Climate Change Impacts and Implications for New Zealand to 2100

Synthesis Report RA3

Identifying Feedbacks, Understanding Cumulative Impacts and Recognising Limits: A National Integrated Assessment

Daniel T. Rutledge[1], Anne-Gaelle E. Ausseil[2], W. Troy Baisden[3], Greg Bodeker[4], Doug Booker[5], Michael P. Cameron[6], Daniel B.G. Collins[5], Adam Daignaeult[7], Mario Fernandez[7], Bob Frame[8], Elizabeth Keller[3], Stefanie Kremser[4], M.U.F. Kirschbaum[9], Jared Lewis[4], Brett Mullan[10], Andy Reisinger[11], Abha Sood[10], Stephen Stuart[10], Andrew Tait[10], Edmar Teixeira[12], Levente Timar[13], Christian Zammit[5]*

[1] Landcare Research Manaaki Whenua Ltd, Hamilton, New Zealand, [2] Landcare Research Manaaki Whenua Ltd, Wellington, New Zealand [3] GNS Science, Lower Hutt, New Zealand, [4] Bodeker Scientific, Alexandra, New Zealand, [5] National Institute of Water & Atmospheric Research Ltd, Chrischurch, New Zealand, [6] University of Waikato, Hamilton, New Zealand, [7] Landcare Research Manaaki Whenua, Auckland, New Zealand, [8] Landcare Research Manaaki Whenua, Lincoln, New Zealand, [9] Landcare Research Manaaki Whenua, Palmerston North, New Zealand, [10] National Institute of Water & Atmospheric Research Ltd, Wellington, New Zealand, [11] AgResearch Ltd, Wellington, New Zealand [12] Plant and Food Research, Wellington, New Zealand, [13] Motu Economic and Public Policy Research, Wellington, New Zealand

* Corresponding author, email: daniel.rutledge@rivm.nl

Cover photo: Otago Mountains by Phillip Brookes

When quoting, citing or distributing this Synthesis Report or its individual sections, please provide the full reference:

Rutledge DT, Ausseil A-GE, Baisden T, Bodeker G, Booker D, Cameron MP, Collins DBG, Daigneault A, Fernandez M, Frame B, Keller E, Kremser S, Kirschbaum MUF, Lewis J, Mullan B, Reisinger A, Sood A, Stuart S, Tait A, Teixeira E, Timar L, Zammit C (2017). Identifying Feedbacks, Understanding Cumulative Impacts and Recognising Limits: A National Integrated Assessment. Synthesis Report RA3. Climate Changes, Impacts and Implications for New Zealand to 2100. MBIE contract C01X1225. 84pp.

CONTENTS

HIGHLIGHTS 5

INTRODUCTION 7

BACKGROUND 8

- Purpose 8
- Key Questions 8
- Goals 8
- RA3 in Context 8

METHODOLOGY 10

- Scenario Specification 10
  - Overview 10
  - Scenario Elements and Key Assumptions 10
  - Scenario Evaluation Protocol 14
- RA3 Loosely-coupled National Human-Natural Systems Model 18
  - Crop Productivity (Maize) – APSIM 20
  - Demographics – National-Regional Cohort-component Model 20
  - Forest Productivity – CenW 21
  - Forestry and Agriculture – NZFARM 21
  - Global-New Zealand Socioeconomic Co-development – CliMAT-DGE 22
  - Hydrology and Water Resources – National TopNet 23
  - Improved Climate Projections – NZ-RCM (RA1) 23
  - Pasture Productivity – Biome-BGC 24
  - Rural Land Use – LURNZ 25
  - Uncertainty in Ecological Effects – Banded Kōkopu Distribution Model 26

RESULTS AND DISCUSSION 29

- Global Scenario Study 29
  - Impacts 29
  - Implications 42
- Improved Climate Projections for New Zealand – NZ-RCM 42
  - Impacts 42
  - Implications 43

Uncertainty in Ecological Effects – Banded Kōkopu Distribution Modelling 43

- Impacts 43
- Implications 46

Crop Productivity (Maize) – APSIM 47

- Impacts 47
- Implications 48

Forestry Productivity (Pinus radiata) – CenW 48

- Impacts 48
- Implications 51

Pasture Productivity – Biome-BGC 51

- Impacts 51
- Implications 56

Hydrology & Water Resources – National TopNet 56
Impacts 56
Global-NZ Socioeconomic Co-Development – CliMAT-DGE 58
Impacts 58
Implications 61
Rural Land Use – LURNZ 62
Impacts 62
Implications 65
Forestry & Agriculture – NZ-FARM 66
Impacts 66
Implications 69
Demographics – National-Regional Cohort Component Model 69
Impacts 69
Implications 71

CONCLUSIONS AND SYNTHESIS 72
Global Context 72
New Zealand 73
Key Caveats 75

FUTURE RESEARCH 76
Key Caveats 76
Hydrology 76
Socioeconomic including Land-use/Land-Cover Change 76
Agricultural Productivity 76
Demographics 76
Expansion 76

ACKNOWLEDGEMENTS 77

REFERENCES 77

APPENDIX 1 – CLIMAT-DGE QUANTITATIVE INPUTS 81

HIGHLIGHTS

- Research Aim 3 (RA3) undertook a national integrated assessment that explored the impacts and implications of climate change to 2100 to better understand feedbacks, cumulative impacts, and limits among economic, social, and environmental outcomes.
- The assessment evaluated six globally linked, New Zealand-focused scenarios using a loosely coupled national human-natural systems model developed for RA3. The systems model integrated a suite of climate, economic, land use, hydrology, and primary productivity models.
- The six scenarios were a subset of 20 global scenarios formulated under a new global scenario architecture developed for the IPCC's 5th assessment.
- Global scenarios combine 1) socioeconomic pathways exploring different levels of challenges to mitigation and adaptation, 2) greenhouse gas concentration pathways, and 3) shared policy assumptions about global efforts to mitigate greenhouse gas emissions.
- By design, socioeconomic pathways evolve independently of greenhouse gas concentration pathways. Any pair of pathways can be combined to form a scenario. As a result, climate change does not directly impact socioeconomic development. Instead, evaluation of climate change impacts and implications occurs indirectly by comparing and contrasting different scenarios.
- A global integrated assessment study found that any global scenario is plausible but not all are equally feasible. Feasibility decreased when pairing socioeconomic pathways with high challenges to mitigation and the lowest greenhouse gas concentration pathway.
- Any global scenario with a mitigation target assumes a functional global carbon market, although that assumption is not equally plausible across all mitigation scenarios.
- RA3 modelling followed global integrated assessment study protocols. Scenario evaluation specified that country-level population and GDP followed fixed projections unique to the selected global socioeconomic pathway and that all climate-related modelling use climate projections based on the selected concentration pathway.
- CCII scenarios also implemented relevant global shared policy assumptions as required, e.g. non-mitigation scenarios assumed no carbon market or carbon price while mitigation scenarios modelled a functional carbon market following global study protocols.
- Improved climate projections for New Zealand reinforce earlier findings that higher greenhouse gas concentrations leading to increasing radiative forcing will likely cause larger degrees of change for New Zealand's climate and its various facets, including means, extremes, frequencies, and shifts in patterns.
- Uncertainty, risks, and vulnerabilities resulting from climate change will also likely scale with increasing concentration pathways. Different locations will experience different impacts depending upon combined changes to daily, seasonal and annual weather patterns.
- Hydrological systems will change both positively and negatively with climate change. Total variability tends to increase with increasing concentration pathways such that low flows become smaller and occur earlier and high flows (i.e. flooding) become larger. Mean flows show more complex spatial patterns but tend to increase in a west-to-east direction.
- Across scenarios, summer soil moisture deficits intensify such that soils become drier except in a few areas of the South Island.
- Climate impacts on primary production varied. Pastoral and forestry (*Pinus radiata*) yields to 2100 increased positively with increasing concentration pathway because positive effects from CO_2 fertilisation outweighed negative effects of higher temperatures.

- Sheep & beef and dairy mean annual pasture productivity increased 1–10% across scenarios in most locations, although changes in seasonal trends might cause larger summer feed gaps.
- Irrigated maize silage modelling demonstrated potential for adaptation for minimising impacts on national maize yields. Nationally, cropping could shift from northern regions showing decreasing yields to southern regions showing increasing yields. Locally, farming could adopt new agronomic practices such as earlier sowing dates and long-cycle genotypes.
- The lack of links between hydrological and primary productivity modelling is a key limitation of the current national systems model and corresponding analysis.
- A novel modelling experiment demonstrated the use of new climate projection ensembles to better characterise and quantify uncertainty. The model developed statistical methods that quantified potential changes and associated uncertainties to habitat suitability for whitebait (banded kōkopu juveniles).
- New Zealand's fixed population projections started at 4.4 million in 2010 and ranged by 2100 from 3.8 (low) to 9.8 (high) million people. The large range in population projections has implications related to and independent of climate change including, for example, land-use change, food security, energy security, water resources, conservation,and biosecurity.
- Demographic modelling found that climate change will cause regional populations to shift north slightly and the magnitude of the shift increases with increasing concentration pathways. For example, under the same socioeconomic pathway, Auckland's population at 2100 was ~30,000 higher under a high concentration pathway than a low concentration pathway.
- New Zealand's fixed GDP projections started at $66,813 billion US_{2005} in 2010 and ranged by 2100 from $277,733 (low) to $1,014,793 (high) billion. New Zealand's GDP per capita begins and always remains higher than the global average for all global socioeconomic pathways. That result suggests that New Zealand remains relatively better off on a global basis although the magnitude of the difference depends on socioeconomic pathway assumptions.
- Agricultural economic and land-use change modelling showed that changes to productivity via climate change will interact with market forces (e.g. price mechanisms) to drive land-use change in complex ways. For example, in one scenario projected global sheep & beef commodity prices went well beyond historic observed ranges and counterbalanced dairy farming expansion that would occur assuming only climate change effects.
- Given global scenario architecture design and assumptions, broad social and economic outcomes for New Zealand, as indicated by population and GDP, depend primarily on the global socioeconomic pathway selected, whereas environmental outcomes reflect a more balanced combination of socioeconomic pathways and concentration pathways.
- Climate change does substantially impact the specific nature of social and economic outcomes. Comparing two scenarios with the same global socioeconomic pathway but a higher and lower concentration pathway, the structure of New Zealand's economy changed substantially. In the high concentration scenario, the economy became more inwardly focused and dominated by domestic household consumption. In the lower concentration scenario, the economy became more outwardly focused and dominated by exports.

INTRODUCTION

The "Climate Changes, Impacts and Implications" (CCII) project was a four-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 brought 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 was based on five inter-related Research Aims (RAs) that provided new climate change projections and advancements in understanding their impacts and implications for New Zealand's environment, economy and society. The five RAs were:

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 RA3 was to study the interplay among:

1) climate change;

2) other key drivers such as land-use change, population, and economic development; and

3) decision-making across a range of scales and explore the cumulative impacts on, and limits of, the environment and evaluate the effects of multiple responses, including the costs and benefits of coordinated versus uncoordinated decision-making.

RA3 developed a loosely coupled national human-natural systems model that linked and adapted a suite of quantitative biophysical, economic, demographic, and land use/land-cover change models. The national systems model evaluated how New Zealand's economy, environment and society might co-evolve under six New Zealand-focused scenarios selected from a larger set of global scenarios developed for the Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment. Global scenarios couple different pathways of socioeconomic development, organised by the simultaneous consideration of challenges to mitigation and organisation, with different future standardised pathways of greenhouse gas concentrations.

The RA3 national systems model used key indicators (e.g. specified trends in population or GDP) and guides (e.g. energy, land use, technology, climate policies) as inputs. Model output was analysed and interpreted both individually and collectively to:

1) characterise and understand the potential range and variation of impacts of climate change for New Zealand under different assumptions (i.e. scenarios) of global development including different greenhouse gas emission and concentration pathways

2) explore the potential implications for different adaptation strategies including where and to what extent New Zealand might have "freedom to operate" or conversely, where future choices might be limited given broader global trends and developments.

BACKGROUND

Purpose

Various national analyses have explored the potential impacts and implications of climate change from different perspectives and for different issues, e.g. biodiversity, infrastructure and hazards, soils, water resources, primary production, land-use change, or ecosystem services (Fowler et al. 2008; Howden-Chapman et al. 2010; McGlone & Walker 2011; Pomeroy 2011; PCE 2016). However, New Zealand lacks a comprehensive systems analysis that considers a range of issues simultaneously and the implications of interactions and feedbacks among them.

The lack of an integrated analysis limits the understanding of potential impacts and implications of climate change across a range of scales, and the ability to consider cumulative or cascading impacts. As a result, we often only learn of environmental limits after they are crossed. Future risks also increase because evaluation of potential mitigation or adaptation strategies lacks consideration of critical system properties, links, and behaviours that can produce misleading projections and associated expectations.

RA3 sought to undertake a first-generation national integrated analysis and assessment to understand the interplay among climate change and other key drivers and considerations including population, economic development, land and land-use change, water and hydrology, and ecosystems. The study of feedbacks and trade-offs among different resources was designed to facilitate study of cumulative impacts and identification of environmental limits and how they vary under different climate change pathways.

Key Questions

- How will climate change, combined with other key drivers (e.g. land use change, invasive species), impact broad-scale terrestrial, freshwater, and coastal/marine ecosystems? What ecosystems are most vulnerable and why? How will impacts vary across ecosystems?
- What are the associated national-scale economic and social implications?
- At what critical time steps might different impacts occur and what are the implications for scheduling, costs and benefits of future management or adaptation? What are the opportunity costs economically, environmentally and socially?
- Which changes present the greatest risks and which generate the greatest opportunities?

Goals

To fulfil its purpose and address the key questions, RA3 had several goals:

1) Enhance NZ's ability to understand fully the potential impacts and implications of climate change, including strengthening an understanding of and linkages to the global context.
2) Undertake an integrated national assessment that simultaneously explored a range of economic, environmental and social trends, assumptions, and issues.
3) Construct a national systems model to foster more integrated thinking and analysis and to identify gaps in knowledge, especially regarding the relationships among economic, environmental and social issues.
4) Outline future research priorities to guide climate change research in New Zealand, with a particular emphasis on improving the collective ability to engage and contribute more proactively in future global climate change research and assessment, e.g. to a future IPCC 6th Assessment from a New Zealand-focused perspective.

RA3 in Context

RA3 operated at a national scale and extent within a broader multi-perspective, multi-scale context (Fig. 1). At the global scale, a recently developed and still evolving global scenario architecture (O'Neill et al. 2014), developed to support the IPCC's 5th Assessment (IPCC 2014), provided the overarching context and assumptions about key global drivers of development and associated implications for climate change. Global scenarios, generated using the new framework, outlined essential qualitative and quantitative assumptions used to guide global climate modelling, impacts, adaptation, and vulnerability assessments, and mitigation strategies.

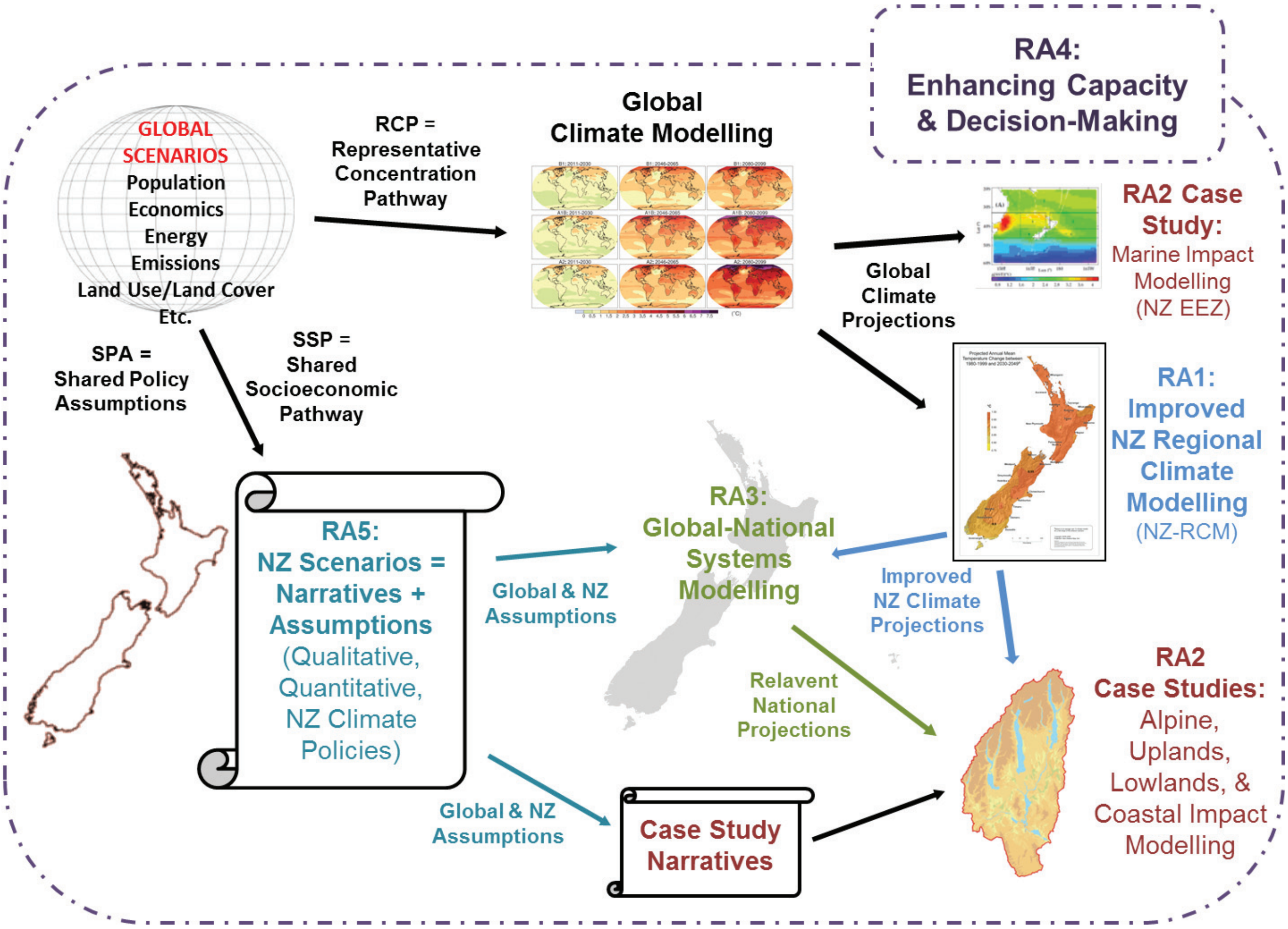


Figure 1 RA3 in the broader CCII context including global climate change scenarios, climate modelling and integrated assessment modelling (black text and arrows) and the four other CCII research aims (coloured text and arrows).

