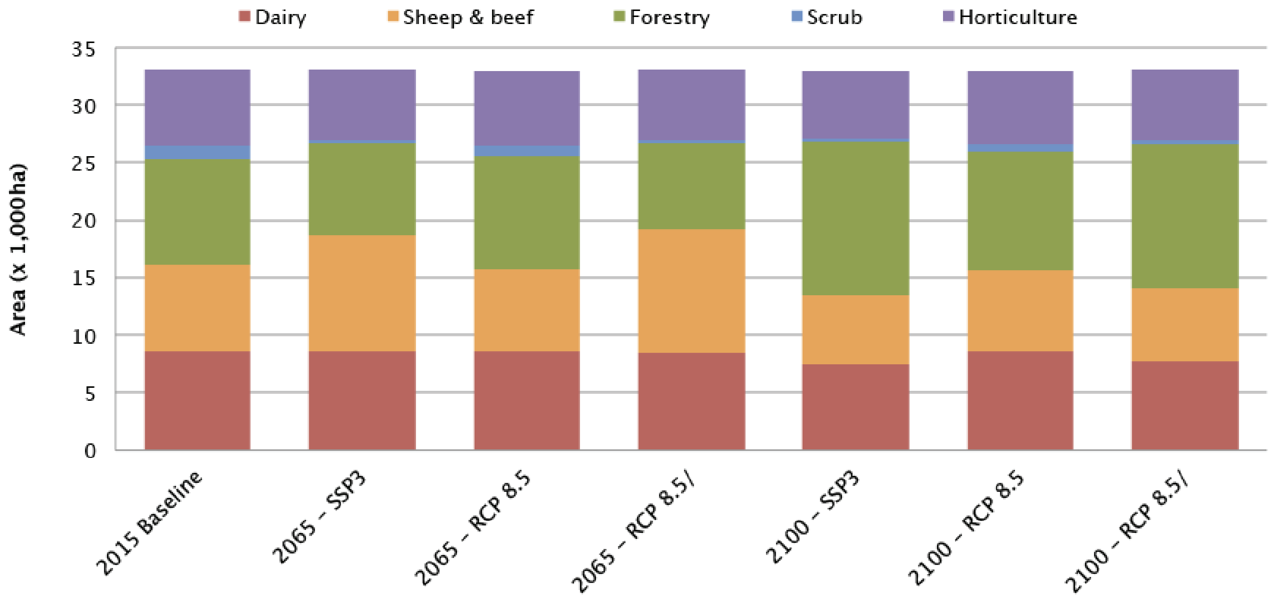

Figure 19: NZFARM estimated land use area (ha) in Kaituna catchment.

The key economic and environmental output estimates for each scenario are summarised in Table 9. These findings indicate that just accounting for the RCP8.5 yield effect results in a relatively small change in aggregate outputs compared with the scenarios that account for the SSP3 effect. When accounting only for yields, net farm revenue is estimated to increase between 7 and 13%, while reducing freshwater environmental outputs by 1–4%[4]. In all cases when SSP3 is included in the simulation, net farm revenue is estimated to increase dramatically – from 176 to 402% over the next century – due to landowners switching into more profitable land uses, producing more output per hectare because of climate-induced yields, and an increase in real commodity prices relative to 2015 (see Fig. 18). As a result of much of the land use change into sheep & beef by 2065, but then to forestry by 2100, environmental outputs increase over the first half of the century before declining as the result of a greater number of trees in the catchment relative to today (and the RCP-only scenarios).

Table 9: Summary of Key Findings for NZFARM analysis (per annum)

Scenario	**Net Revenue (million $)**	**Gross GHG Emissions (t)**	**Net GHG Emissions (t)**	**N Leaching (t)**	**P Loss (t)**	**Soil Erosion (t)**
2015 Baseline	**$80.3**	**139,186**	**-129,557**	**507**	**21**	**54,533**
% Change from BaselineConstant CO$_2$						
2065 – RCP | 8.5/SSP3	187%	7%	–29%	3%	13%	4%
2065 – RCP 8.5	7%	–2%	12%	–1%	–2%	–2%
2065 – SSP3	176%	9%	–41%	3%	16%	6%
2100 – RCP | 8.5/SSP3	402%	–13%	85%	–10%	–14%	–11%
2100 – RCP 8.5	13%	–2%	21%	–1%	–3%	–4%
2100 – SSP3	346%	–10%	66%	–8%	–10%	–9%

4.1.6.3 LURNZ

High-resolution land use change scenarios were also developed using the LURNZ model. The model and scenarios were set up to be as closely comparable to NZFARM scenarios as possible. Complete consistency across the two models, however, was not feasible due to their different structure and data requirements.

Being based on econometrically estimated functions, LURNZ may be more sensitive to situations in which projected values of an explanatory variable lie outside the historical range. This feature of the model will have implications for the interpretation of our simulation results as projections of future prices under SSP3 are far beyond their sample range.

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[4] N.B. baseline net GHG emissions are negative as annual forest caron sequestration is greater than livestock, crop, and fertiliser emissions

Figure 20 summarises the LURNZ results for the Kaituna catchment. Only dairy, sheep & beef, forestry, scrub and horticulture areas are modelled and hence reported.

LURNZ suggests that the majority of land-use adjustment in the catchment occurs between sheep & beef and dairy farming. By comparison forestry and scrub changes were relatively small. This contrasts with the NZFARM results, where the greatest land-use change was between forestry and sheep & beef farming[5].

Two important caveats affect the validity of the SSP3 results in LURNZ. First, the commodity price paths under SSP3 stretch the model beyond its traditional use and limits. Figure 21 shows both historical prices, on which LURNZ is estimated, and projections of future prices under SSP3. All commodity prices exceed their historical maximums by the end of the century, with sheep & beef and forestry prices experiencing a three-to-five-fold increase from 2012. We do not expect out-of-sample predictions from LURNZ to be reliable under these extreme circumstances because the estimated relationship between prices and land-use areas is unlikely to hold. Second, price effects are best modelled at the national (or regional) scale in LURNZ – the small size of the Kaituna catchment renders the results more sensitive to modelling artefacts arising from the spatial allocation algorithm.

Therefore, the estimated SSP (and hence the combined RCP & SSP) scenarios are not expected to be robust under SSP3. We discuss these only briefly for completeness.

Due to the dynamic nature of the LURNZ model, the interpretation of its land-use results is slightly different to NZFARM. In LURNZ, it is necessary to account for what would have happened to land use without the SSP3 price or RCP8.5 yield changes under the future baseline (Fig. 22).

Panel b of Figure 23 puts the land-use change under the various price and yield scenarios in context of the baseline change[6]. For example, the projected baseline afforestation of around 1,500 hectares of sheep & beef land is averted under SSP3 due to the steep rise in sheep & beef prices. The direction of this SSP3 price effect is consistent with the NZFARM results. Also, by the end of the century, high log prices cause forestry to rebound and increase beyond baseline levels in both models.