At the global-national scale, the RA5 team guided and helped the RA3 team to interpret the global assumptions from the scenarios generated by the new global scenario architecture by developing New Zealand-focused scenarios (Frame & Reisinger 2016). The RA3 team used the globally linked, New Zealand-focused scenarios to specify the values of required inputs needed to run the RA3 national systems model. The RA3 systems model used improved regional New Zealand climate projections generated by the RA1 team based on global climate modelling as inputs (Tait et al. 2016). The RA1 and RA3 teams worked collaboratively to improve the quality and utility of the RA1 projections for use by RA3 models and integrated assessment and impact modelling more generally.

At the sub-national scale, a series of four case studies in RA2 (Ausseil et al. 2017; Barron et al. 2016; McBride et al. 2016; Rutledge et al. 2017) complemented the national RA3 modelling by undertaking more detailed assessments of climate change impacts and implications, both thematically and geographically. Variables such as projections of future commodity product prices generated by the RA3 national systems model served as inputs to corresponding modelling in some case studies. A fifth RA2 case study, the Marine Case Study (Law et al. 2016), also complemented the RA3 study geographically and thematically by focusing on key impacts and implications for marine resources across New Zealand's Exclusive Economic Zone, which extends 200 km from the coast.

Lastly RA4 took a "bird's eye view" of the CCII project by improving understanding of how and why decision makers use or do not use climate change knowledge. RA4 used collaborative and participatory research methods to engage with a wide range of stakeholders and better understand how decision-making processes consider climate change impacts and implications. RA4 recommended how the CCII project could produce more relevant and useful findings to a range of decision-makers and decision-making contexts and processes (Lawrence et al. 2016).

METHODOLOGY

SCENARIO SPECIFICATION

Overview

The recently developed global scenario architecture and accompanying global scenarios (O'Neill et al. 2014, 2017) provided the global context and associated key assumptions needed for RA3 national systems modelling and analyses. This section outlines the elements needed for scenario formulation and their implementation within RA3 and the understanding needed to help interpret RA3 systems model outputs within the broader global context.

A global scenario has two required elements: Shared Socioeconomic Pathways or SSPs (O'Neill et al. 2014, 2017) and Representative Concentration Pathways or RCPs (van Vurren et al. 2011) (Table 1).

Scenarios can be one of two types: non-mitigation or mitigation. Non-mitigation scenarios assume no global efforts or corresponding policies to reduce greenhouse gas emissions. In non-mitigation scenarios, global greenhouse gas emissions evolve according to the selected SSP assumptions.

Mitigation scenarios include a global mitigation target, i.e. RCP6.0 or lower. They include a third element called Shared Policy Assumptions (SPAs) that outline assumptions about global mitigation policies needed to achieve the selected mitigation target/RCP (Kriegler et al. 2014).

Table 1: Global Scenario Elements

Scenario Element	Abbreviation	Status	Number	Labels
Shared Socioeconomic Pathway	SSP	Required	5	SSP1 SSP2 SSP3 SSP4 SSP5
Representative Concentration Pathway	RCP	Required	4	RCP8.5 (highest radiative forcing) RCP6.0 RCP4.5 RCP2.6 (lowest radiative forcing)
Shared Policy Assumptions	SPA	Optional	5	SPA1 SPA2 SPA3 SPA4 SPA5

Scenario Elements and Key Assumptions

Shared Socioeconomic Pathways (SSPs)

Shared Socioeconomic Pathways (SSPs) represent a structured approach to assumptions about future global development organised along two primary axes: challenges to adaptation and challenges to mitigation (van Vuuren & Riahi 2017) (Fig. 2). There are five SSPs, each titled with a "road" allusion to provide a sense of their overall nature, composition, and direction of global development or "travel" (O'Neill et al. 2017).

Each SSP includes a broad overall narrative supplemented by more detailed qualitative and quantitative assumptions. The global climate change literature contains more details about the new global SSP architecture (e.g. O'Neill et al. 2017) and implementation of specific SSPs (Calvin et al. 2017; Fricko et al. 2017; Fujimori et al. 2017; Kriegler et al. 2017; van Vuuren et al. 2017).

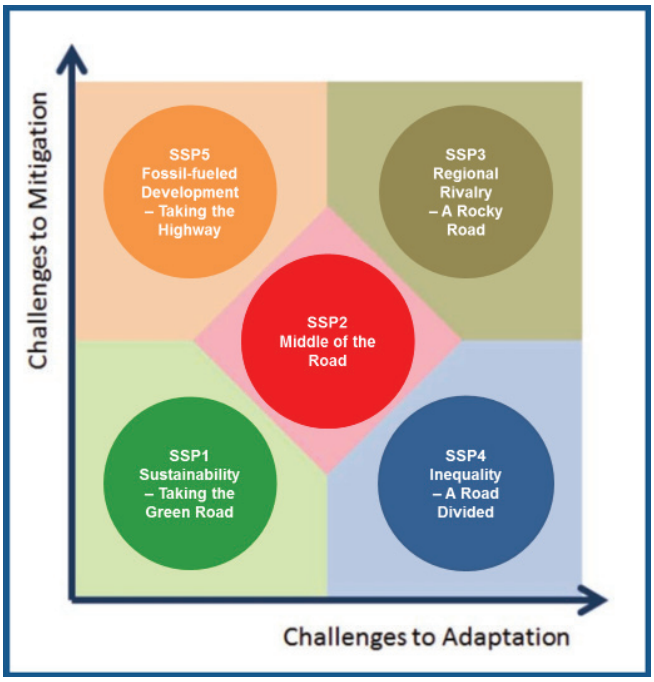


Figure 2 Shared Socioeconomic Pathway numbering and titles (adapted from Ebi et al. 2014 and O'Neill et al. 2014, 2017).

Representative Concentration Pathways (RCPs)

Representative Concentration Pathways (RCPs) comprise a set of four standardised pathways of future global greenhouse gas concentrations (van Vuuren et al. 2011). RCPs facilitate comparative exploration of the potential impacts and implications of climate change across the full range of likely future global greenhouse gas emissions and resulting radiative forcing. While called "concentration pathways", the naming convention actually refers to the resulting additional radiative forcing at 2100 in watts per meter squared (W/m^2) relative to pre-industrial (1850–1900) levels (Fig. 3).

The RA1 synthesis report (Tait et al. 2016) contains more information about RCPs and their use in generating the latest set of global climate projections. Global climate projections, in turn, served as the basis for running the New Zealand Regional Climate Model that generated the improved climate projections used by RA3.

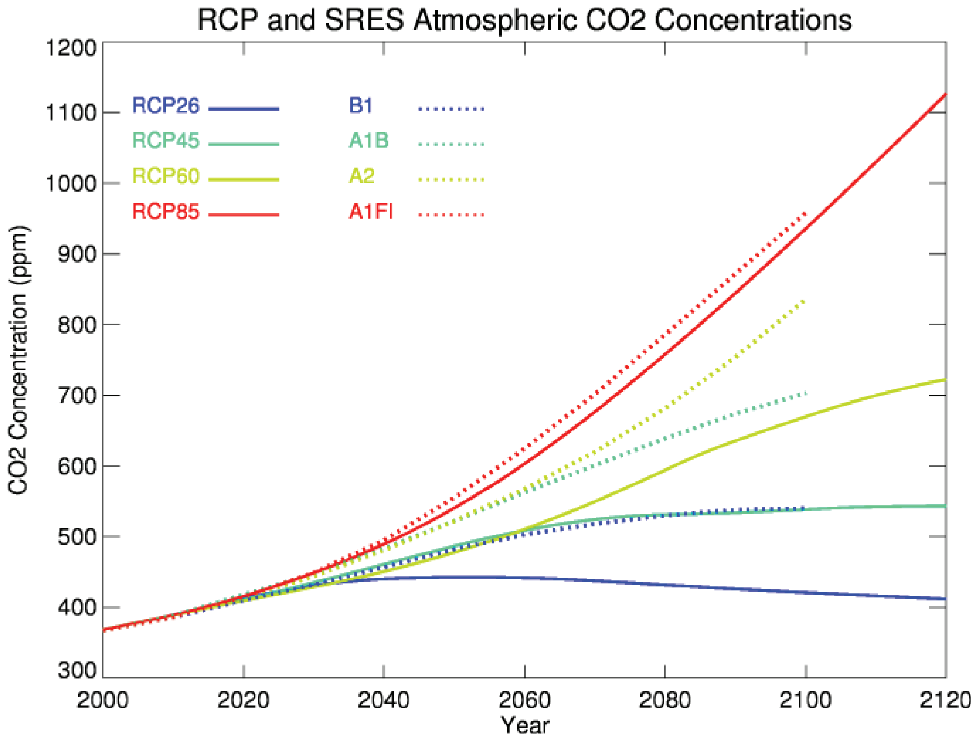


Figure 3 Atmospheric CO_2-equivalent concentrations (in parts-per-million-by-volume) under the four Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011).

SPAs: Shared Policy Assumptions

Shared Policy Assumptions (SPAs) outline assumptions about development of future global climate policies targeting mitigation of greenhouse gas emissions (Kriegler et al. 2014). SPAs include:

1. Climate Policy Goals: emissions reductions targets or different levels of ambition in limiting residual climate damages.
2. Policy Regimes and Measures:
   a. Mitigation: policy measures could be globally harmonized or regionally differentiated carbon taxes, an international emissions trading scheme with a particular burden sharing mechanism, a mix of different policy instruments ranging from emissions pricing to low carbon technology subsidies to regulatory policies, or a mix of different approaches in different sectors, e.g. including transport policies and schemes to protect tropical forest.
   b. Adaptation: the suite of adaptation measures available for implementation (e.g. more efficient irrigation techniques) and level of international support for adaptation in developing countries.
3. Implementation Limits and Obstacles: identification of circumstances that would limit policy implementation, such as excluding emissions from some land uses and/or regions due to practical constraints.

Shared Policy Assumptions for New Zealand (SPANZs)

The RA5 team developed a new framework for developing New Zealand-focused scenarios nested within global scenarios (Frame & Reisinger 2016). The framework links global, national and local modelling of climate change and its impacts and implications with a range of key quantitative and qualitative indicators. The new framework includes narratives specific to New Zealand's situation that broadly outline developments in the Pacific region and New Zealand's climate and non-climate policy dimensions.

The new framework also introduced Shared Policy Assumptions for New Zealand (SPANZs). SPANZs consist of a structured set of assumptions about how New Zealand climate policies relate to global climate policies as outlined in global SPAs. By default, New Zealand climate policy follows global developments as outlined in the relevant SPA. Most commonly, New Zealand climate policies develop following assumptions that apply to all OECD countries.

The specification of SPANZs allows exploration of scenarios in which New Zealand policies diverge from globally-specified trends (Frame & Reisinger 2016). The six SPANZ developed for CCII structured consideration of New Zealand's shared policy assumptions such that New Zealand's approach could lead, remain consistent with, or lag global efforts regarding challenges to mitigation and adaptation (Table 2).

Table 2: Shared Policy Assumptions for New Zealand (SPANZ)

SHARED POLICY ASSUMPTIONS FOR NEW ZEALAND (SPANZs)		DOMESTIC APPROACH TO ADAPTATION (relative to SSP)	
		Short-sighted: Incremental and Focussed on Short-term Gains	Long-sighted: Strategic and Transformational
DOMESTIC APPROACH TO MITIGATION (relative to SSP)	Lags behind global efforts	A NZ lags relative to global mitigation efforts. Adaptation tends to be incremental and reactive on a piecemeal basis, influenced by short-term economic gains and vested interests. This policy stance is dominated by a strong focus to minimise near-term costs and avoid transformational approaches to both mitigation and adaptation. Adherence to international expectations is minimal.	D NZ lags relative to global mitigation efforts. A strategic perspective guides adaptation and includes transformational changes where necessary to achieve long-term goals. This policy stance is driven by a perception that NZ has no meaningful role to play in mitigating climate change through mitigation. Instead NZ must focus on securing its own long-term resilience and viability by adapting to inevitable changes.
	Consistent with global efforts	B NZ neither leads nor lags relative to global mitigation efforts. Adaptation tends to be incremental and reactive on a piecemeal basis, influenced by short-term economic gains and vested interests. This policy stance is dominated by a strong focus to minimise near-term costs and fundamental transformations in adaptation while complying with international expectations on mitigation.	E NZ neither leads nor lags relative to global mitigation efforts. A strategic perspective guides adaptation and includes transformational changes where necessary to achieve long-term goals. This policy stance is dominated by a sense that compliance with international expectations on mitigation is necessary but the real key to long-term prosperity and resilience lies in effective adaptation.
	Leads global efforts	C NZ leads global mitigation efforts in terms of ambition and innovation. Adaptation tends to be incremental and reactive on a piecemeal basis, influenced by short-term economic gains and vested interests. This policy stance is dominated by an assumption that strong mitigation is the only solution that protects NZ's international reputation and market access. Adaptation is a 'second-best' response to climate change.	F NZ leads global mitigation efforts in terms of ambition and innovation. A strategic perspective guide adaptation and includes transformational changes where necessary to achieve long-term goals. This policy stance reflects an assumption that adapting to change, including through transformation, is key to NZ's well-being. Adaptation, as well as mitigation, will secure NZ's international reputation and market access as well as moral obligations.

Scenario formulation in RA3 occurred by first selecting a global scenario that combined a specific SSP with a specific RCP (Fig. 4). Incorporation of SPAs was optional and depended on the RCP selected. Mitigation scenarios included RCP2.6, RCP4.5, or RCP6.0. Non-mitigation scenarios did not standardise on an RCP (e.g. RCP8.5). Instead global greenhouse gas emissions evolved according to the SSP assumptions.

Mitigation scenarios involving RCP2.6, RCP4.5, or RCP6.0 included an optional SSP-specific SPA that outlines global climate policy assumptions and developments. Non-mitigation scenarios assume that no global climate policy assumptions operate and have no corresponding SPA. However for consistency and completeness, non-mitigation scenarios were considered to include "SPA0."

CCII scenarios also included a SPANZ as specified in the new framework developed by RA5.

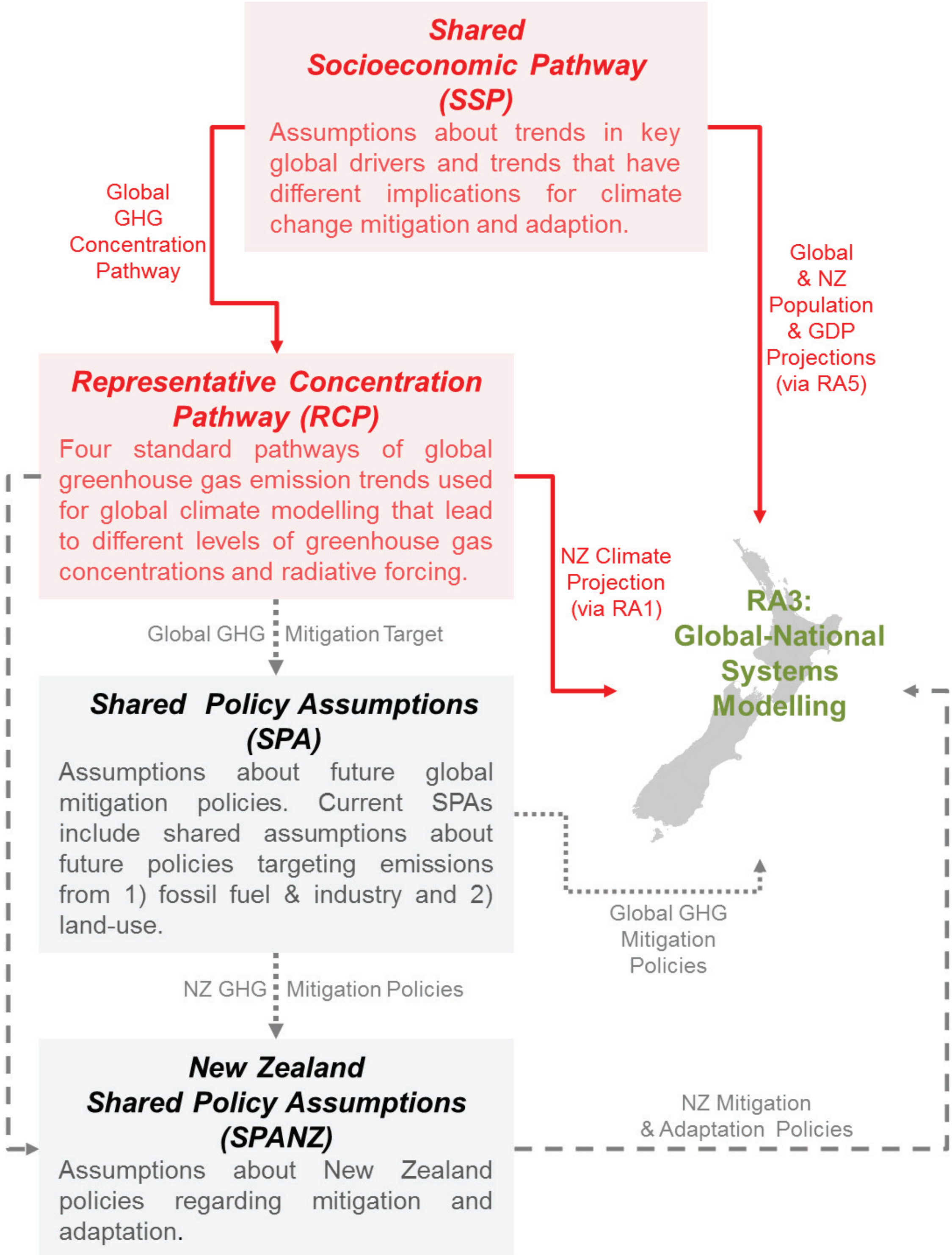


Figure 4 Schematic of RA3 climate change scenario formulation including key assumptions and relationships. Mandatory elements = red boxes and arrows. Optional elements = grey boxes and arrows.

Scenario Evaluation Protocol

The RA3 team followed the same protocol developed in a global integrated assessment modelling study that evaluated the new set of global climate change scenarios ("global scenario study" hereafter). Six global integrated assessment modelling teams participated in the global scenario study. They published a study protocol (Riahi et al. 2015) outlining the assumptions used, including specific SPAs implemented, and the steps followed. They also published a harmonised set of modelling outputs[1] to foster broad understanding, ease of use, analysis, and comparability.

The global scenario study implemented the following protocol to evaluate a global scenario:

1) Select the global scenario to evaluate, i.e. the combined SSP and RCP.

2) For the selected SSP, specify fixed projections for population (Samir & Lutz 2017) and economic development (as GDP) (Dellink et al. 2017) out to 2100 and use the coupled quantitative projections as targets for subsequent modelling.

3) Implement an SSP-specific set of assumptions about energy demand and supply, technology, land-use, agriculture, etc. (Note: Global modelling teams had the flexibility to implement assumptions subject to the constraints and internal assumptions of their respective integrated assessment model).

4) For mitigation scenarios involving RCP2.6, RCP4.5, or RCP6.0, implement an SSP-specific SPA developed for the study such that the modelled RCP out to 2100 matches the selected RCP.

The fixed, coupled population-GDP projections served as the quantitative basis for all scenarios (Dellink et al. 2017, Samir & Lutz 2017). In four SSPs (1, 2, 4, 5) global population peaks and then starts to decline before 2100 (Fig. 5a). The timing and magnitude of the peaks vary, such that the final population at 2100 ranges from 6.8 billion for SSP1 to 9.2 billion for SSP4. SSP3 shows continuous population growth and a resulting global 2100 population of 12.6 billion. For comparison, the medium variant of the United Nations Population Division's 2015 World Population Prospect projects global population to grow to 11.2 billion by 2100 (UNPD 2015).

All five SSPs assume that global GDP grows from 2010 to 2100 (Fig. 5a) (Dellink et al. 2017). Final global GDP differs substantially among the five SSPs, reflecting the differences among their narratives and broad qualitative assumptions. SSP5 produces the most growth, such that its final global GDP is double the value of the next two nearest SSPs, SSP1 and SSP2, which have equivalent final global GDP values. SSP4 and SSP3 rank 4th and 5th, respectively.

New Zealand's assumed population trends range broadly and do not always mirror global trends (Fig. 5b). SSP3 has the highest global population at 2100, whereas New Zealand's population peaks earliest and then declines to the lowest final value of 3.8 million or ~600,000 less than its initial 2010 value. SSP5, in contrast, assumes the second lowest global population at 2100 but assumes New Zealand population will more than double to almost 10 million by 2100. SSP1 has the lowest global population and an intermediate New Zealand population of 6.5 million by 2100. SSP2 and SSP4 show more similar trends globally and for New Zealand.

Unlike population, New Zealand's economic development mirrors global trends, as indicated by both the relative ranking and magnitude and of NZ GDP in 2100. Final NZ GDP ranks in the same order: SSP5, SSP1/SSP2, SSP4, and SSP3. SSP5 assumes substantially higher growth, while SSP3 assumes the least. The main difference between global and NZ GDP trends is that final NZ GDP for SSP4 more closely matches SSP1 and SSP2.

In the global scenario study protocol, non-mitigation scenarios referred to global greenhouse gas concentration pathways as reference ("REF" for short) pathways, i.e. scenario SSP4-REF. As discussed earlier, global greenhouse emissions evolved according to SSP assumptions. Emissions also varied depending on the assumptions, structure and dynamics of different global integrated assessment models. As a result, greenhouse gas concentration pathways in non-mitigation, REF-based scenarios were not standardised, e.g., did not follow RCP8.5.

[1] Global SSP Database available at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

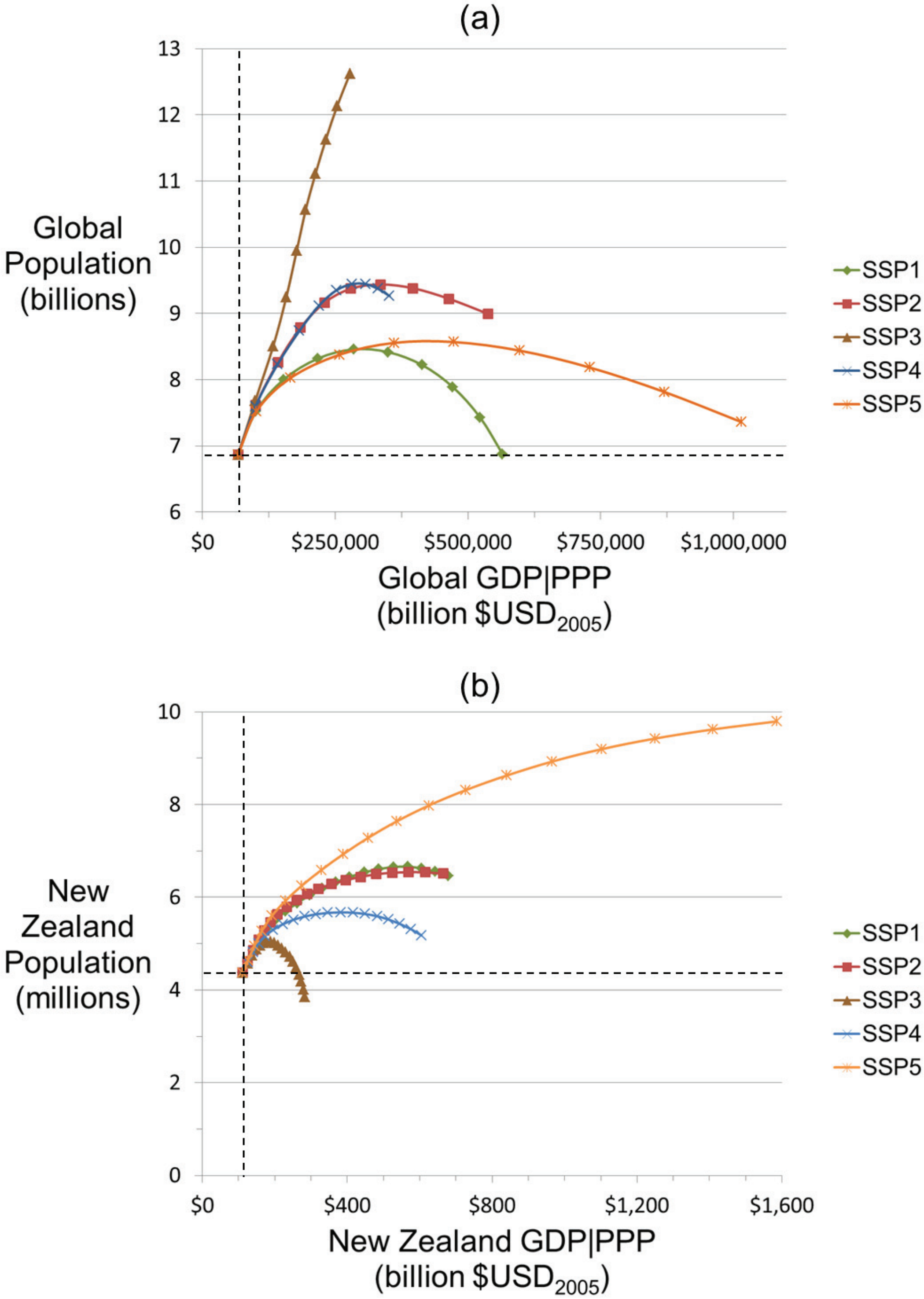


Figure 5 Global (a) and New Zealand (b) coupled population-GDP|PPP trajectories from 2010 to 2100 for the five SSPs that served as the basis for quantitative modelling. Dashed lines indicate change relative to 2010 starting values. Data from the global SSP Database Version 1: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

Coupling an SSP with RCP2.6, RCP4.5, or RCP6.0 created "mitigation" scenarios with the requirement of reproducing the selected RCP subject to the narrative, assumptions and constraints of the selected SSP. Achieving the RCP required the implementation of an SPA consistent with the SSP. In the SPAs developed for the global scenario study, "highly developed countries" including New Zealand implement a common set of policies, which may or may not be the same as policies implemented by the other global regions modelled.

While formulation of a broad range of SPAs consistent with SSP assumptions was possible, for practical reasons the global scenario study generated a single SPA for each SSP, e.g. SPA1 for SSP1, SPA2 for SSP2, etc. The SPAs outlined shared assumptions about policies related to GHG gas emissions from both fossil fuels & industry and land use (Fig. 6). Three different cases were developed for both fossil fuels & industry and land use, and different cases were then combined to formulate an overall SPA.

For fossil fuels and industry, SPAs differed according to how quickly global regions converged to a shared GHG emissions policy. From a quantitative modelling standpoint, each SPA specified how quickly regional carbon prices converged to a single global carbon price from the current fragmented situation. For land use, SPAs differed according to whether, to what degree, and/or how quickly land-use GHG emissions became included in carbon pricing schemes.

Finally, as discussed in the RA5 synthesis report (Frame & Reisinger 2016), the number of possible scenarios to evaluate based on all possible combination of SSPs + RCPs + SPAs grows geometrically and quickly eclipses available resources. As a result, the CCII team selected a subset of six scenarios to evaluate given available time and resources (Fig. 7). The six selected CCII scenarios focused more effort on scenarios with higher challenges to mitigation than adaptation given current New Zealand priorities i.e. to inform discussion over New Zealand's position in post-Kyoto climate change mitigation negotiations. Ideally, of course, we would have evaluated the full suite of scenarios.

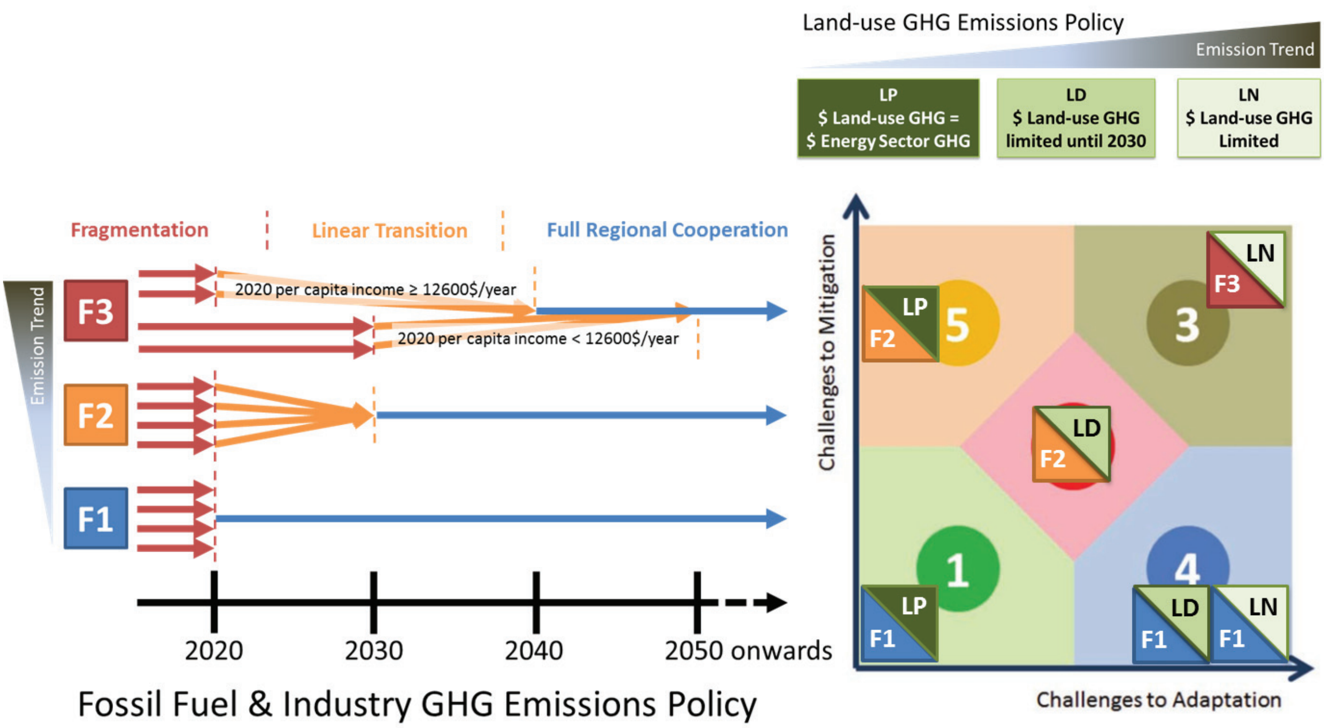


Figure 6 Shared Policy Assumptions (SPAs) combining assumptions about Fossil Fuel & Industry GHG Emissions and Land-use GHG Emissions used in the global scenario study. The placement of the coloured boxes (SPAs) within an SSP indicates the relative implications for GHG emissions trends on an imaginary 3x3 grid within each SSP. Placement towards the bottom (top) or right (left) implies a relatively lower (higher) GHG emission trend, respectively, for Fossil Fuel & Industry GHG Emissions Policy (grid rows) and Land-use GHG Emission Policy (grid columns). The combined placement provides a relative indication of likely emissions trends among all nine possible combinations. For example, SPA1 developed for SSP1 assumed rapid convergence to global Fossil Fuel & Industry GHG emissions (F1) and pricing of GHG emissions from land use equal to those from the energy sector (LP). When combined, F1+LP would lead to the lowest emission trends overall relative to other combinations, such that the combination is placed at the bottom left of SSP1. The relatively lower emission trends would help reduce or minimise challenges to mitigation and adaptation. Conversely, SPA3 developed for SSP3 assumed combined policies leading to higher challenges for mitigation and adaptation. The study protocol specified a single combination of policies for each SSP, except SSP4, in which case integrated assessment modelling teams participating in the study could choose between F1+LD or F1+LN.

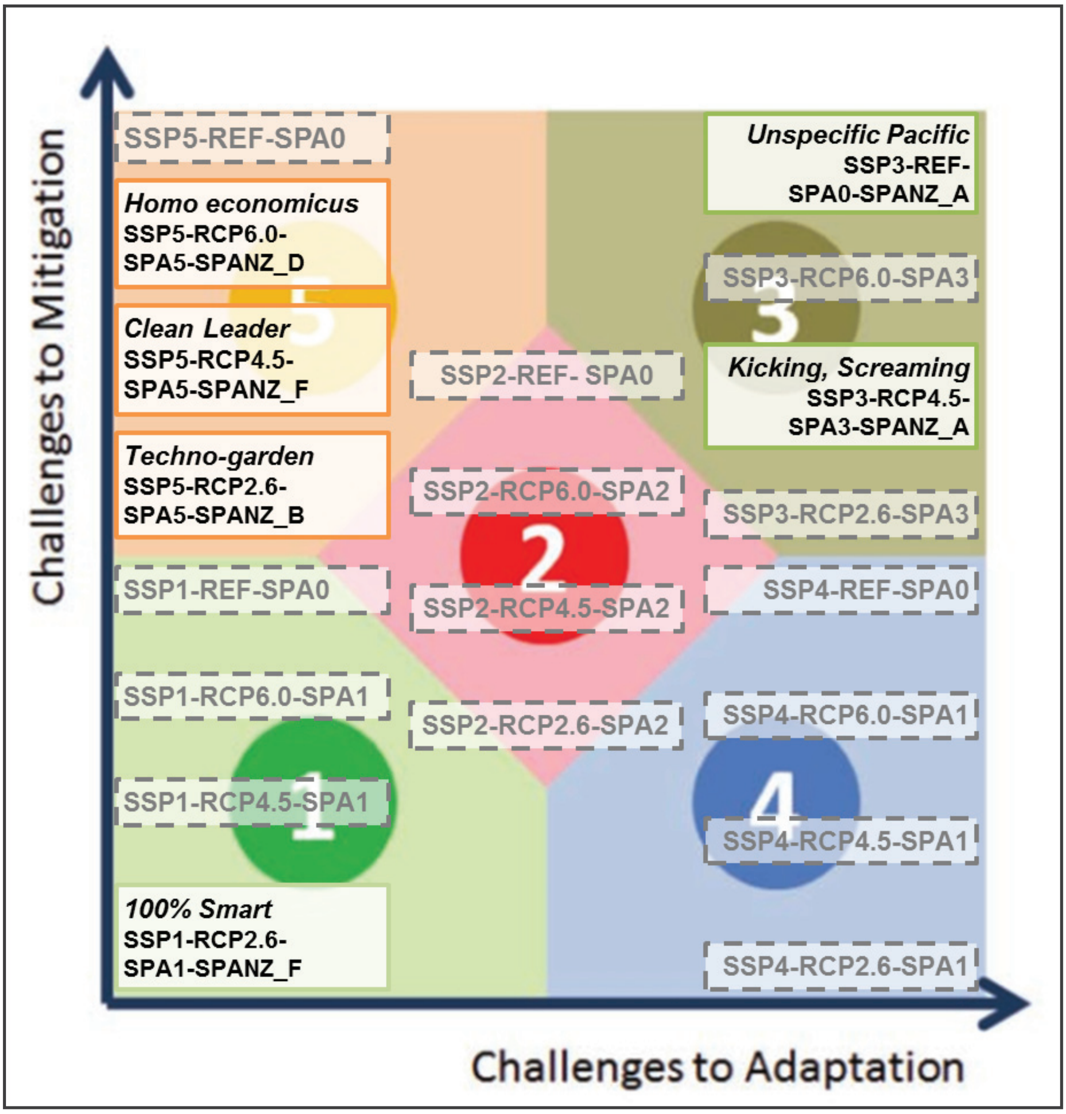


Figure 7 Six CCII scenarios within the broader global scenario architecture. The global scenario architecture organises global socioeconomic development into five discrete pathways (SSPs) along two axes: challenges to adaptation (horizontal axis) and challenges to mitigation (vertical axis). CCII aimed to evaluate six (black) of the possible 20 global scenarios (unevaluated scenarios are shown in grey). Scenario nomenclature follows the global scenario study protocol as follows: SSP = Shared Socioeconomic Pathway (1–5); RCP = Representative Concentration Pathway (2.6, 4.5, 6.0, REF) arranged vertically within each SSP to reflect increasing global GHG concentration; Shared Policy Assumptions (0–5); SPANZ = Shared Policy Assumption for New Zealand (A–F).