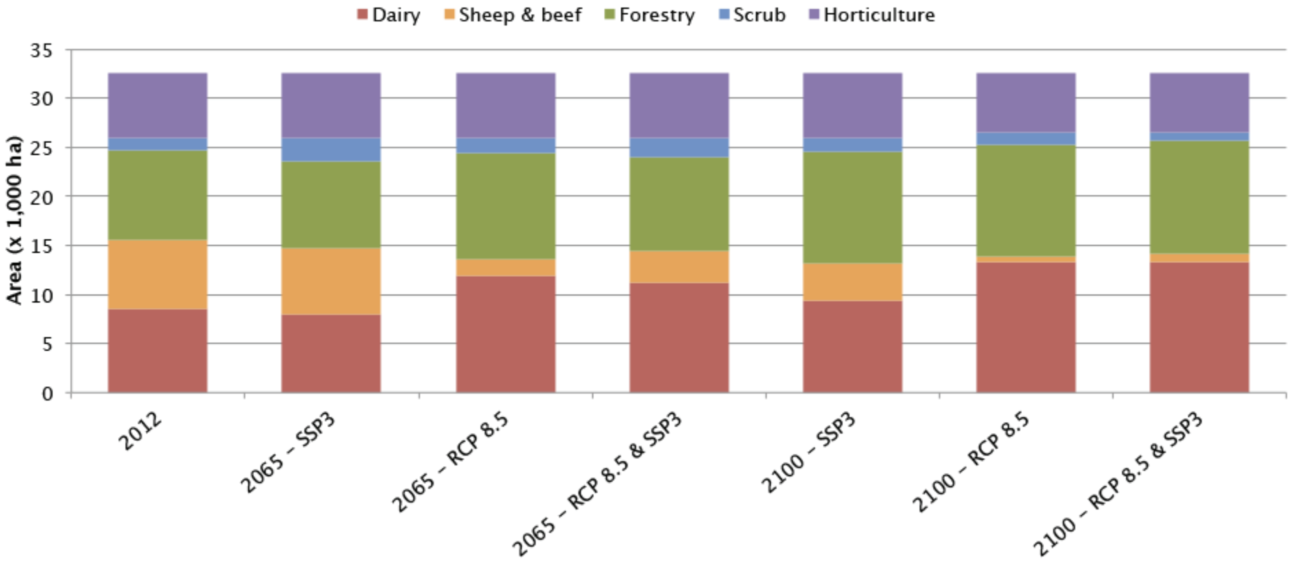

Figure 20: Projected distribution of land uses in the lower Kaituna.

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[5] However, it will be shown that accounting for baseline change leads to more consistency across the model results.

[6] Technically, the baseline depicted is for 2065. However, the 2100 baseline is nearly identical: as there are no price changes beyond 2019 and modelled baseline land-use has nearly reached its equilibrium by 2065.

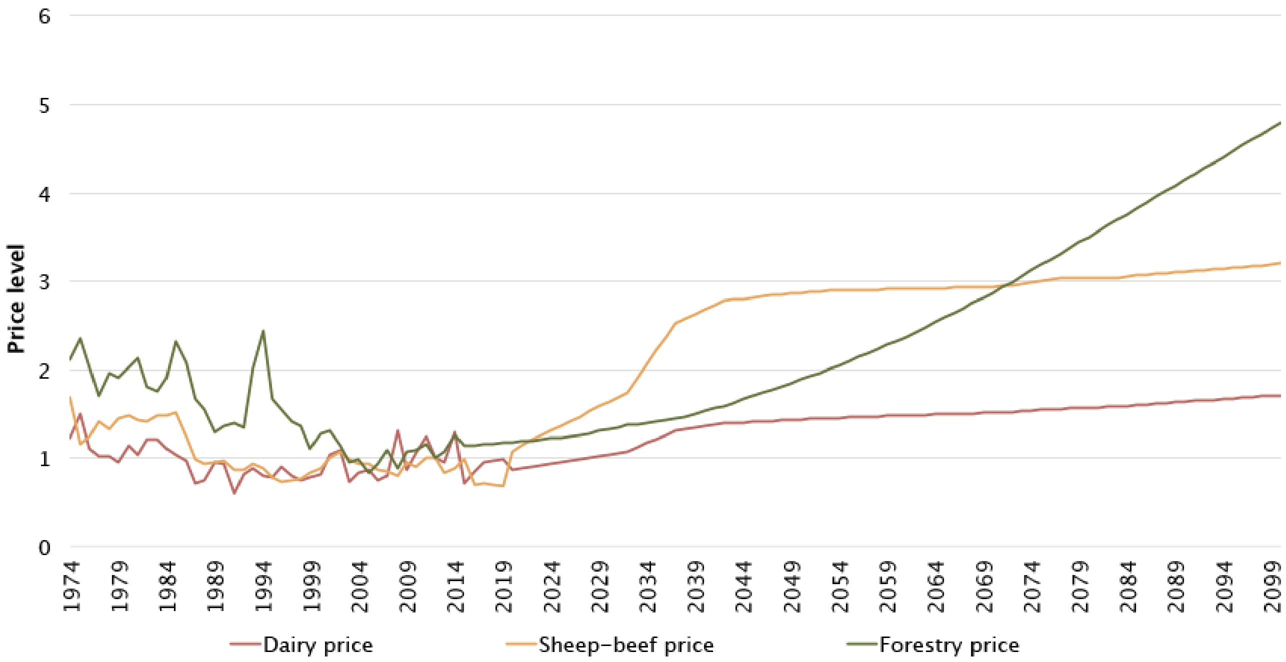

Figure 21: Historical prices and SSP3 price projections (scaled to the 2012 price level).

The main effect of yield changes is projected to be a shift from sheep & beef to dairy[7]. This is intuitively consistent with the general increase in pasture yields, and also with relative yield changes in the two pastoral sectors: the biophysical modelling suggests that the increase in dairy yields generally exceeds the increase in sheep & beef yields (Timar 2016). There is also a reduction in scrub area (relative to the baseline) with small changes only in forestry and horticulture land uses within the catchment[8].

These yield effects are based on average predictions from the six GCMs listed in the previous section. Testing has revealed that the choice of climate model is not driving these results[9]: the projected land-use change under each of the six individual GCMs is largely consistent with the results in Figure 23.

The LURNZ estimates therefore suggest that both economic and climate conditions under RCP8.5 and SSP3 may lead to further intensification of land use in the catchment. In particular, the area of land in dairy rises in all scenarios by the end of the century. The large increase in dairy area could put pressure on the catchment's water resources. On the other hand, some negative environmental consequences may be mitigated by the projected increase in forestry area by (and beyond) 2100.

While the magnitude of land-use responses is relatively large in LURNZ, it is important to note that the implied rate of land-use change over the simulation horizon is not larger than the rate at which land use in New Zealand has been changing historically.

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[7] The yield effect in LURNZ i.e. captures changes in pasture yields only. However, to the extent that these are correlated with yields in other land uses, some of the effect of other yields will also be reflected in the results (Timar 2016).

[8] A robustness check was performed by repeating the catchment-scale modelling using a probabilistic method that bypasseses LURNZ's spatial allocation algorithm. For Lower Kaituna, the probabilistic method tends to decrease the size of the yield effect: changes in dairy and sheep & beef are reduced by about 25%, and the change in scrub is much smaller using this alternative method.

[9] Sensitivity testing of NZFARM revealed the same finding.

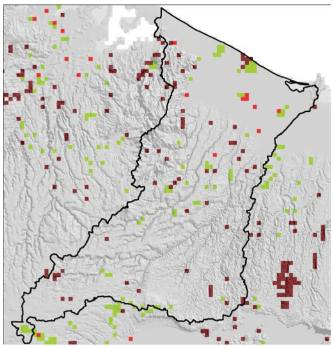
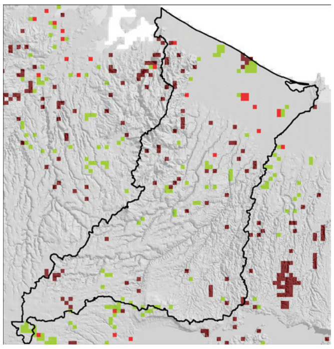
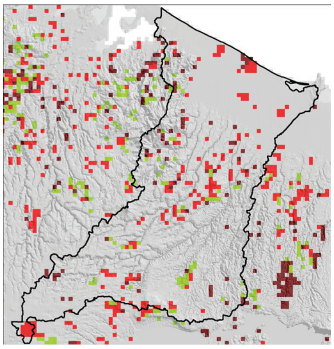
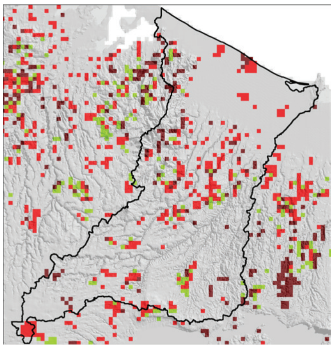
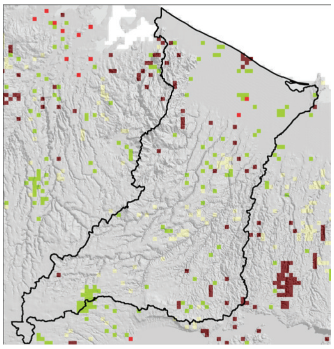
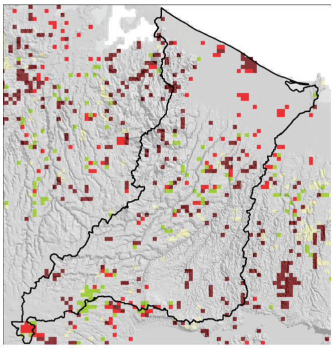
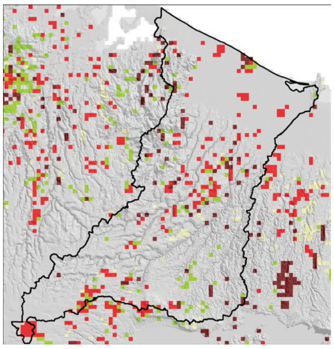
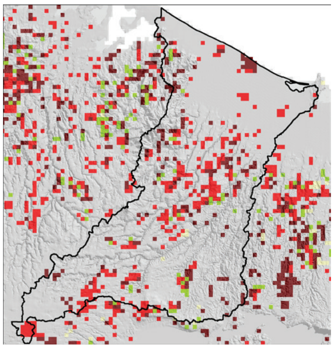
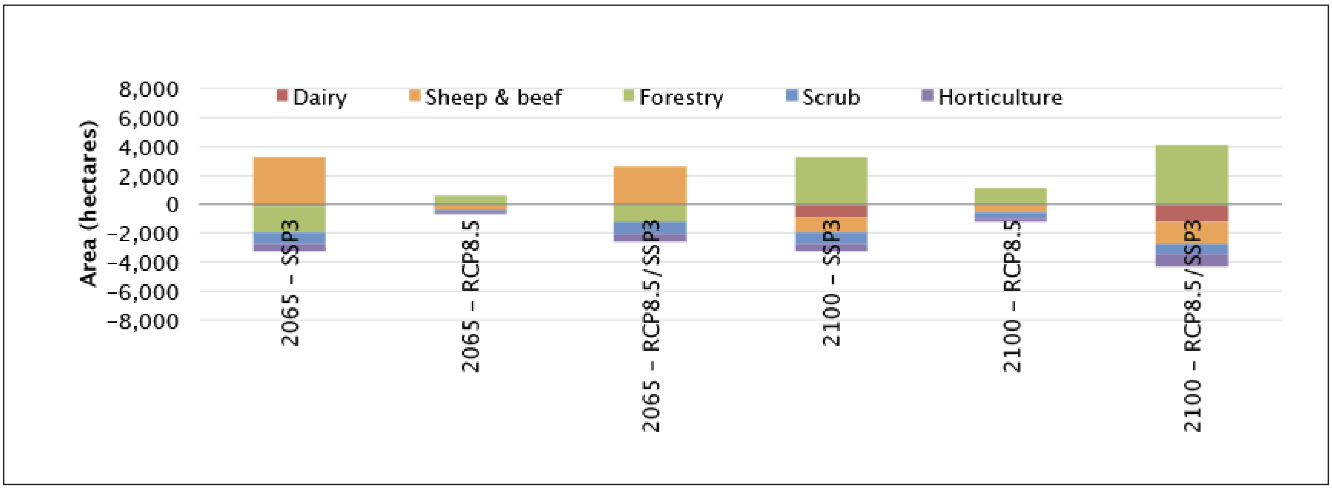
Legend ☐ Kaituna catchment ⬜ No change 🟥 New dairy 🟨 New sheep and beef 🟫 New forestry 🟩 New scrub	**2065**	**2100**
Baseline change		
RCP8.5		
SSP3		
RCP8.5 & SSP3		

Figure 22: LURNZ results of projected changes in land use in 2065 and 2100 from 2012, for the baseline, RCP8.5 only, SSP3 only and RCP8.5 and SSP3 combined scenarios.