Note: The global study introduced a fifth forcing target (3.4) for evaluation to foster consideration and evaluation of mitigation outcomes between RCP2.6 and RCP4.5. CCII could not consider the new 3.4 target because no corresponding global climate modelling results were available for RA1 to generate 3.4-based improved climate projections for New Zealand. Hence global scenarios incorporating the 3.4 target are not shown.

RA3 LOOSELY-COUPLED NATIONAL HUMAN-NATURAL SYSTEMS MODEL

RA3 developed a loosely coupled national human-natural systems model (Table 3, Fig. 8) that integrated a suite of NZ-based models. In loosely coupled models, researchers manually facilitate information and/or data exchange among model components. Below we briefly overview the RA3 models, organised alphabetically by theme, and outline the methods they used for scenario evaluation.

Given the complexity and effort required for CCII scenario evaluation, the resources available and substantial challenges that delayed delivery of the improved climate projections for use in RA3, the RA3 team could not completely evaluate all six CCII scenarios. Table 3 below lists the CCII scenarios evaluated by each RA3 model. SSP3-based scenarios received higher priority because they included high challenges to both mitigation and adaptation.

Table 3: RA3 scenario evaluation by model theme (listed alphabetically)

		CCII Scenarios Evaluated					
Model Theme	Model Name	100% Smart (SSP1-RCP2.6-SPA1-SPANZ_F)	Kicking, Screaming (SSP3-RCP4.5-SPA3-SPANZ_A)	Unspecific Pacific (SSP3-REF-SPA0-SPANZ_A)	Techno-garden (SSP5-RCP2.6-SPA5-SPANZ_B)	Clean Leader (SSP5-RCP4.5-SPA56-SPANZ_F)	Homo economicus (SSP5-REF-SPA0-SPANZ_D)
Crop Productivity (Maize)	APSIM			✓			
Demographics*	Cohort-Component Model		✓	✓			
Forestry and Agriculture‡	NZ-FARM	✓	✓	✓	✓	✓	✓
Forest Productivity (Pinus radiata)†	CenW	✓	✓	✓	✓	✓	✓
Global-New Zealand Socioeconomic Co-Development	CliMAT-DGE	✓	✓	✓	✓	✓	✓
Hydrology & Water Resources†	TopNet	✓	✓	✓	✓	✓	✓
Improved Climate Projections†	NZ-RCM (RA1)	✓	✓	✓	✓	✓	✓
Pasture Productivity†	BIOME-BGC	✓	✓	✓	✓	✓	✓
Rural Land Use	LURNZ			✓			
Uncertainty in Ecological Effects†	Fish Distribution			✓			

*Also evaluated RCP2.6 and RCP6.0 for SSP3

‡Full analysis for Unspecific Pacific, partial analysis for all others

†RCP-only based analysis

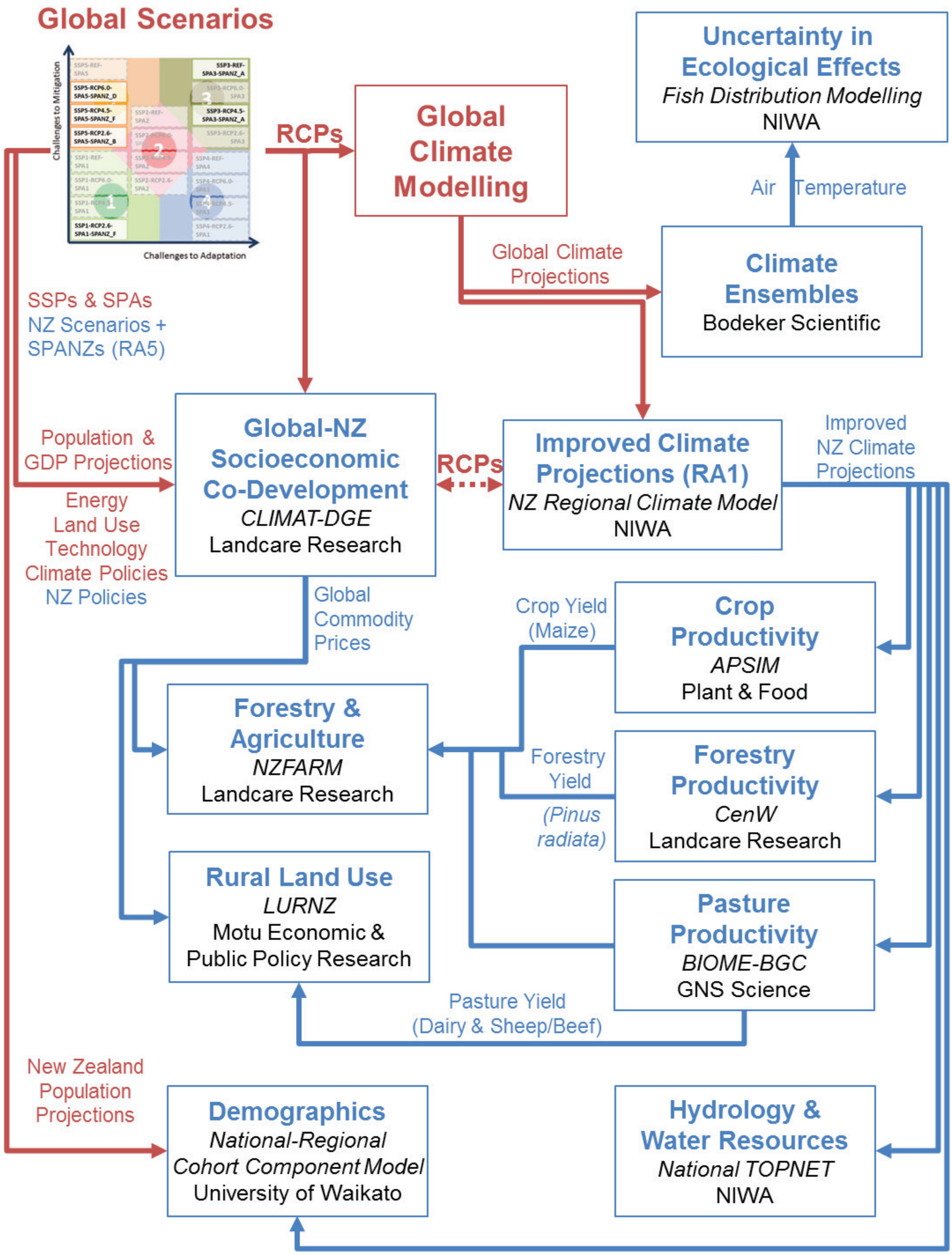


Figure 8 Diagram of the RA3 national loosely-coupled human-natural systems model used in the national integrated assessment and scenario evaluation and its links to global scenarios. Boxes = system components including models. Arrows = data and/or information links or exchanges (i.e. inputs and outputs). Global scenarios, components and links are in red. RA3 components and links are in blue. The red dashed line labelled "RCPs" between Global-NZ Socioeconomic Co-Development and Improved Climate Projections (RA1) indicates the requirement to standardise the RCP-component of the scenarios across all modelling for consistency and comparability.

Crop Productivity (Maize) – APSIM

We simulated silage maize growth with the Agricultural Production Systems sIMulator (APSIM) (Holzworth et al. 2014; Teixeira et al. 2015) at daily time steps across arable lands as delineated by the Land Cover Database Version 4.1 (https://lris.scinfo.org.nz/) at the same 0.05° x 0.05° (~5 km x 5 km) resolution as the improved New Zealand climate projections. Model runs were carried out for historical climate (1971–2000, ERA-40 dataset) and three time-slices (1985–2005, 2045–2065, 2079–2099) using results from the HadGEM2-ES climate model under RCP8.5 only.

Simulations assumed fully irrigated conditions and a single hypothetical soil type with high water-holding capacity (160 mm/m) to isolate temperature effects. Baseline results were tested in collaboration with experts from the Foundation for Arable Research (FAR) and The Institute for Plant & Food Research Limited (PFR), and through sensitivity analysis (Teixeira et al. 2016a,b). Two adaptation options were tested: (i) changing sowing to earlier dates, and (ii) adjusting genotype maturity (i.e. use long-cycle genotypes).

Demographics – National-Regional Cohort-component Model

We modelled future demographic trends for New Zealand using a cohort-component model (CCM). The CCM projects future annual population for each region in New Zealand by 1-year age-sex cohorts, e.g. the number of females aged 24–25 in the Taranaki region in 2037, and then sums regional projections to produce national projections.

The CCM relies on assumptions of projections for three components: (1) fertility rates (births) for females in reproductive age cohorts; (2) mortality rates (deaths) or survivorship for all age-sex cohorts; and (3) migration, both internally among regions within New Zealand and internationally between New Zealand and the rest of the world.

An earlier literature review (Cameron 2013) established that climate change would not significantly impact either human fertility or mortality in New Zealand. Future net international migration rates depended on assumptions of future global development and associated future political developments, i.e. SSP assumptions, whereas climate change impacts are uncertain. Therefore we assumed that climate change would not impact (assumed) net international migration rates but could impact New Zealand population (number and distribution) by altering internal migration dynamics.

We estimated a gravity model of internal migration flows in New Zealand, using 5-year migration flow data from the 1996–2013 Censuses. The gravity model regresses the log of migration flows from region i to region j on the logs of the populations of i and j, and the log of the distance between them. We augmented the gravity model by including a dummy variable for contiguity, a dummy variable for inter-island flows, and origin and destination fixed effects to account for time-invariant differences in push and pull factors.

To assess the potential impact of climate change on internal migration, we introduced historical data for 13 climate variables, one at a time, into the gravity model specification at both the origin and destination and tested their statistical significance. After identifying an initial set of variables that were individually statistically significant, we used backward stepwise regression to test the full model and reduce the number of included climate variables to those that remained statistically significant. The gravity model of internal migration with climate variables was then integrated into the CCM (Cameron & Poot 2014).

We evaluated New Zealand regional and national population trends for scenarios under SSP3 combined with each of the four RCPs (2.6, 4.5, 6.0, and 8.5). Statistics New Zealand sub-national projections were used for fertility and mortality rates. SSP3-based projections for New Zealand (Samir et al. 2013; Samir & Lutz 2017) were used for international migration flows (immigration and emigration). We adjusted net migration rates in 5-year periods to calibrate the gravity CCM to reproduce the SSP3 population projection for New Zealand from an initial value of 4.368 million in 2010, to a peak of 5.039 million in 2045, to 3.847 million in 2100. CCM projections matched New Zealand SSP3 projections to +/– 0.03%.

From an RCP perspective, we used NZ-RCM results based on the HadGEM3 global climate model for each RCP to test potential impacts of climate change. Grid-based climate variables were converted to averages for New Zealand Census Area Unit using raster zonal statistics in ArcGIS. Population-weighted Census Area Unit averages were then aggregated to calculate climate variable values for each region.

Forest Productivity – CenW

The simulation results described here used the comprehensive process-based ecophysiological model CenW 4.1 to simulate the growth of *Pinus radiata* across New Zealand (Kirschbaum & Watt 2011). CenW had 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 models *P. radiata* growth over 30 years within inputs including stand densities and thinning regimes (Kirschbaum et al. 2012).

CenW modelling operated on a daily time step corresponding to the availability of daily improved climate projections from RA1. In past work, only average changes in weather parameters were available, and weather anomalies had to be added to a current-day weather sequence. That preserved a realistic pattern of seasonal changes in the selected weather parameter, but did not include any possible changes in those patterns themselves. RA3 analyses used daily NZ-RCM outputs based on global GCMs and thus incorporated 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 as changes in productivity between three 30-year averages (1981–2010 vs 2041–2070 and 2071–2100), and as progressive annual changes in productivity by running the model over successive, overlapping 30 year periods, e.g. 1981–2010, 1982–2011, 1983–2012, and so on.

Forestry and Agriculture – 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 (Daigneault et al. 2017). NZFARM assesses 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 (Fig. 9).

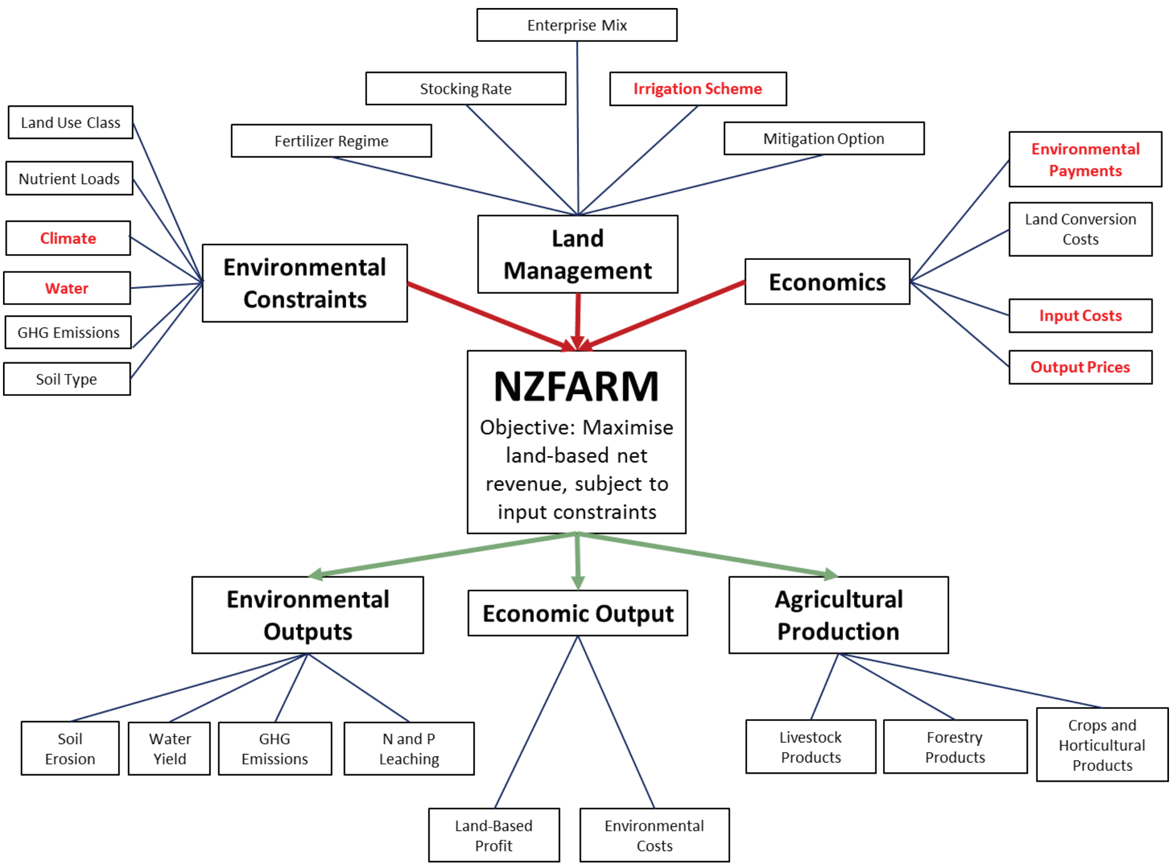


Figure 9 Diagram of inputs and outputs from NZFARM.

In this study, we use NZFARM to assess the implications on farm income, land use and the environment, when New Zealand landowners 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 not only indicating 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 management zone.

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. (2017).

The full set of biophysical and socio-economic data required for NZFARM to conduct a national-level analysis was only available for the 8.5/3/A scenario. As a result, we primarily focus on that set of results. However, we also conducted a suite of scenario analysis for just the commodity and GHG price changes estimated in CliMAT-DGE for all RCP/SSP/SPA combinations. This allowed us to estimate the possible effect of various socio-economic and policy pathways, but ignore any potential that climate change may have on agricultural yields.

Global-New Zealand Socioeconomic Co-development – CliMAT-DGE

We used the Climate and Trade Dynamic General Equilibrium (CliMAT-DGE) to assess global and New Zealand socioeconomic development under the six CCII scenarios. CliMAT-DGE is a multiregional, multi-sectoral, forward-looking dynamic general equilibrium model with a 100-year or longer time horizon (Fernandez & Daigneault 2015). This model was developed to study 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, CliMAT-DGE projects the behaviour of the economy, energy use, and emissions by global regions and sector (Fæhn et al. 2013).

CliMAT-DGE covers 18 aggregated production 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 RA3, the objective of CliMAT-DGE modelling was to replicate the global scenario study for the six CCII scenarios. For each scenario, we constrained CliMAT-DGE to reproduce simultaneously 1) the SSP-based global coupled population-GDP projections (Fig. 5); 2) SSP-based New Zealand coupled population-GDP projections (Fig. 5); and 3) the selected RCP (Fig. 3), subject to SSP, SPA, and/or SPANZ assumptions. See Appendix 1 for the full list of CliMAT-DGE input values used for scenario evaluation.