a) *NZFARM*



b) *LURNZ*

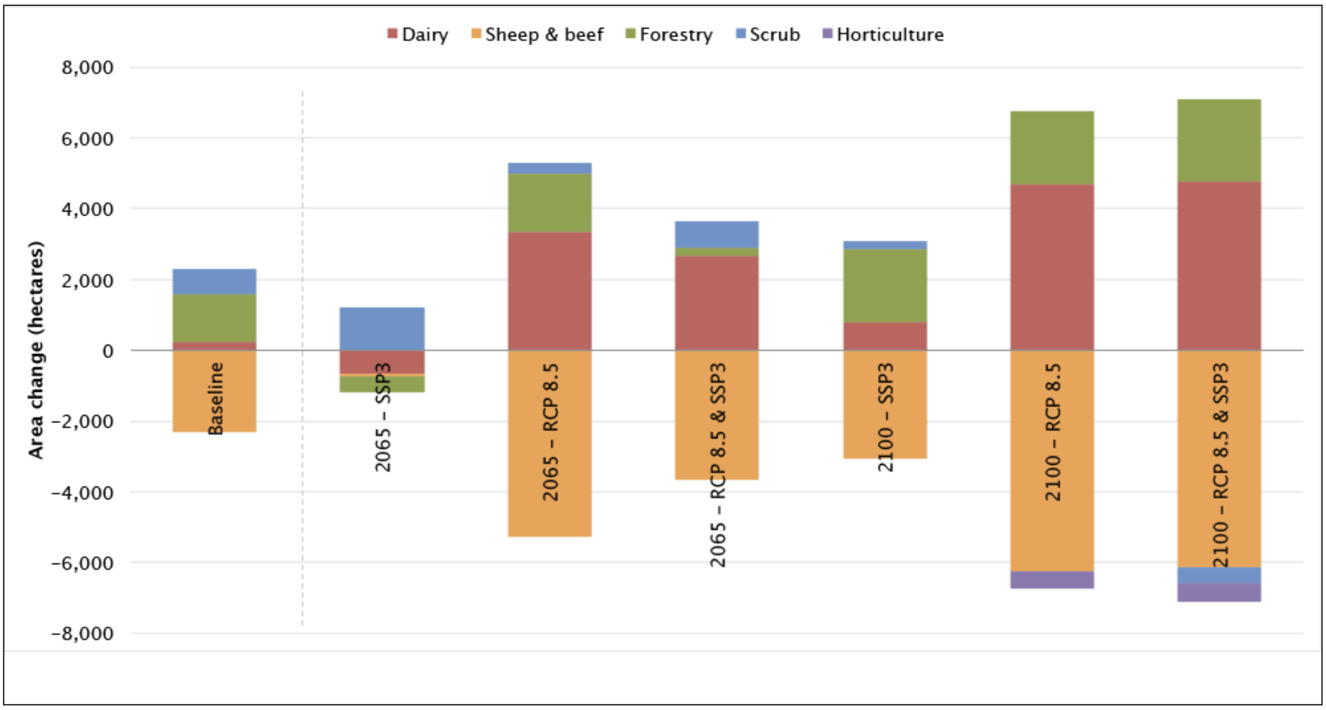


Figure 23: Comparison of area change from 2012 in (a) NZFARM and (b) LURNZ.

Implications – Land-use changes in the Kaituna catchment are projected to be affected by both the socio-economic pathways and climate change. The SSP3 scenario is projecting high log and sheep & beef prices compared with dairy prices. By comparing two land-use change models, we found there is generally a shift from sheep & beef farming to forestry by the end of the century. High log prices cause forestry to increase beyond baseline levels in both models. However, discrepancies in model assumptions (NZFARM accounts for arable and forestry biophysical condition changes) and structure (LURNZ accounts for historical changes) meant there were differences in dairy changes (opposite directions) and magnitude. This implies further investigations on scenario settings to better understand the future contribution of economic versus climatic factors. Regardless, the consistent result of an increase in afforestation by 2100 suggests that environmental outputs such as GHG emissions and freshwater contaminant loads could be offset or reduced over the next century, even if there is some intensification in other parts of the catchment.

4.2 Integrated assessment for scenario RCP8.5/3/A

Following the results from the previous sections, we assessed a scenario for combination RCP8.5/3/A (Ausseil et al, 2016). Table 10 shows the direction of change up to 2100 from the quantitative models relative to a 'baseline' case with no climate change and historical socio-economic conditions. These quantitative results were interpreted to support narrative statements for each element of Table 4, which we discuss in more detail below.

Table 10: Results from the quantitative assessment for scenario RCP8.5/SSP3/A (a ○ is less than 5% change, white triangle is a minor change, >5% and <=10%; grey is a medium change, >10%; black is a major change, >20%;)

Categories	Elements	Change
Demographics	Total population	○
Economic Development	Land-use change:	
	Area in dairy	▲
	Area in sheep & beef	▼
	Area in forestry	▲
	Forestry productivity	○
	Maize	△
	Pasture	△
	Kiwifruit suitability	▼
Environmental and ecological factors	Wetland vulnerability	○
	Erosion (soil loss)	▲
	Pests and disease suitable areas	▲
Resources	Water (river) discharge	▽
	Land at risk of sea level rise	▲

Table 11: Narrative implication results for scenario RCP8.5/SSP3/A

1 Demographics The rural population could continue to decline. Rural areas typically have older populations, which leads to lower natural increase (or even natural decrease) of the population (Jackson & Cameron 2015). Ageing is likely to lead to a less mobile population that is less able to avoid hazardous situations like flood events. The New Zealand population is projected to peak at 5 million in 2040 (compared with the current population of just over 4 million). Development on coastal areas may slow or stop. As a result of a declining rural population there is likely to be further agglomeration of farm enterprises (Cameron et al. 2010)
2 Economic development In general, we could expect a decline in New Zealand's economic health. Food security, both internationally and within New Zealand, is expected to be a major driver, leading to a decline in overseas markets/trade (e.g. kiwifruit) and increase in diverse, local markets. The limiting factor for primary production is likely to be appropriate and consistent access to water and the impacts of any extreme weather events. For our scenario, we found that dairy farming and forestry is likely to increase to the detriment of sheep farming. A concern for the catchment might be the decline of kiwifruit biophysical suitability due to lack of winter chilling, adding extra costs to production by requiring the use of chemicals to improve flowering (Linsley-Noakes 1989). This could be exacerbated by increased costs due to disease outbreaks and infrastructure costs. Regional climatic suitability for agricultural crops will change. For example, areas currently limited by low temperatures will be more suitable for cropping and rain-fed agriculture will become more vulnerable to drought, particularly for soils with low water holding capacity. However, low prices for grains relative to other commodities (Fig. 18) may continue to limit growth in area of arable cropping in the catchment.
3 Environmental and ecological factors If land is abandoned due to unfavourable climatic or trade changes, it could revert to natural wetlands. On the other hand, the productive land affected by sea level rise could also shift to existing wetlands. However, lack of funding for control measures could exacerbate the spread of exotic plants in wetland areas and create a risk for weed infestation of nearby cropping and pastoral farming. Native forests, wetlands and rivers could see a decline or altered biodiversity due to pest invasions, increased sedimentation, water diversion for economic uses, salinisation in the coastal zone and lack of funding for conservation. With warmer temperatures, pests currently limited to warmer climates could expand their range into the case study area and become more prolific, causing a reduction in abundance or loss of native species. Water discharge could reduce due to a reduction in precipitation, creating water stress during summer. An estimated increase in the area of pine plantations could reduce freshwater contaminant loads and GHG emissions (Table 9).
4 Resources Fuel costs are expected to rise with an increased reliance on fossil fuel-based electricity, primarily coal. This, in turn, could increase primary production and household utility costs and use of public transport. The tourism sector could suffer from these additional costs through greater travel costs. The coastal zone could be impacted by sea level rise, affecting agricultural land (mainly dairy and maize cropping).
5 Human development/welfare Sea level rise is expected to lead to a decline in coastal property values and eventual abandonment of the most vulnerable properties due to coastal encroachment. Human vulnerability to natural disasters could increase due to more frequent extreme events (e.g. floods). Life expectancy may decline, especially with potential reduced funding for healthcare services and the likely increases in the incidence of infectious diseases, with coastal areas becoming an increasingly important reservoir for disease vectors such as mosquitoes.
6 Institutions & governance (excluding climate policies) Due to limited investment in sector/catchment-scale adaptation options to reduce risks, flood events could increase dramatically from added sedimentation in the rivers and lack of funding to raise stop banks. Road networks are likely to deteriorate, worsening the economic conditions in the region. Social inequality could deepen due to increased costs to farmers and inability to pay. Global agreements such as Kyoto Protocol could be regularly breached and contingent liability could be transferred to central government.
7 Technological development We assume that no new climate change mitigation options will be developed, but that local adaptation solutions will be created in a reactive way, lagging behind global initiatives. We expect that fewer research efforts will be funded by government and more by industry.
8 Broader social factors There could be a general disconnect from nature; recreation in and aesthetic appreciation of the outdoors rank low on the list of people's priorities due to the high cost of living.
9 Policies (excluding climate policies) Loss of population and sea level rise could lead to ad hoc coastal protection. Insurance may be difficult to obtain or would not cover natural events. Development initiatives could be market-driven and lacking policies to include social, environmental or cultural elements.

This integrated assessment provides an overview of potential future impacts of both climate change and socio-economic changes in a typical lowland environment of New Zealand. We demonstrated the use of quantitative models and narrative statements for one particular scenario (RCP8.5/SSP3/A), in which there is almost no attempt to curtail climate change on a global scale and only very limited, reactive local efforts. In this scenario, costs of production would generally increase due to a need for increased environmental management for pest control and water shortages, with a higher risk for a decline in commodity prices due to increased global competition.

While we used categories of key elements from O'Neil et al. (2013), not all elements could be modelled quantitatively, either because our understanding of the behaviour of societies is not sufficient to model or predict anything, or because models were not calibrated for future projections. However, this provided a framework in which to form a coherent story and to incorporate narrative and quantitative statements about one possible future. This process highlighted the inter-dependencies between elements, and gave insight into the complex chain of events and feedbacks that could occur in the future. For example, the impact of climate change on some primary sectors can trigger land-use change creating trade-offs between food and timber provision (Dunford et al. 2015).

The quantitative models had a degree of integration via "soft-coupling" because biophysical outputs for production changes were linked to economic models to drive land-use decisions. There is potential for additional interdependencies that we would like to explore in the future, with dynamic feedbacks to be modelled by hard-coupling of models, e.g. linking hydrological models with the land-use change model. However, the extra computational efforts need to be balanced with the value of added information. For example, if the land-use effect is revealed to be negligible then the hydrology model could assume a constant land-use pattern over time. The integrated assessment was the first of its kind that would integrate various social, economic and environment aspects through models. However, we acknowledge the high degree of uncertainty and stress the challenge involved in this exercise. In particular, each quantitative model introduces slightly different assumptions – as seen with the land-use change modelling exercise – that highlighted the impact of assumptions on the discrepancies in the results. This report is a first important step but more continued efforts are needed to create better estimates of future impact and implications.

5 CONCLUSIONS

Our process was highly interdisciplinary, mixing biophysical and social science, and helped bridge the gap between research and policy.

The modelling approach provided insights into potential negative or positive changes on key land uses for primary production. These in turn will have implications on land-use change decisions that should not solely rely on socio-economic context but also on the biophysical impact of climate change. The combination of the three dimensions represented by RCP, SSP and SPA enables us to create a mix of New Zealand-specific scenarios of high relevance to stakeholders. However, this multiplies the number of possible scenarios, given the number of RCPs, SSPs, and SPAs. The goal then is not to describe every possible policy landscape but to select a finite number of representative central policy assumptions to produce a set of climate policy scenarios that are plausible within the global RCP/SSP architecture. The approach would provide key messages to decision makers, giving trade-offs and synergies between positive and negative outcomes from climate and socio-economic pathways.

Further work should continue to develop scenarios to provide some individually plausible yet contrasting exemplifications of socio-economic developments in New Zealand that could matter for the future impacts of climate change, societal vulnerability to climate change, and adaptation options.

6 ACKNOWLEDGEMENTS

We would like to thank Alex Herzig for his useful comments on the report and Graham McBride for coordination and advice. This work was funded by MBIE (NZ) Contract C01X1225 (CCII), and core funding for Landcare Research. We would also like to thank the World Climate Research Programme's Working Group on Coupled Modelling for access to the CMIP5 model output (via https://pcmdi.llnl.gov/projects/cmip5/).

7 GLOSSARY

AR5	Fifth Assessment Report from the IPCC
GCM	General Circulation Models
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
MHWS	Mean High-Water Springs
MSL	Mean sea level of the sea relative to a vertical datum
MVD-53	Mean Sea Level (MSL) Datum for the Bay of Plenty (Moturiki Vertical Datum–1953)
RA	Research Aim
RCP	Representative Concentration Pathways
SLR	Sea Level Rise
SPA	Shared climate Policy Assumptions
SSP	Shared Socio-Economic Pathway
VCSN	Virtual Climate Stations Network

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9 APPENDIX

9.1 Future concentration scenarios

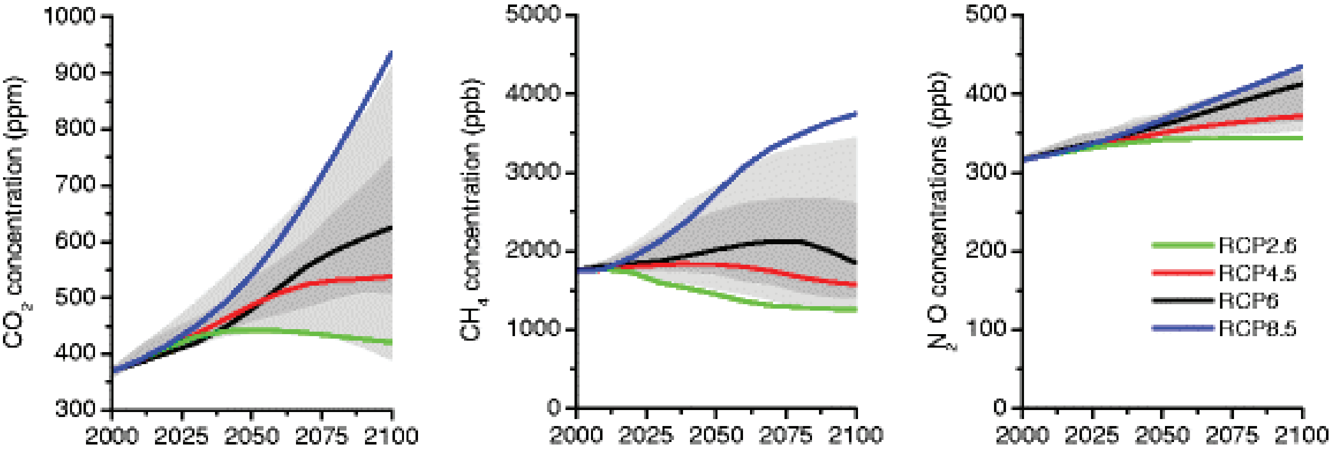

Figure 1: Atmospheric CO_2-equivalent concentrations (in parts-per-million-by-volume) under the four Relative Concentration Pathways (RCPs) (van Vuuren et al. 2011).

9.2 Description of models used in the lowland case study

9.2.1 Demographic model

We developed a bottom-up sub-national population projections model, wherein gross migration between pairs of regions in New Zealand (n=16) is modelled using a set of age-sex-specific gravity models. Our model allows all inter-regional migration flows to be estimated and projected in a common framework with a single set of assumptions. This method offers a number of advantages over traditional methods, in particular that factors known to affect migration flows (such as climate, etc.) can be explicitly (based on regression modelling) incorporated into the population projections in a transparent and justifiable manner.