Hydrology and Water Resources – National TopNet

The hydrological model used in this study is TopNet (Clark et al. 2008), which is routinely used for surface water hydrological modelling applications in New Zealand (Fig. 10). It is a spatially semi-distributed, time-stepping model of water balance. It is driven by time-series of precipitation and temperature, and of additional weather elements where available. TopNet simulates water storage in the snowpack, plant canopy, rooting zone, shallow subsurface, lakes and rivers. It produces time-series of modelled river flow (without consideration of water abstraction, impoundments or discharges) throughout the modelled river network, as well as evapotranspiration, and does not consider irrigation. TopNet has two major components: a basin module and a flow routing module.

As inputs TopNet uses the same 0.05° x 0.05° grid as the improved New Zealand climate projections (Tait et al. 2016) on a daily time step for the historic period and improved climate projections from RA1 for the period 2006–2100. For both data sets daily data were disaggregated to hourly resolution following the methods in Clark et al. (2008).

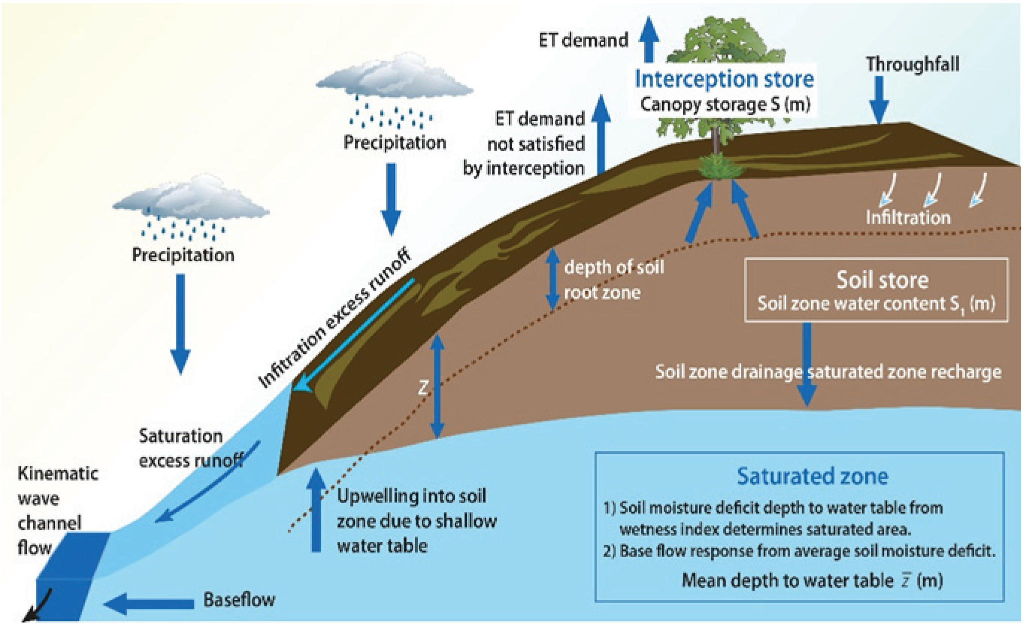


Figure 10 Conceptual diagram of the TopNet hydrological model.

Improved Climate Projections – NZ-RCM (RA1)

RA1 used the New Zealand Regional Climate Model (NZ-RCM) to produce improved climate projections to 2100 for New Zealand for use by RA3 (Fig. 8).

Table 4 and Table 5 summarise the direct outputs of the NZ-RCM. The RA1 team also generated additional derived outputs (e.g. annual values, potential evapotranspiration) as needed by particular models in CCII. Below is a brief overview of RA1 methods for ease of reference. For more detail, consult the RA1 synthesis report (Tait et al. 2016).

Global climate modelling carried out for the IPCC 5th Assessment (IPCC 2014) served as the basis for the improved New Zealand climate projections (Fig. 1; Fig. 8). Global climate modelling teams used historic and future (i.e. the four RCPs) GHG emission time series as inputs to global Earth System Models/Global Circulation Models. The global models produced simulated historic climate conditions and projected future climate conditions for each RCP, resulting in 5 output data sets (1 historic + 4 RCPs) from each global climate model (e.g. HadGEM3).

The RA1 team evaluated the suite of global modelling outputs to determine which global models best simulated historic climate conditions for New Zealand. Based on the evaluation, the RA1 team selected outputs from six global climate models as inputs to the NZ-RCM (Mullan et al. 2013a, b) to generate improved higher resolution climate projections for New Zealand. Global model outputs provided both boundary and starting conditions for running the finer-scale NZ-RCM.

Table 4: Specifications of improved New Zealand climate projections data produced by RA1 using the NZ Regional Climate Model.

Specification	Detail
Spatial Extent	New Zealand Main & Inshore Islands
Spatial Resolution	0.05° x 0.05° or ~5 km x 5 km corresponding to the NZ Virtual Climate Station Network (VCSN)
Temporal Extent	Historic: 1979 to 2005 Projected: 2006 to 2100 or 2120 (varies by global climate model)
Temporal Resolution	Daily

Table 5: Climate variables produced by the NZ Regional Climate Model

Climate Variable	Units
Maximum Air Temperature	degrees kelvin = °K
Minimum Air Temperature	degrees kelvin = °K
Precipitation (total)	millimetres = mm
Average Solar Radiation	mega joules per meter squared = MJ/m^2
Average Wind Speed at 10 m height	meters per second = m/s
Average Mean Sea Level Pressure	hectopascals = hPa
Average Relative Humidity	percent = %

Pasture Productivity – Biome-BGC

We used the Biome-BGC model (Version 4.2) (Thornton et al. 2002, 2005) to model pasture productivity for two New Zealand managed grassland systems. 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. The model includes the CO_2 fertilization effect that enhances both the rate of photosynthesis and reduces water loss in plants under elevated atmospheric CO_2 concentrations.

We calibrated Biome-BGC to model two New Zealand managed grassland systems: Sheep & Beef (low intensity) and Dairy (high intensity). 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). 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 and removed from the system. The dairy parameterization effectively results in increased water-use efficiency and very little nitrogen limitation on growth. Irrigation is not simulated in either system.

Model parameters were calibrated using observed data for pasture growth data and historic climate and validated for both dairy and sheep systems (Keller et al. 2014). Climate inputs included minimum air temperature, daily maximum air temperature, precipitation, vapour pressure deficit, and solar radiation, all at a daily time step.

For scenario evaluation, the Sheep & Beef and Dairy models were run for 24 combinations of RCP (4) and NZ-RCM output (6 in total based on the selected GCMs) on a daily time step at the same 0.05°x0.05° (~5 km x 5 km) spatial resolution as the improved NZ climate projections. Soil texture and rooting depth was obtained from the New Zealand Fundamental Soil Layers data set.[2]

A reference or 'baseline' pasture production for each GCM was simulated using the simulated past climate representative of modern day conditions, averaged over the nominal years 1986–2005. For all future scenarios, the model was first 'spun up' to an equilibrium steady state using RCP past climate, and then restarted and run as a transient simulation from 2005 to 2100 using each model- and RCP-specific projected climate. We note that these transient simulations contrast previous work (Keller et al. 2014) that only included equilibrium model runs during each future period.

Results are reported as a model ensemble mean for each RCP by calculating average pasture production across all six GCMs within each grid cell. Scenarios were evaluated by comparing averages from 20-year baseline conditions (1986–2005) to mid-century (2046–2065) and end-of-century (2081–2100) conditions.

[2] Available at https://lris.scinfo.org.nz/

Rural Land Use – LURNZ

We used the Land Use in Rural New Zealand (LURNZ) model to better understand pressures on land use and the rural environment from climate change and related socio-economic changes in New Zealand (Fig. 11).

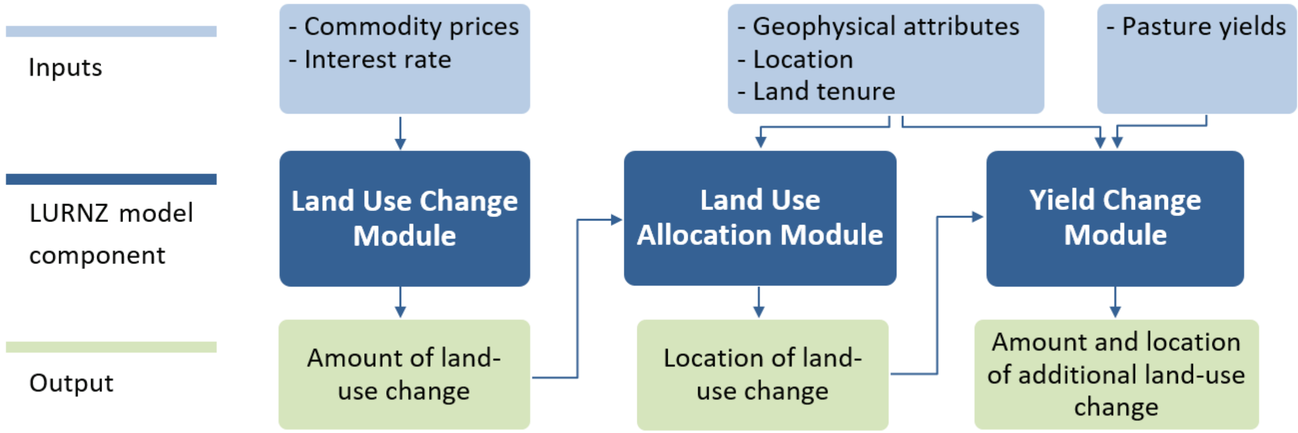


Figure 11 A schematic diagram of modelling land use in LURNZ.

The LURNZ model is built upon econometrically estimated functions that establish the relationship between observed drivers of land use and land-use outcomes (Kerr et al. 2012; Timar 2011, 2016). Because the model is data driven, it does not require strong assumptions about the motivations of rural decision makers. On the other hand, estimated relationships may not work well for out-of-sample predictions, e.g. when drivers of land use change go outside their historical range.

LURNZ simulations handle economic and climate drivers of land use change in a consistent framework. We used commodity price projections under SSP 3 from CliMAT-DGE (Fig. 12) and pasture yield projections under RCP 8.5 from Biome-BGC as inputs. The simulations are evaluated relative to a baseline land-use scenario that is defined by commodity price projections from the Ministry for Primary Industry's Situation and Outlook for Primary Industries (SOPI) (MPI 2016) until 2019 (and constant prices thereafter) and current climate.

Land use in a future baseline is not equivalent to current land use because of the dynamic nature of LURNZ: the adjustment to historical price changes continues in the simulation period.

To disentangle the effects of economic and climate drivers, we performed simulations in which we first isolated and then combined the two types of drivers. RCP only runs used baseline commodity prices. We then repeated the RCP runs with yield projections based on downscaled climate data from each individual GCM, thereby testing the importance of the choice of climate model on land-use outcomes.

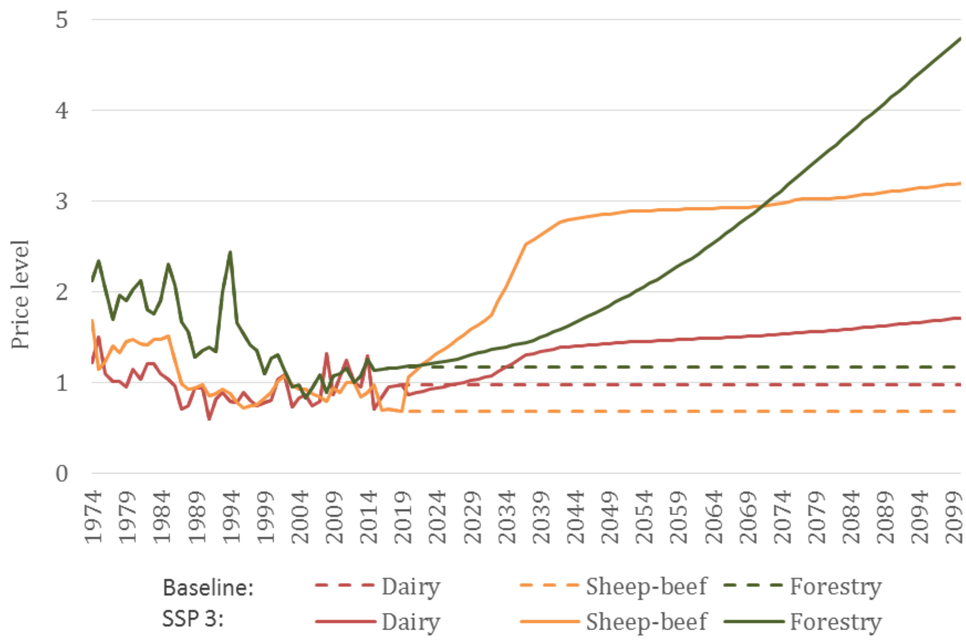


Figure 12 Historical prices, baseline and SSP 3 price projections (scaled to the 2012 price level).

Uncertainty in Ecological Effects – Banded Kōkopu Distribution Model

Overview

Predicting the effects of climate change is vital for managing ecosystems. However, climate models often do not provide environmental variables pertinent to the ecosystem of interest. Several steps are often needed to translate future climate predictions into assessments of likely ecological effects, each of which can introduce mathematical uncertainty in addition to climate prediction uncertainty.

A novel approach was developed for objectively expressing uncertainty when using climate change predictions of available variables to predict future impacts on unavailable, but related, variables relevant to the ecological effects of interest. The ability to make valid predictions was tested using differences in the observed data as an analogy to differences between current and future conditions.

The approach is demonstrated using the example of increases in river water temperature on the juvenile life stage of the banded kōkopu (*Galaxias fasiatus*), a New Zealand native fish species. Banded kōkopu are an amphidromous species[3] that are widely distributed across New Zealand due to their known ability to penetrate well inland. Juveniles, commonly called whitebait, enter fresh water around mid-spring and steadily migrate upstream after a larval marine life stage.

Information relating suitability of environmental conditions is available in the form of preferred water temperatures. Methods are available for simulating water temperature from an available variable (air temperature). However, there are several sources of mathematical uncertainty associated with: 1) fish temperature preferences; 2) air–water temperature relationships; and 3) future predictions of air temperatures. The situation is further complicated because air-water temperature relationships are site-specific, the processes of freezing and evaporation can cause non-linearities at the extremes of the air–water temperature relationship, and climate change often requires predictions to extrapolate outside the bounds of observed conditions.

Approach

The approach developed involves fourteen technical steps (Table 6). The approach quantifies the suitability of future water temperatures, expressed alongside whether future predictions fall within the range of observed conditions (interpolation within the observed conditions) or fall beyond the range of observed conditions (extrapolation outside the observed

[3] Amphidromous fish species regularly migrate in both directions between freshwater and the ocean, but not for the purpose of breeding, as in anadromous and catadromous fish species.

conditions). The approach was applied using two methods for describing air-water relationships, and predictions of many possible futures for each of three RCP's at four sites. Air–water relationships were modelled by fitting a linear model and a non-linear model designed to cope with evaporation and freezing effects (Mohseni et al. 1998).

Previous laboratory work has shown that individual juvenile banded kōkopu temperature preferences are centred on 16.1 °C with an interquartile range of 14.8–17.7 °C (Richardson et al. 1994). For this analysis it was assumed that the 5th and 95th range of temperature preferences matched those of other New Zealand native species as suggested by Figure 2 of Richardson et al. (1994). Temperatures preferred by banded kōkopu were compared to mean daily river water temperature on the 10th hottest day of July to June years. The 10th hottest day was chosen to represent a time of potential high stress due to warm conditions. Models fitted to the closest observed year to the future year were used to predict future water temperatures from future predicted air temperatures.

Table 6: Technical steps that comprise the approach. For this example, x = air temperature, y = water temperature, obs = observed, sim = simulated, "~" represents "modelled as a function of"

Step	Description	Example	What is produced
1	Define method for predicting y as a function of x	Linear regression $y_{obs} \sim m\ x_{obs} + c$	A method for specifying y = f(x)
2	Separate observed data into discrete fitting periods	1996, 1997, 1998, 1999, 2000, etc.	Groups of observed data from each July to June period
3	Randomly select n fitting periods from those with sufficient data	Ten randomly selected years: 1998, 1997, 1999, etc.	n fitting periods each with at least 330 daily values
4	Fit/train/calibrate using data from each period separately	$y_{obs} \sim m_{1997}\ x_{obs} + c_{1997}$	Separate regression models fitted to each observed period
5	Apply model fitted using each period to predict for all other periods	Predict 1998, 1999 etc. with 1997 fitted model	Predictions for each period produced from each other period
6	Quantify accuracy bias and precision for each set of predictions	1997 fitted model predicts conditions well for 1998, but not well for 1999	Quantification of how well the model derived from each period performs when predicting each independent period
7	Quantify differences in observed conditions between each pair of periods	$\bar{x}_{diff} = \bar{x}_{obs1997} - \bar{x}_{obs1998}$	Quantification of how different each period was to each other
8	Compare accuracy of y (from Step 6) with differences in x (from Step 7)	$y_{residuals} \sim \bar{x}_{diff}$	Relationship between performance and difference in conditions within the observed range of conditions
9	Separate simulated climate change data into discrete time periods	2099, 2100, 2101, etc.	Groups of future data from each period
10	Compare climate change simulations and observed values for coinciding periods	$\bar{x}_{obs1997} - \bar{x}_{sim1997}$	Quantification of bias in climate change predictions
11	Quantify differences between each fitting period and future period	$\bar{x}_{obs1997} - \bar{x}_{sim2100}$	Quantification of difference between future predictions and each observed period
12	For each future period, apply model that is fitted to the least different period	predict y_{2100} 2100 with 1997 model	Predictions of future conditions with the most analogous model
13	Compare observed-future differences with observed-observed differences	$\bar{x}_{2100} - \bar{x}_{1997} > \bar{x}_{1999} - \bar{x}_{1997}$	Quantification of interpolation vs extrapolation
14	Compare future predictions with ecological preferences	y_{2100} > preferred water temperatures?	Predictions of suitability of future conditions

Sites

The approach was applied using at least 10 whole years of continuously (at least hourly) river water temperature data observed at each of four sites located in the regions of Southland (ES), Horizons (HRC), Otago (ORC) and Taranaki (TRC). The four selected sites represent a range of air and water temperature magnitudes and seasonal patterns (Fig. 13) rather than typical conditions within each region.