The estimated internal migration gravity model demonstrated that climate variables (sunshine, rainfall) had statistically significant but very small effects on internal migration in New Zealand.
As such, most of the projected population change in New Zealand is likely to be driven by other factors (e.g. economic factors, population ageing and momentum, etc.), as discussed in Cameron (2013).

9.2.2 Sea-level rise (SLR)

The Intergovernmental Panel for Climate Change (IPCC) released its Fifth Assessment Report (AR5) in 2013-2014 (IPCC 2014). The report showed that the primary climate driver for SLR is global and regional surface temperature, which in turn is strongly influenced by greenhouse gas emissions. SLR occurs as a result of ocean warming, which causes thermal expansion of the sea, and melting of glacial ice, both of which have contributed to sea level rise throughout the 20th century.

In New Zealand, the sea level rose by an average of 0.18 m around the country last century, relative to the land mass. It is rising relatively faster in some locations where the landmass is subsiding, such as Wellington. The rate of SLR was approximately linear over the last century, but is forecast to accelerate over the next century due to global warming and possible rapid melting of the Greenland and Antarctic ice sheets. The Ministry for the Environment Guidance Manual (MfE 2008) recommends that, for planning and decision timeframes out to the 2090s (2090–2099), at the very least, all assessments should consider the consequences of a mean sea-level rise of at least 0.8 m relative to the 1980–1999 average.

9.2.3 Primary production

9.2.3.1 Pasture growth modelling

To model pasture growth, we used the Biome-BGC model v4.2 (Thornton et al. 2002, 2005), adapted to two types of New Zealand managed grassland systems: sheep & beef (low intensity) and dairy (high intensity). The Biome-BGC model is an ecosystem process model that simulates the biological and physical processes controlling fluxes of carbon, nitrogen and water in vegetation and soil in terrestrial ecosystems. This includes the CO_2 fertilization effect, which enhances the rate of photosynthesis and reduces water loss in plants under elevated CO_2 atmospheric concentrations. We used the model's built-in C3 grasslands mode, with some key ecological parameters modified and re-interpreted to represent managed pasture and the presence of grazing animals (Keller et al. 2014). Model parameters were calibrated against New Zealand pasture growth data and validated for both dairy and sheep systems as described in Keller et al. (2014). The primary model inputs, daily minimum and maximum temperature, precipitation, vapour pressure deficit, and solar radiation were derived from the outputs of the 6 GCMs listed in section 4.2.1.

Unique parameterizations were assigned to both sheep and dairy 'ecosystems'. The main difference between the two is the intensity of farming: dairy systems receive more nitrogen inputs (to simulate more fertiliser use), more grass is eaten (in the form of increased whole-plant mortality), and more animal products (milk or meat) are extracted from the system. In addition, the dairy parameterization effectively results in increased water-use efficiency. Note that irrigation is not simulated in either system.

The model was run for each 5 km × 5 km VCSN grid square in the Kaituna catchment with location-specific weather inputs, soil texture and rooting depth. A reference or 'baseline' pasture production for each GCM was simulated using the RCP past climate input (representative of modern day conditions) and averaged over the nominal years 1985–2005. For all future scenarios, the model was first spun up using RCP past climate, and then restarted and run as a transient simulation from 2005 to 2100 using each model- and scenario-specific projected climate.

9.2.3.2 Forestry

The simulation results described here used the comprehensive process-based ecophysiological model CenW 4.1 to simulate the growth of *Pinus radiata* in the Bay of Plenty region. The model had previously been parameterised for the growth of *P. radiata* based on data from the whole of New Zealand (Kirschbaum & Watt 2011). It had also previously been used for climate-change impact assessments for New Zealand (Kirschbaum et al. 2012), and essentially the same modelling procedure was followed here. It principally models tree growth over 30 years, with initial stand densities and thinning regimes as described by Kirschbaum et al. (2012).

The novel aspect of the present work is the availability of actual daily output of key weather parameters from six different GCMs for each day up to 2100. In past work, only average changes in weather parameters were available, and these weather anomalies had to be added to a current-day weather sequence. That preserved a realistic pattern of seasonal changes in weather parameter, but did not include any possible changes in those patterns themselves. The climatic data used here are the direct output from GCM runs and thus include any possible changes in weather patterns (such as changing inter-annual frequency of drought periods, or changes in seasonal temperature or rainfall patterns).

Data are presented both as changes from current (1980–2010) productivity to productivity in 2055 (2040–2070) or 2085 (2070–2100), and as progressive changes by running the model to simulate productivity from 1980 to 2010, followed by a run with data from 1981 to 2011, and so on.

9.2.3.3 Crop modelling

The Agricultural Production Systems sIMulator (APSIM) is a biophysical model that simulates crop growth at daily time-steps in response to climate, soil, and crop management (Holzworth et al. 2014). The model represents processes that control dynamics of carbon, water and nitrogen in plants and soils. The timing and specifications of management interventions (e.g. sowing, harvesting, fertiliser and water application) are also represented in APSIM. In RA2, to extend APSIM applications beyond its original point-basis configuration (i.e. single location) to a catchment scale (~5 km resolution), dynamic simulations of crop management (sowing dates, fertiliser application and crop type choice) in response to environmental conditions were developed. Model simulations did not account for biotic stresses (insects, pathogens and weed competition) or damage by extreme events (e.g. floods, heat waves or storms). Simulations were performed for silage maize *(Zea mays)*. Maize was selected as an indicator of climatic suitability to arable cropping due to its importance as a forage option for the dairy sector and its wide presence across New Zealand. To explore adaptation options to climate change, APSIM runs were performed for two maize genotypes (short- and long-maturity hybrids) with and without considering adaptation of sowing dates (i.e. sowing early in response to warmer climates). Simulations were performed for a baseline (1986–2005), mid-century (2046–2065) and end-century (2081–2099) with the six selected GCMs. Simulations were run continuously, with a spin-up period of 3–8 years depending on data availability. As maize in the Kaituna catchment is typically grown under rain-fed conditions on soils with high water-holding capacity (assumed 160 mm/m), these conditions were therefore assumed in simulations. A 30-year baseline model run using the historical climate (ERA databases from 1971 to 2000) was used to calibrate and test the model. Sowing dates and yields of historical model runs were scrutinised by maize crop experts (Dr John de Ruiter, Senior Scientist at Plant and Food Research – PFR and Mr Allister Holmes, Research & Extension Team Leader at the Foundation for Arable Research – FAR). In addition, model results for historical weather were compared with data from an online-survey, developed by FAR and PFR, with maize growers across New Zealand. Model results were analysed for grid cells other than lake areas.

9.2.4 Economics and land use

9.2.4.1 Climat-DGE

To estimate the effect of global SSP on the New Zealand economy, we used the climate and trade dynamic general equilibrium (CliMAT-DGE) model developed by Landcare Research. CliMAT-DGE is a multiregional, multi-sectoral, forward-looking dynamic general equilibrium model with a relatively long time horizon of 100 years or more. This model is suited to studying the efficient (re) allocation of resources within the economy and the response over time to resource or productivity shocks. CliMAT-DGE primarily uses the Global Trade Analysis Project (GTAP) version 8 data set. The base year of the benchmark projection is 2007. The model then develops a benchmark projection of the economic variables and GHG emissions, and simulates scenarios to evaluate the impacts of mitigation policies. Based on long-run conditions and constraints on physical resources, which restrict the opportunity set of agents, the model predicts the behaviour of the economy, energy use, and emissions by region and sector (Fæhn et al. 2013).

CliMAT-DGE covers 18 aggregated production sectors; we focused on the cattle and food sectors. Model dynamics follow a forward-looking behaviour where decisions made today about production, consumption and investment are based on future expectations, estimated in 5-year time steps. The economic agents have perfect foresight and know exactly what will happen in all future periods of the time horizon. Thus, households are able to smooth their consumption over time in anticipation of large price shocks that may arise as a result of resource constraints or environmental taxes. For a thorough description of CliMAT-DGE, see Fernandez and Daigneault (2015).

9.2.4.2 NZFARM

The New Zealand Forest and Agriculture Regional Model (NZFARM) is a comparative-static, non-linear, partial equilibrium mathematical programming model of New Zealand land use operating at the catchment scale developed by Landcare Research (Daigneault et al. 2014, 2017). In this study it was used to assess how changes in climate (i.e. yields), socio-economic conditions (e.g. commodity prices and input costs), resource constraints, and environmental policy (e.g. GHG reduction pathways) could affect a host of economic or environmental performance indicators that are important to decision-makers and rural landowners. The version of the model used for this analysis can track changes in land use, land management, agricultural production, freshwater contaminant loads, and GHG emissions (see Fig. 25).

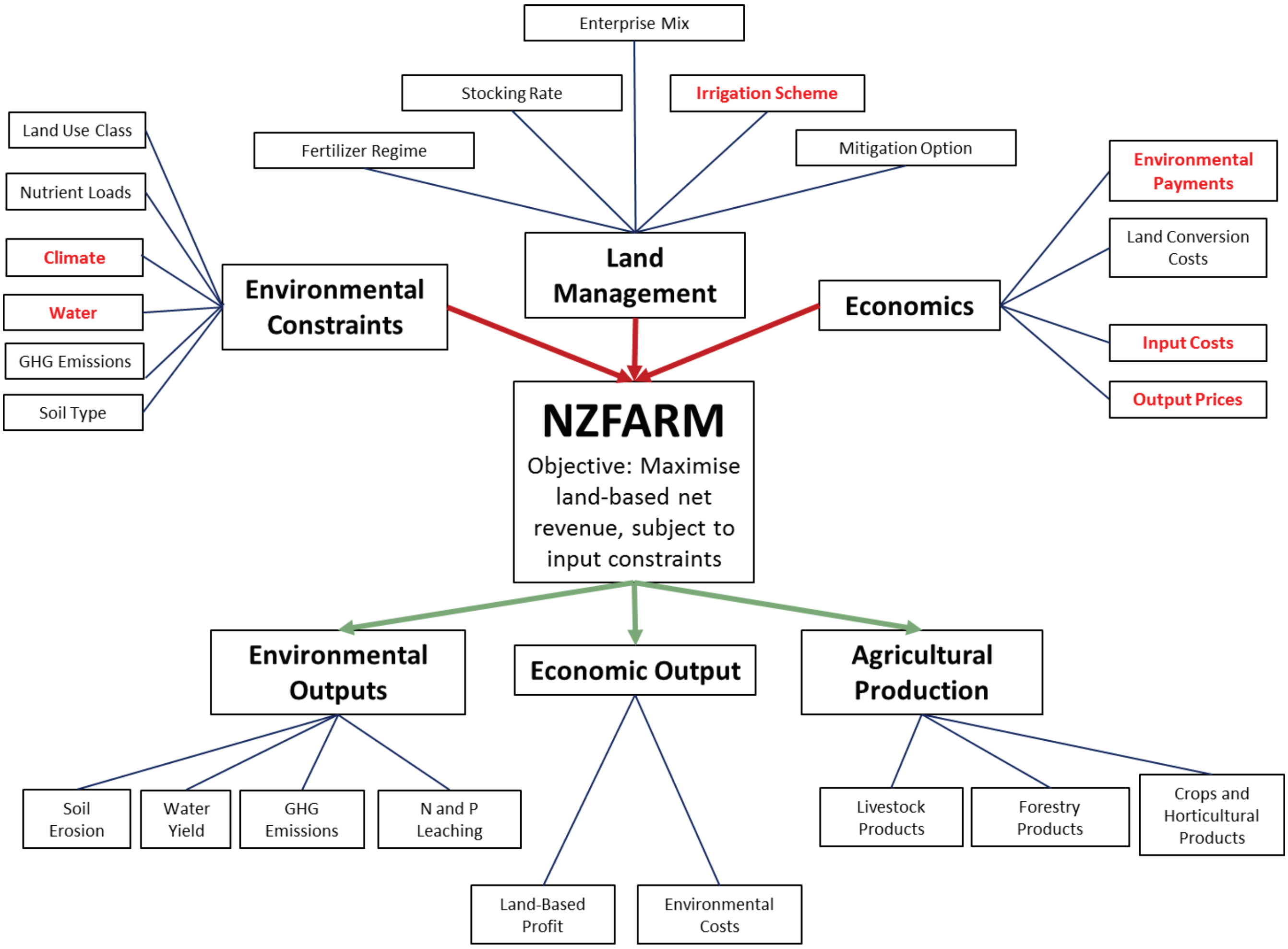

Figure 25: Diagram of inputs and outputs from NZFARM.

In this case study, we use NZFARM to assess the implications on farm income, land use and the environment when farmers in the Kaituna catchment are faced with variations in agricultural yields due to climate change and/or alternative shared socio-economic pathways. This analysis builds on previous work on climate change impacts on agriculture and forestry in New Zealand by indicating not only the likely impact of climate change on production, but also the effect that landowner adaptation may have on land use, economics, production, and environmental outputs within a simultaneous modelling framework.

The model's objective function maximizes the net revenue of agricultural production, subject to land use and land management options, production costs and output prices, and environmental factors such as soil type, water available for irrigation, and any regulated environmental outputs (e.g. GHG emissions taxes) imposed on the catchment. Catchments can be disaggregated into sub-regions (i.e. zones) based on different criteria (e.g. land use capability, irrigation schemes) such that all land in the same zone will yield similar levels of productivity for a given enterprise and land management option. In this case, each VCSN grid cell is modelled as an individual zone within the Kaituna catchment.

Simulating endogenous land management is an integral part of the model, which can differentiate between 'baseline' land use and farm practices based on average yields achieved under the current climate and those that could be experienced under a range of RCPs. Landowner responses to changing climate and socio-economic conditions are parameterised using estimates from biophysical models described elsewhere in this report, commodity prices estimated from CliMAT-DGE, and farm budgeting models described in Daigneault et al. (2016).

9.2.4.3 LURNZ

The Land Use in Rural New Zealand (LURNZ) model is a spatially explicit integrated model of national land use (Kerr et al. 2012; Anastasiadis et al. 2014). LURNZ is built upon econometrically estimated functions that establish the relationship between observed drivers of land use and land-use outcomes (Kerr & Olssen 2012; Timar 2011, 2016). This structure enables us to make relatively few assumptions about the individual motivations of rural decision makers, making the model generally robust and transparent. On the other hand, its empirical foundation can also make the model less flexible and more prone to data limitations. For example, LURNZ simulations may become unreliable when future values of the explanatory variables lie outside their historical range.