No sites included more than a few days where mean daily air temperatures were below freezing or above 25°C. Air–water temperature relationships were strong at each site, but their patterns varied across sites due to factors relating to hydrology, geology and shading. Mean daily air temperature from the Virtual Climate Station Network (VCSN; Tait et al. 2016) was used as a surrogate for observed air temperatures.

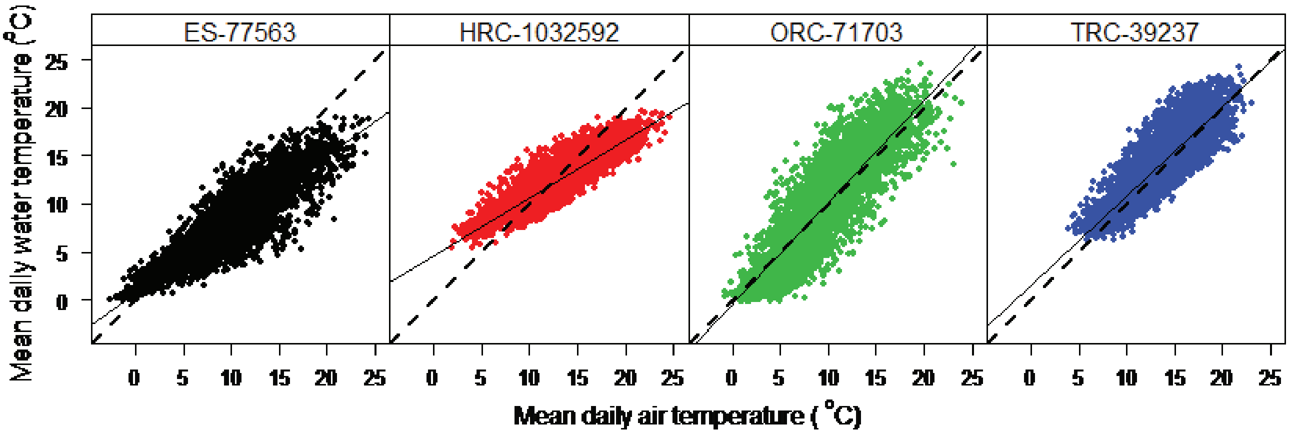


Figure 13 Mean daily river water and air temperatures for 10 randomly selected years at four sites. Black dashed line is 1:1. Black line is linear regression.

RESULTS AND DISCUSSION

This section presents the results of the CCII scenario evaluation. We begin with a brief overview of key global impacts and implications from the global scenario study. We then discuss results for New Zealand by model theme (Table 3), following the flow of information and data in the national systems model (Fig. 8), first from the RCP viewpoint and second from the SSP viewpoint. We chose that order given the dependencies among the themes/models. Understanding impacts and implications for climate is necessary for understanding potential impacts and implications for the suite of biophysical models that depend on climate (Crop Productivity, Forest Productivity, Pasture Productivity, Hydrology & Water Resources). Understanding impacts and implications from biophysical models is in turn important for understanding impacts and implications for the suite of socioeconomic models that use climate data directly, i.e. the demographic cohort-component model or indirectly via biophysical productivity models, i.e. NZFARM and LURNZ.

Global Scenario Study

Robust understanding and interpretation of the potential impacts and implications of climate change for New Zealand requires understanding the corresponding global context. Below we provide an overview of global scenario study results to foster familiarisation with key trends in global development, concentrating primarily on the six scenarios selected for evaluation by the CCII team. This overview serves as a primer to more detailed examination and exploration of any scenario.

Six international integrated assessment modelling teams participated in the global scenario study. The six teams published a study protocol that outlined the key assumptions and guidelines used to evaluate global climate scenarios developed to support the IPCC's 5th assessment. Each team ran their integrated assessment model to evaluate scenarios. Not every team evaluated all scenarios. For each SSP, results from one modelling team became "marker scenarios." For example, the results of AIM (Asia-Pacific Integrated Model) from the National Institute for Environmental Studies in Japan became the marker scenarios for SSP3-based scenarios.

To help comparability of climate results and potential impacts and implications, each modelling team ran the same global climate model called MAGICC (v6.8) (Wigley & Raper 1992, 2002) using the resulting GHG emissions from their modelling runs. MAGICC is a simpler model compared with more complex, full-featured earth system/global circulation models and has the key advantages of ease of use, quick run times, and, for the purposes of the global scenario study, standardisation.

Impacts

Impacts from the global scenario study are organised into five themes: socioeconomic development, climate, energy and technology, land use/land-use change, and climate policy.

Socioeconomic Development

The global scenario study modelled five global regions (Africa Middle East, Asia, Former Soviet Union, Latin America and Mexico, OECD) and included country-level assumptions for some trends. For brevity, we present only global results or New Zealand results as needed.

Socioeconomic development proceeds as outlined in the SSP narratives and as specified in more detail by additional qualitative (e.g. SPAs) and quantitative assumptions, especially the fixed coupled population-GDP projections (Fig. 5a). SSP1 and SSP5 lead to relatively wealthier worlds with relatively fewer people, where wealth distribution is more equitable. SSP3 and SSP4 lead to relatively less wealthy worlds with relatively more people, where wealth distribution is relatively less equitable. SSP2, as the "middle of the road," falls in between, with both intermediate levels of wealth and population.

In terms of global GDP per capita, SSPs show a clear ranking and an order-of-magnitude range in final 2100 values (Fig. 14). SSP3 ("A Rocky Road"), given its combination of highest population growth and lowest economic growth, shows just over a doubling of GDP per capita from \$9,700 to \$22,000 US$_{2005}$ from 2010 to 2100. SSP5 ("Taking the Highway"), by virtue of its strong economic growth and relatively lower population of 7.4 billion by 2100, which is about the same as currently, shows a 14-fold increase in GDP per capita from $9,700 to $138,000. SSP2 ("Middle of the Road"), at $60,000, ranks in the middle (3rd). SSP1 ("The Green Road") ranks 2nd ($82,000), and SSP4 ("A Road Divided") ranks 4th ($38,000). Global statistics can mask critical disparities and should be interpreted, if possible, in combination with finer-scaled regional and national statistics and indicators.

New Zealand GDP per capita shows a broadly similar pattern to global GDP per capita, with some differences (Fig. 14). The final range for New Zealand is smaller than the final global range. SSP5 ranks highest and SSP3 ranks lowest both globally and for New Zealand. SSP1, SSP2, and SSP4 differ from global results in that overall they cluster together more closely and SSP4's rank changes from 4th globally to 2nd for New Zealand.

Comparatively, New Zealand values begin and remain higher on an absolute basis than global values (Fig. 14). Trends among SSPs differ regarding the relative magnitude of the difference. In 2010 New Zealand GDP per capita is 2.6 times global GDP per capita: $25,385 versus $7,726 US_{2005}. In SSP1 and SSP5, which have higher relative growth and also a more global outlook, the ratio halves over time to 1.2 and 1.3, respectively. In SSP2, the ratio also decreases, but not as much to 1.7. In SSP3 and SSP4, which have lower overall growth and more pronounced regional differences, the ratio increases to 3.1 and 3.3, respectively.

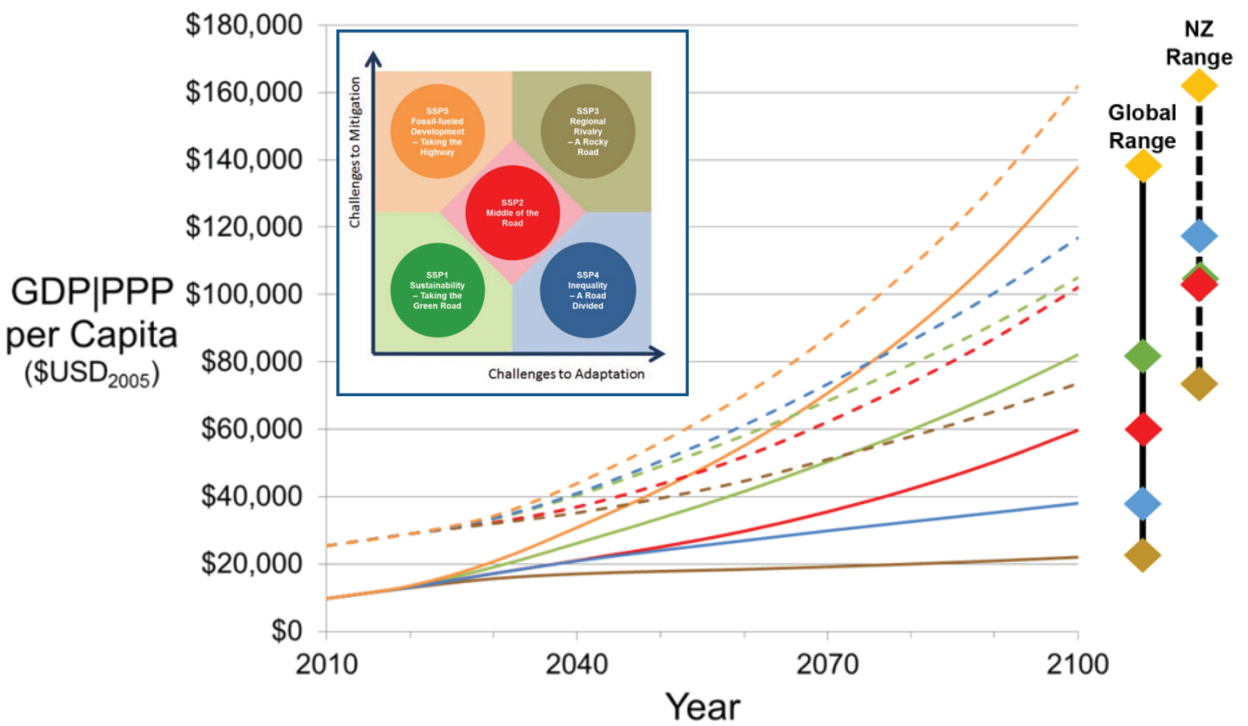


Figure 14 Global (solid lines) and New Zealand (dashed lines) GDP|PPP per capita trends for the five SSPs. Line colours correspond to the colour of the SSP represented in the inset SSP diagram in the upper left-hand corner. SSP1 = green, SSP2 = red, SSP3 = brown, SSP4 = blue, SSP5 = orange. Black bars to the right indicate the global (solid line) and New Zealand (dashed line) ranges across all SSPs.

Climate

Changes in mean global radiative forcing and mean global air temperature ranged widely based on results from MAGICC modelling (Table 7). On average, both radiative forcing and temperature increased with higher greenhouse gas emissions, e.g. from RC2.6 to REF, as would be expected.

Non-mitigation (REF) scenarios ranged more broadly across both radiative forcing and temperature, largely reflecting the differences among the SSPs. SSP1- and SSP4-based scenarios (low challenges to mitigation) had the lowest values, SSP3- and SSP5-based scenarios (high challenges to mitigation) had the highest values, and SSP2 scenarios (moderate challenges to mitigation) were intermediate. Among all 22 non-mitigation scenarios runs across all SSPs, only two produced radiative forcing equivalent to RCP8.5. The other 20 produced radiative forcing at 2100 of +8.05 W/m^2 or lower.

Mitigation scenarios showed smaller ranges for both radiative forcing and temperature than non-mitigation scenarios, indicating that global modelling teams consistently met the objective of reproducing the target mitigation RCP despite the inherent diversity among the models used or any tailored assumptions implemented.

Table 7: Changes in mean global radiative forcing and mean global air temperature at 2100 compared with pre-industrial (1850–1900) levels based on results from the global scenario study

		Radiative Forcing (W/m²)			Mean Global Temperature (°C)		
Mitigation	RCP	Min	Mean	Max	Min	Mean	Max
No	REF	+5.01	+6.56	+8.85	+3.03	+3.85	+5.15
Yes	6.0	+5.38	+5.44	+5.64	+3.16	+3.23	+3.33
Yes	4.5	+4.12	+4.22	+4.37	+2.52	+2.61	+2.70
Yes	2.6	+2.51	+2.61	+2.76	+1.65	+1.74	+1.82

Energy

To reduce the net greenhouse gas emissions from human sources requires mitigation. In assessing the potential human contribution to future global GHG concentrations, the global scenario study considered emissions from energy and land use/land-use change. In this section we overview energy contributions and in the next section we overview land use/land-use change contributions.

Conceptually mitigation strategies employ one of three tactics, either individually or in combination, to achieve a desired level of radiative forcing (Table 8). In mitigation scenarios, global modelling teams attempted to mitigate global GHG emissions to reproduce the desired radiative forcing target (i.e. RCP) while remaining faithful to SSP assumptions.

Global primary energy trends, represented by results from marker scenarios, broadly reflected the narratives and assumptions of the corresponding SSP (Fig. 15) and, to a lesser degree, the tendencies of the corresponding model. The set of SSP5- and SSP1-based scenarios showed overall the highest and lowest, respectively, primary energy trends. SSP2, SSP3, and SSP4 overlapped considerably in the middle of the primary energy range and in a few scenarios had trends similar to the lower RCP-based SSP5 scenarios.

Table 8: Greenhouse gas emission mitigation tactics

Tactic	Description	Examples
Reduce	Use less energy from GHG-emitting sources	Avoidance (e.g. lower heating temperature) Higher energy efficiency (e.g. higher fuel efficiency)
Replace	Substitute energy from GHG-emitting sources with non-GHG emitting sources	Hybrid or electric vehicles Renewable energy generation
Remove	Actively remove GHG gases from the atmosphere	Forest sinks (e.g. REDD) Carbon capture & storage (CCS – also referred to as "backstop" technologies)

The relationship between total primary energy supply and radiative forcing is not straightforward (Fig. 15). A broad range of primary energy trends can produce the same RCP. For example, primary energy at 2100 for the five RCP4.5-based marker scenarios were: 589 (SSP1), 786 (SSP4), 829 (SSP3), 1083 (SSP2), and 1287 (SSP5) exajoules per year.

With regard to mitigation-based scenarios, global modelling teams implemented different strategies consistent with the assumptions of the relevant SSP and associated SPA to reduce GHG gas emissions and meet the desired radiative forcing target. Meeting a particular radiative forcing target did not require attaining a specific level of energy use (Fig. 15, coloured arrows).

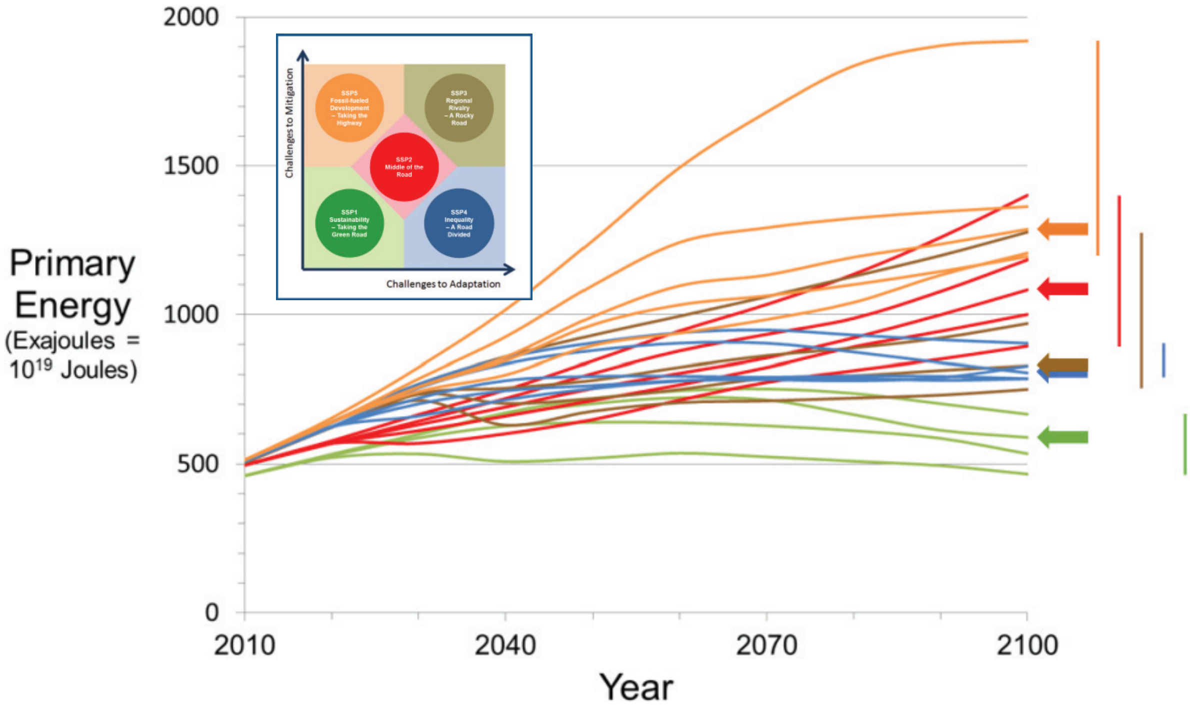


Figure 15 Global primary energy trends for SSP marker scenarios. Line colours correspond to the colour of the SSP represented in the inset SSP diagram in the upper left-hand corner. SSP1 = Green, SSP2 = Red, SSP3 = Brown, SSP4 = Blue, SSP5 = Orange. Coloured bars on the right indicate the range of 2100 primary energy values for each SSP. Coloured arrows on the right indicate the 2100 primary energy values for five RCP4.5-based scenarios. Figure includes 3.4 W/m²-based scenario results.

Examining and comparing the evolution of energy trends in more detail within and among the six CCII scenarios helps illustrate the similarities and differences among mitigation strategies and the mix of possible tactics (Fig. 16). Reduction is a common tactic in reducing overall emissions, both from an SSP and RCP perspective. From an SSP perspective, primary energy tends to decrease as challenges to mitigation decrease, i.e. from SSP3 and SSP5 scenarios compared to SSP1. Scenario SSP1-RCP2.6 shows the most extreme reduction or, perhaps more correctly, avoidance. In that scenario, global primary energy grows by less than 1 exajoule per year.

From an RCP perspective, primary energy also tends to decrease from higher to lower RCPs, although the magnitude of the reduction varies substantially (Fig. 16). Going from the REF to the RCP4.5 scenario in SSP3 involved a 388 EJ (32%) reduction in primary energy; going from the RCP6.0 to RCP2.5 scenarios in SSP5 involved a 175 EJ (13%) reduction.

Most mitigation scenarios also employ some degree of replacement (Fig. 16). The proportion of fossil energy tends to decrease, while the proportion of both biomass and non-renewable biomass energy increases. Nuclear energy is more variable but overall constitutes a relatively minor proportion of the energy mix.

The three SSP5-based scenarios best demonstrate the outcome from increasing energy replacement (Fig. 16, upper left). While total primary energy only declines by 13% from RCP6.0 to RCP2.6, the primary energy mix changes substantially. For RCP6.0, fossil sources still comprise the majority of primary energy by 2100. For RCP4.5, renewables (biomass and non-renewable biomass) comprise the majority of primary energy. For RCP2.6, fossil sources are almost completely phased out and renewables dominate. SSP1-RCP2.6 and SSP3-RCP4.5 show a similar evolutionary pattern in terms of the increasing proportion of renewables in primary energy.

Finally, mitigation strategies usually employ removal tactics (Fig. 16). The proportion of primary energy from fossil or biomass sources with associated CCS tends to increase with lower RCPs. CCS serves two functions. First, CCS helps mitigation by offsetting GHG emissions from the continued use of fossil fuels. All six scenarios, and in fact all scenarios modelled, show some continued use, sometimes substantial, of fossil fuels to 2100. The lowest level of fossil energy use by 2100 for any scenario was 18 EJ for the SSP1-RCP2.6

scenario run by the REMIND-MAGPIE model.[4] To give a sense of the amount of energy that represents, total global non-biomass renewable energy modelled in 2010 ranged from 12.6 to 17.9 EJ. Second, CCS can help reduce the concentration of greenhouse gases already in the atmosphere, including via afforestation or pairing CCS with carbon-neutral biomass energy sources to shift net emissions from positive to negative.

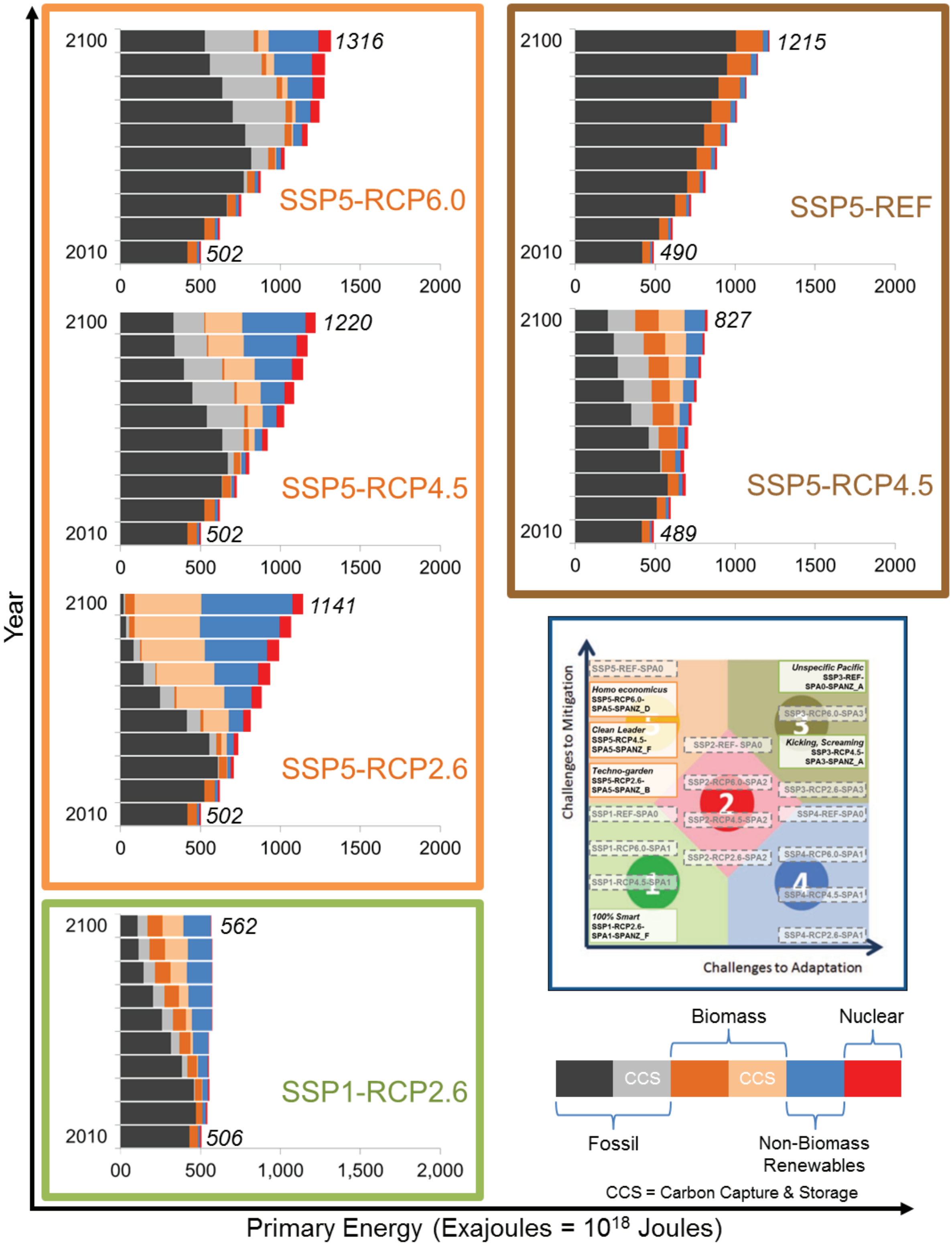


Figure 16 Decadal evolution of global primary energy supply from 2010 to 2100 for the six CCII scenarios (coloured boxes) arranged in the inset SSP diagram. The coloured bars show both total primary energy supply (total bar length) and the relative proportion of primary energy supply types (coloured bars). Non-biomass renewables = geothermal + hydro + solar + wind. Quantitative values of starting (2010) and final (2100) total primary energy supply are shown for reference at the right hand side of the corresponding bars. Primary energy supply data based on outputs from relevant marker scenarios from the SSP Public

[4] As an interesting aside, REMIND-MAGPIE also modelled the highest amount of fossil energy supply among all modelled scenarios at 1530 EJ compared with a value of 387 EJ in 2010 for scenario SSP5-REF.

Database Version 1.1.

Land-use & Land-Cover Change

Similar to energy trends, land-use and land-cover change trends evolved according to complex interactions among SSPs and SPAs, the radiative forcing level involved, and internal assumptions and workings of global integrated assessment models. Differing interpretations, characterisations, and delineations of land use and land cover among different global modelling teams posed further complications. The global scenario study harmonised modelling and reporting of land use and land cover to help minimise those complications and maximise comparability and usability across modelling results (Hurtt et al. 2011; Popp et al. 2017).

Given the challenges and complexities involved in trying to understand impacts of land-use/land-cover change, we first identify broad emergent patterns or trends across all scenarios and second provide examples of more specific impacts based on evaluation of the six CCII scenarios. The latter serves as a guide to aid further exploration of particular questions or issues.

Five of the six global modelling teams provided land-use and land-cover data to the SSP database (Table 9). Total land areas modelled ranged from 12.48 to 13.30 billion hectares, with a mean of 12.86 billion hectares and standard deviation of +/–311 million hectares. Four of the five classes appeared consistent in terms of 2010 starting area, with standard deviations within 9% or less of the mean. Built-up Area proved the most inconsistent, including one model that did not include it.

Global Integrated Assessment Model		Total	Built-up Area	Cropland	Forest	Other Natural Land	Pasture
AIM/CGE		13,305	61	1,549	3,886	4,448	3,360
GCAM4		12,691	61	1,502	4,090	3,786	3,253
IMAGE		12,964	67	1,583	3,706	4,428	3,185
MESSAGE-GLOBIOM		12,477	0	1,546	3,893	3,620	3,417
REMIND-MAGPIE		12,907	133	1,521	4,162	4,008	3,085
Model Ensemble	Mean	12,859	46	1,545	3,894	4,070	3,304
	Standard Deviation	310	47	31	181	373	133

Table 9: Initial total land area and area by class of land use/ land cover at 2010 reported by five global modelling teams. All values in millions of hectares. Data from the SSP Database Version 1.1

Considering changes in land use and land cover from 2010 to 2100, Built-up Area again showed the most variable results. Therefore we summarise those results briefly first, and then discuss results for the remaining four classes in more depth, first broadly considering all scenario results, and second in more detail for the six CCII scenarios.

Of the four models reporting Built-up Area, only the IMAGE model reported any changes. Total area increased from 63 to 116 (+53), 120 (+57), and 112 (+49) million hectares for SSP1, SSP2, and SSP3, respectively. The IMAGE team did not model SSP4- and SSP5-based scenarios. For the other three models, Built-up Area did not change for any scenario.

For the remaining four land-use/land-cover classes, a broad pattern of land-use/land-cover change emerges when assessing how frequently each class gained or lost area from 2010 to 2100, regardless of the magnitude of change (Fig. 17). Cropland usually gained area, except for SSP1 where losses outnumbered gains and SSP5 where losses occurred for one model for the REF, RCP6.0, and RCP4.5-based scenarios.

Conversely, Pasture usually lost area (Fig. 17). Persistent gains only occurred in SSP3-based scenarios. For SSP2 and SSP4 Pasture showed mixed results, bearing in mind that SSP2 includes results from five models while SSP4 only includes results from two models.

Forest and Other Natural Land proved more dynamic overall, although some discernible patterns emerged (Fig. 17). Both tended to lose area more frequently as either challenges to adaptation or mitigation increased, with frequency of losses maximised in SSP3 where challenges to mitigation and adaptation were

scenarios. Total areas across all classes also tended to converge in the SSP3-based scenarios and remain more divergent in the SSP1- and SSP5-based scenarios.

Figure 17 Frequency of gain or loss in total area from 2010 to 2100 by land-use/land-cover class organised hierarchically by SSP (coloured boxes) -> class -> RCP. Total bar length (Gains + Losses) indicates the number of models (maximum = 5) reporting data for a scenario (SSP x RCP or 3.4 W/m² target). The location and colour of the SSP boxes correspond to SSP location and colours shown in the inset SSP diagram. Based on data from public SSP Database Version 1.1.

both high. They also showed similar overall patterns by SSP, e.g. mostly gains in SSP1, mostly losses in SSP3, mixed in SSP2 and SSP5. The exception was SSP4, where Forest had more mixed results whereas Other Natural Land had only losses, although bearing in mind again that SSP4 results come from only two global integrated assessment models.

Viewing the same gains and losses along an RCP-gradient within SSPs shows the same patterns as before but helps visualise differences among SSPs and trends in realising lower radiative forcing outcomes with regard to land-use outcomes (Fig. 18). In SSP1 more consistent gains in Forest and Other Natural Land reflect that SSP's assumptions about environmental preferences and assumptions (e.g. The Green Road). SSP3, at the opposite end of the spectrum, shows an inverse trend for Forest and Other Natural Land, while Pasture shows mostly gains, in contrast to other SSPs. Those gains reflect the need to feed a global population of 12 billion.

The SSPs along the diagonal from upper left to lower right (SSP5 to SSP2 to SSP4) show broadly similar patterns, both in terms of the shift from primarily challenges to mitigation (SSP5) to challenges to adaptation (SSP4) and the shift from higher to lower radiative forcing outcomes. Both across and within the SSPs, the balance for Forest and Other Natural Land shifts from losses to gains as radiative forcing outcomes become lower. Pasture gains decrease, with REF-based scenarios being somewhat balanced to all losses for the three RCP 2.6-based scenarios.

Quantitative examination of land-use/land-cover change trends in the six CCII scenarios reinforces the more qualitative findings discussed above and provides some additional insights (Fig. 19). Cropland area increases across all scenarios, although the magnitude of the increase varies. Pasture increases slightly in SSP3-based scenarios and decreases in SSP1- and SSP5-based scenarios. Forestry and Other Natural Land show more variability as before. Both tend to either gain area or remain more stable with lower radiative forcing targets.

Among different models, trends appear broadly consistent as indicated both by the general shape of the trend lines and the final range of areas for each class in each scenario (coloured bars to the right of each panel) (Fig. 19). SSP3-based scenarios had much tighter ranges than the SSP1- or the SSP5-based

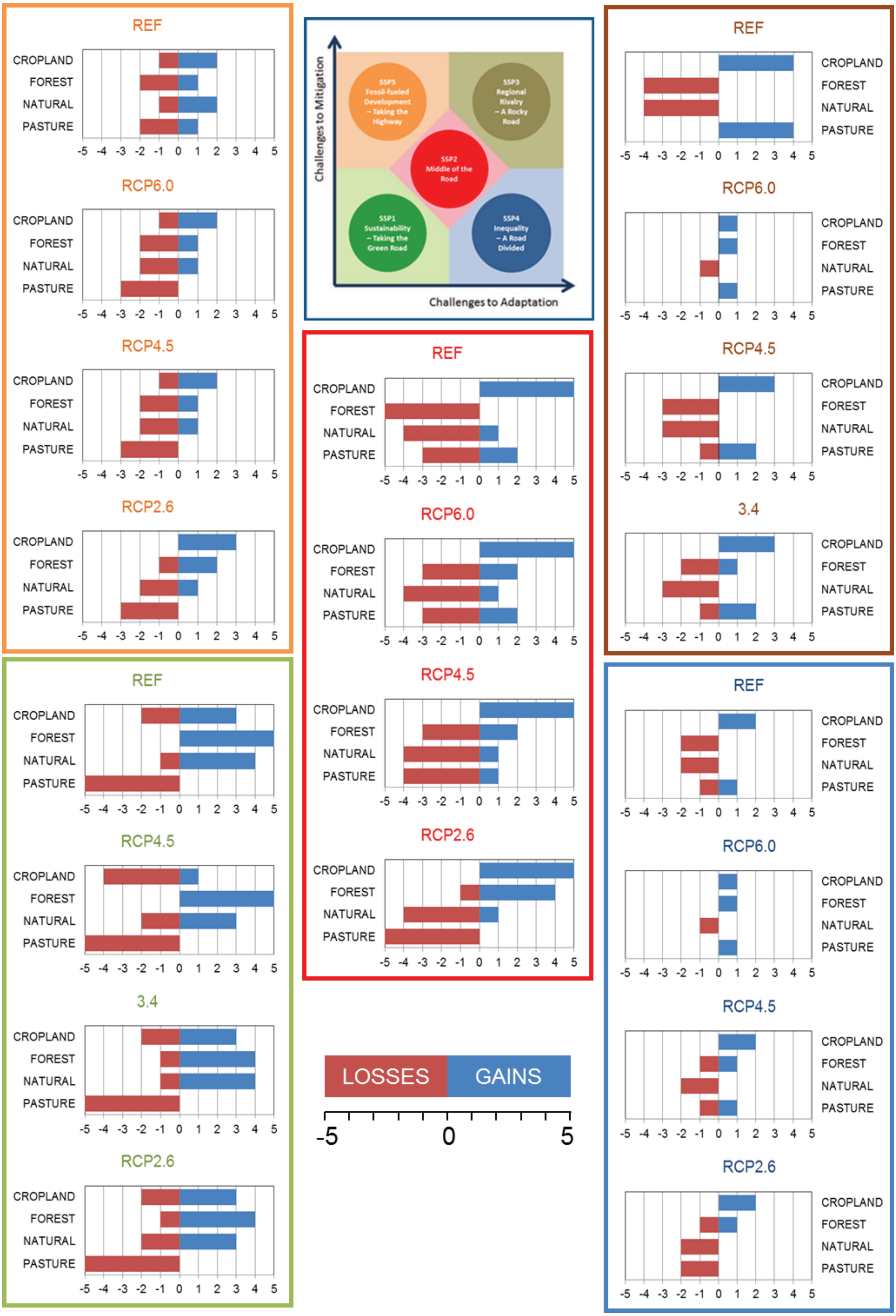


Figure 18 Frequency of gain or loss in total area from 2010 to 2100 by land-use/land-cover class organised hierarchically by SSP (coloured boxes) -> RCP -> class. Total bar length (Gains + Losses) indicates the number of models (maximum = 5) reporting data for that scenario (SSP x RCP or 3.4 W/m² target). The location and colour of the SSP boxes correspond to SSP location and colours shown in the inset SSP diagram. Based on data from public SSP Database Version 1.1.