Under the RCP 8.5 & SSP 3 scenario, both climate and economic parameters are expected to change. The LURNZ (and NZFARM) simulations were designed to try to disentangle the effects of climate and economic drivers. Accordingly, we performed four sets of mid-century and end-of-century simulations using the 25-hectare version of LURNZ:

1) The "Baseline" runs use Situation and Outlook for Primary Industries (SOPI) commodity price projections through 2020 and constant prices thereafter. These runs provide the basis against which the other simulations can be evaluated.

2) Under the "Price only" runs, climate parameters are held at their baseline values and only prices are allowed to change. Specifically, these runs are based on commodity price projections from the CLiMAT-DGE model under SSP3.

3) Under the "Yield only" runs, prices are held at their baseline values, and only climate-induced changes in productivity are allowed. Projected changes in pasture yields from the Biome-BGC model (Keller et al. 2014) are included spatially (Timar, forthcoming). Forestry yields cannot be accommodated in LURNZ spatially, so here we apply the projected proportional increase in the Lower Kaituna forestry yields to national forestry prices as an approximation.

4) The "Combined" runs combine the price and yield effects. The two effects are approximately additive at the national level (but not necessarily at other spatial scales).

All simulations are carried out at the national level. Therefore, catchment-specific outcomes represent a subset of the national outcomes.

9.2.5 Pest modelling

9.2.5.1 Climate data

The climate data, projections and the VCSN has been described elsewhere in this report. This analysis used both the monthly data as well as 20-year time period climate normals centred on 2005, 2050, and 2090. Data was provided as netCDF files. These were manipulated in Python to create the input datasets required by Climex. An audit was undertaken to ensure that transformation did not corrupt the data. Due to database size limitations, separate Climex data files were created for the monthly data, on a 5 year time step, for each Species X RCM X RCP, and one climate input file for the normals data set. Locations are national for each 5-km grid cell in the VCSN. Climate change projection data was loaded into the climate input file by repurposing variables of continent, country, state to hold RCM, RCP and year labels.

9.2.5.2 Climex simulations

Climex v 4.02 was used for the simulations, using the compare location (1 species, extended) function. All parameters, other than meta data and species, were kept to the default.

Due to the large numbers of simulations, automation software (WinAutomation V6) was used to automate the importing of data into input files (Metman) and to run the compare locations algorithm.

Two climate data sets where used to run the simulations:

- Each species is modelled at 5 year intervals (2015–2120), for each RCM and RCP, capturing the inter-annual variation in potential distribution.
- Each species is modelled using the 20-year normal data centred on 2005, 2050, 2090 for each RCM and RCP.
- These data were reduced by using the maximum EI for each cell from each of the RCM, i.e. the worst case scenario of EI risk is presented.

9.2.5.3 Species

The models were provided by John Kean (Agresearch) via the Climenz website (http://b3.net.nz/climenz/index.php see Table 13), and were able to be downloaded as climex ready parameter files, saving considerable time as well as ensuring parameter accuracy.

55 species modelled were selected from a range of sources that identified pests or unwanted organisms in NZ, such as the National Pest Plant Accord, legal sources (notifiable organisms) and those recommend as pests either as have been modelled in NZ before using earlier climate data sets, or as potential threats to biodiversity or production systems.

Table 13: Species modelled and Climex Model references

Pest	**Source**
Acantholybas brunneus	Steinbauer MJ, Yonow T, Reid IA, Cant R 2002. Ecological biogeography of species of Gelonus, Acantholybas and Amorbus in Australia. Austral Ecology 27: 1–25. DOI: 10.1046/j.1442-9993.2002.01146.x
Alternanthera philoxeroides Alligator Weed	Julien MH, Skarratt B, Maywald GF 1995. Potential geographical distribution of alligator weed and its biological control by Agasicles hydrophila. Journal of Aquatic Plant Management 33: 55–60.
Amorbus rhombifer Eucalyptus tip-wilter bug	Steinbauer MJ, Yonow T, Reid IA, Cant R 2002. Ecological biogeography of species of Gelonus, Acantholybas and Amorbus in Australia. Austral Ecology 27: 1–25. DOI: 10.1046/j.1442-9993.2002.01146.x
Amorbus robustus Clown bug	Steinbauer MJ, Yonow T, Reid IA, Cant R 2002. Ecological biogeography of species of Gelonus, Acantholybas and Amorbus in Australia. Austral Ecology 27: 1–25. DOI: 10.1046/j.1442-9993.2002.01146.x
Anastrepha obliqua West Indian fruit	Fu L, Li ZH, Huang GS, Wu XX, Ni WL, Qu WW 2014. The current and future potential geographic range of West Indian fruit fly, Anastrepha obliqua (Diptera: Tephritidae). Insect Science 21: 234–244. DOI: 10.1111/1744-7917.12018
Asparagus aethiopicus Bushy Asparagus	Scott JK, Batchelor KL 2006. Climate-based prediction of potential distributions of introduced Asparagus species in Australia. Plant Protection Quarterly 21: 91–98.
Baccharis halimifolia Groundsel Bush	Sims-Chilton NM, Zalucki MP, Buckley YM 2010. Long term climate effects are confounded with the biological control programme against the invasive weed Baccharis halimifolia in Australia. Biological Invasions 12: 3145-3155. DOI: 10.1007/s10530-010-9705-z
Bactrocera correcta Guava Fruit fly	Wengang L, Deng Y, Li Z, Lin W, Wan F, Wang Z 2010. A prediction of potential geographical distribution of guava fruit fly, Bactrocera (Bactrocera) correcta (Bezzi) in China. Acta Phytophylacica Sinica 37: 529–534.
Bactrocera cucumis Cucumber fruit fly	Kriticos DJ 2007. Risks of establishment of fruit flies in New Zealand under climate change. Ensis client report 12244, 26 pp.
Bactrocera cucurbitae Melon fly	Lingbin W, Wei L, Zhihing L, Fangbao W, Zhiling W, Guansheng H 2008. A prediction of potential geographic distribution of melon fruit fly based on CLIMEX and DIVA-GIS. Acta Phytophylacica Sinica 35: 148–154.
Bactrocera dorsalis Oriental fruit fly	Sridhar V, Verghese A, Vinesh LS, JayashankarM, Kamala Jayanthi PD 2014. CLIMEX simulated predictions of Oriental fruit fly, Bactrocera dorsalis (Hendel) (Diptera: Tephritidae) geographical distribution under climate change situations in India. Current Science 106: 1702–1710.
Bactrocera musae Banana fly	Kriticos DJ 2007. Risks of establishment of fruit flies in New Zealand under climate change. Ensis client report 12244, 26 pp.
Bactrocera neohumeralis	Kriticos DJ 2007. Risks of establishment of fruit flies in New Zealand under climate change. Ensis client report 12244, 26 pp.
Bactrocera tryoni Queensland Fruit Fly	Yonow T, Sutherst RW 1998. The geographical distribution of the Queensland fruit fly, Bactrocera (Dacus) tryoni, in relation to climate. Australian Journal of Agricultural Research 49: 935-953. DOI: 10.1071/A97152
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(Source: CLIMENZ)