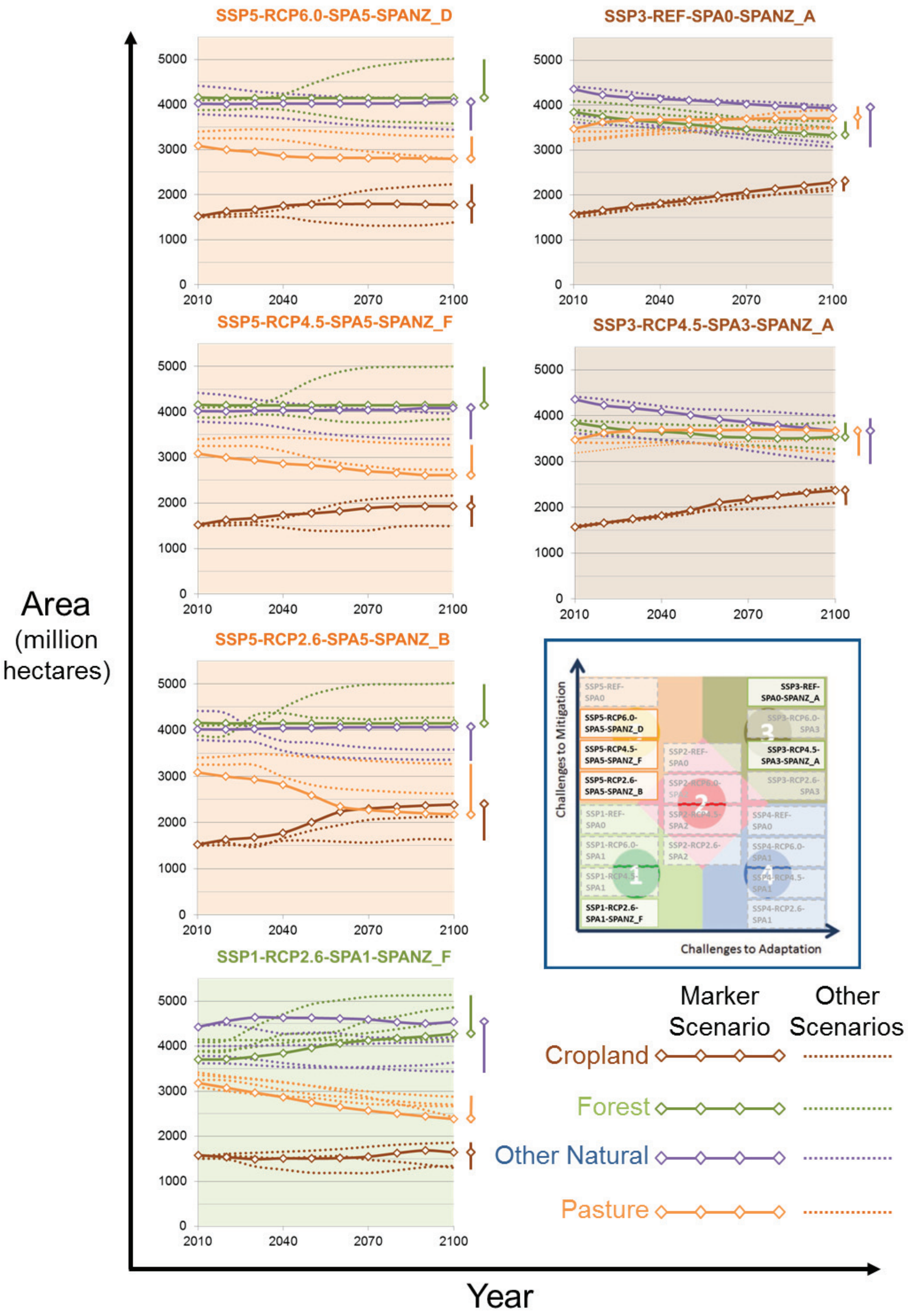


Figure 19 Land-use/land-cover change trends for the six CCII scenarios arranged as shown in the inset CCII scenarios diagram. Coloured bars to the right of each panel indicate the range of final values across all global modelling results. Coloured diamonds indicate marker scenario values. Based on data from the SSP Public Database Version 1.1.

Climate Policies and Carbon Prices

The global scenario study implemented assumptions about the evolution of climate policies as part of SPAs (Fig. 6). In non-mitigation (REF) scenarios, no climate policies operated and carbon price (price per tonne of CO_2 in constant $\$US_{2005}$ dollars) was set to zero for the entire simulation period. In mitigation scenarios, the global carbon price evolved as needed to produce the desired radiative forcing target subject to the assumptions of the SSP and SPA and internal assumptions, parameterisations, etc., of the corresponding global integrated assessment model.

Across all mitigation scenarios global carbon price trajectories varied such that the final price at 2100 ranged from a minimum of $0.03 for SSP4-RCP6.0 to $8,320.68 USD_{2005} per tonne CO_2 for SSP2-RCP2.6 (Fig. 20). Both the minimum and maximum carbon prices resulted from runs involving the same global integrated assessment model (WITCH-GLOBIOM). Differences among global integrated assessment models proved the largest source of variability in carbon price trajectories. The WITCH-GLOBIOM model consistently produced the highest carbon price trajectories, while the IMAGE and AIM models produced the lowest carbon prices trajectories.

Compared with the variability among models, variability among SSPs appeared reasonably consistent in terms of the overall range and tendency (Fig. 20). Carbon price trajectories tended to cluster towards the lower end of the carbon price range at less than $2,000 per tonne of CO_2.

Carbon prices also tended to increase with decreasing radiative forcing targets, as illustrated by the differences among carbon price trajectories for the six CCII scenarios (Fig. 21), although the magnitude of the difference varied among SSP-RCP-model combinations. For the three SSP5-based scenarios, carbon prices increased consistently going from RCP6.0 to RCP2.6. Comparing the two RCP 2.6-based scenarios, SSP1 showed a tendency for a lower carbon price trajectory than SSP3, except in one case. That one case also involved the WITCH-GLOBIOM model, which produced a 2100 carbon price of $7098 USD_{2005} per tonne of CO_2. The other runs produced final 2100 carbon prices roughly an order of magnitude lower, ranging from a low of $134 for the marker scenario to a high of $844. The SSP3 and SSP5 RCP4.5-based scenarios showed more consistency. The one outlier was also a WITCH-GLOBIOM-based run in SSP5-RCP4.5 that produced a carbon price at 2100 of $1,634, which was four times the second highest value of $411.

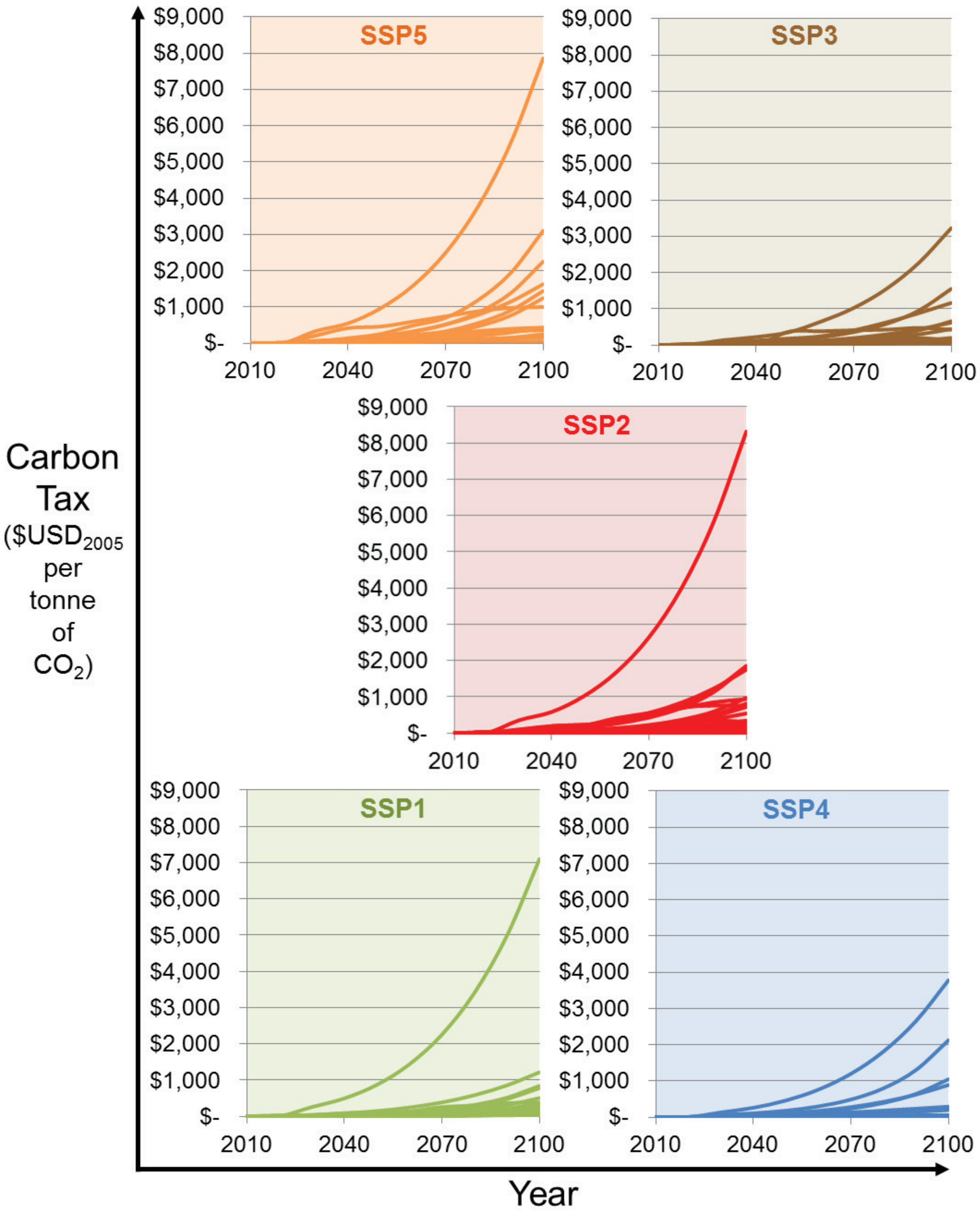


Figure 20 Evolution of global carbon price per tonne of CO_2 in constant 2005 $US dollars organised by SSP. All axes scaled identically. Based on data from the SSP Public Database Version 1.1.

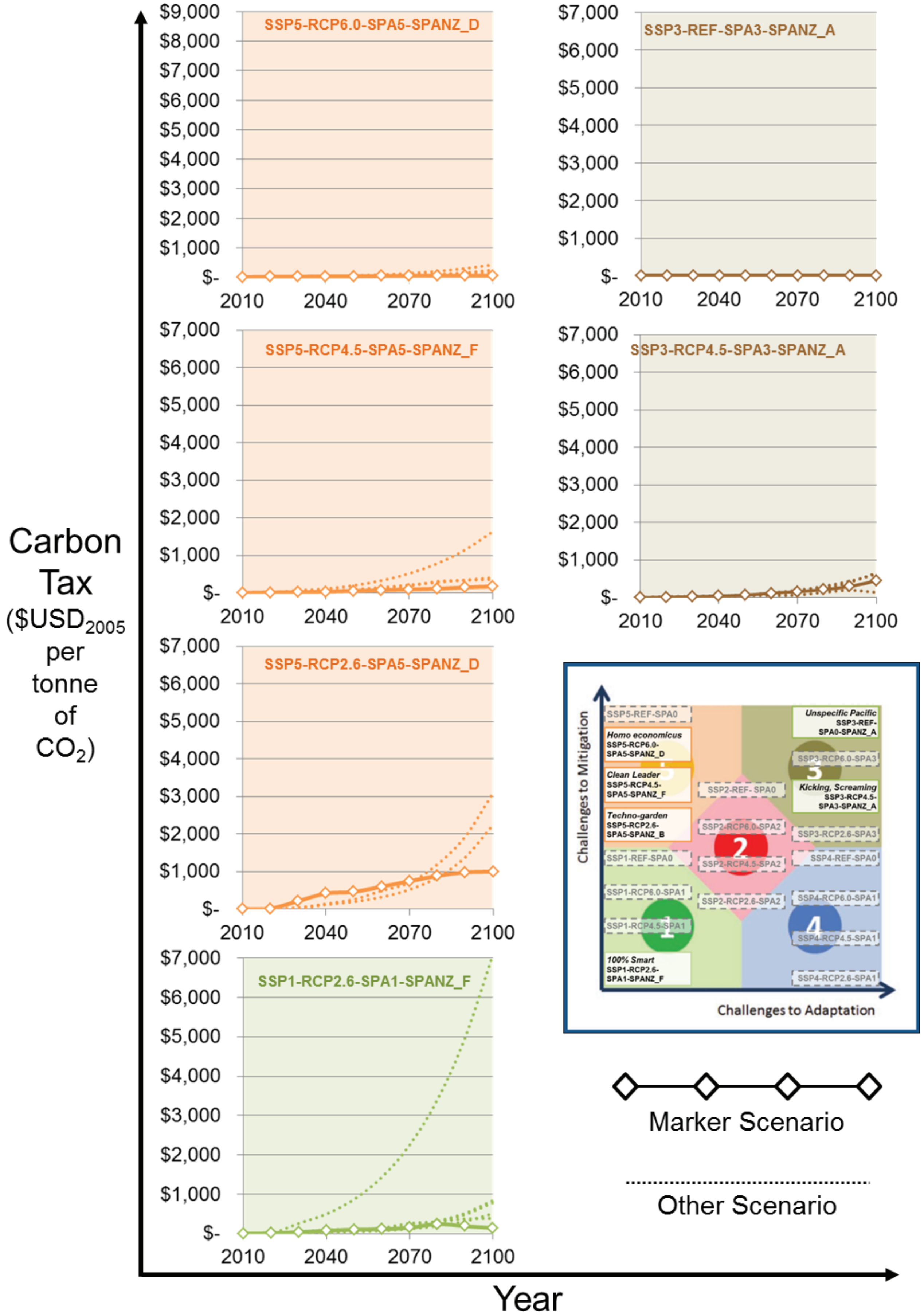


Figure 21 Evolution of global carbon price per tonne of CO2 in constant US_{2005}$ dollars for the six CCII scenarios arranged according to the inset CCII scenarios diagram. Each box shows the change in carbon price for the results from the relevant marker scenario and any other runs from the global scenario study. All axes scaled identically. Based on data from the SSP Public Database Version 1.1.

Implications

The overall implication from the global scenarios and results from their evaluation by global integrated assessment modelling suggest that climate change, while important, has a smaller impact on future global development than other key drivers of change. However, that implication is largely by design, as the new global scenario architecture deliberately decouples global socioeconomic development from climate change.

Decoupling has key benefits and drawbacks. Key benefits include the ability to explore a broader range of global futures via the combination of different SSPs, RCPs, SPAs and SPANZs in the case of New Zealand. It also fostered shorter scenario development time compared to previous global assessments.

Last, and perhaps most important for New Zealand, there is enhanced flexibility and ability to adapt global scenarios to aid formulation and exploration of regional (sub-global), national, and sub-national scenarios and climate change impact and implications assessment. That includes CCII's adaptation and enhancement of the global scenarios to formulate more New Zealand-focused yet still globally-linked scenarios. Increasing public availability and transparency of global assumptions and integrated assessment modelling results also aids adaptation and understanding via the substantial body of literature describing the SSPs, RCPs, and SPAs and the publically available global SSP database.

The key drawback of decoupling is that climate change cannot directly impact socioeconomic development, at least in terms of the two key indicators of population and economic development (GDP) that formed the basis of quantitative integrated assessment modelling in the global scenario study. In that sense, climate change impacts could only be explored indirectly by assessing the relative feasibility of different scenarios, i.e. evaluating how easy or difficult it would be to achieve a particular climate outcome (RCP) within a given socioeconomic development pathway (SSP).

In the global scenario study, 24 scenarios were evaluated out of 25 possible: 5 SSPs x 5 climate outcomes (3 RCPs + new 3.4 W/m^2 target + REF). SSP1-RCP6.0 was not evaluated. Of the 24 scenarios evaluated, 22 had 100% success as measured by the number of modelled solutions/number of modelling attempts. Scenario SSP5-RCP2.6 had a 75% success rate (3 out of 4). Scenario SSP3-RCP2.6 had the lowest success rate (25% = 1 out of 4), reflecting its combination of both high challenges to mitigation and adaptation and the lowest RCP.

Therefore, the global scenario study found that any scenario is plausible, in that global modelling teams could solve any SSP+RCP combination. Those results imply that the world could theoretically meet any mitigation target (RCP), regardless of socioeconomic circumstances (SSP). However, the most stringent mitigation target (RCP2.6) is more unlikely/difficult under SSP3 and SSP5, both of which assume high challenges to mitigation, as indicated by their lower success rate. Also, all mitigation scenarios assumed an operating global carbon market via the relevant SPA. The assumption of such a market is less plausible for some SSPs (SSP3, SSP4) than others (SSP1, SSP2, SSP5).

Improved Climate Projections for New Zealand – NZ-RCM

Below we briefly summarise key impacts and implications from the Ministry for the Environment (2016) report on climate change projections for New Zealand based on the IPCC's 5th assessment. Refer to the report for further details.

Impacts

Temperature

Overall temperature projections generally increase with time and with the level of radiative forcing. Relative to 1986–2005, temperatures are projected to increase nationally between 0.7°C (RCP2.6) and 1.0°C (RCP8.5) by 2040 (2031–2050) and between 0.7°C (RCP2.6) and 3.0°C (RCP8.5) by 2090 (2081–2100) with a small north-south gradient.

The NZ-RCM warming signal has more spatial structure than the pattern produced by statistical downscaling. A strong warming signal from the RCM simulations over higher elevations is evident in all seasons, but is most prominent in the spring and summer seasons.

Daily maximum temperature is expected to increase faster than the overnight daily minimum temperature, meaning that the daily temperature range (maximum minus minimum) is also expected to increase over time.

Precipitation

Precipitation projections vary by region, time and global climate model results used. The overall pattern shows a reduction in annual precipitation for the north and east of the North Island. Increases occur almost everywhere else, especially on the South Island's West Coast, which showed up to 40% increases under RCP8.5 by 2090.

Regional and seasonal precipitation trends show no clear patterns given the variability observed among projections from the six global models evaluated. Winter showed the clearest trend, with precipitation expected to increase (very likely, between 90 and 100 percent) by the end of the century under RCP8.5. Spring showed similar trends to winter, while autumn was intermediate between summer and winter.

In terms of extremes, wet days (precipitation ⩾ 99th percentile) become more frequent over most of the country. The south of the South Island shows the largest increases (⩾ 20%), followed by the remainder of the South Island, and the remainder of the North Island, except for Northland and Hawke's Bay, which show no change. Dry day (< 1 millimetre precipitation) frequency increases with RCP and over time for most of the North Island and for high altitudes in the South Island. Frequency of dry days decreases on the west and east coast areas of the South Island.

Wind

Daily extreme winds increase in eastern regions, especially in Marlborough and Canterbury.

Relative Humidity

Relative humidity reduces almost everywhere, except for the West Coast in winter where there are large rainfall increases.

Implications

The RA1 improved climate projections, based on the latest global climate modelling and NZ-RCM, both reinforce and enhance previous findings regarding the future implications of climate change for New Zealand. The improved projections reinforce the finding that higher levels of radiative forcing will overall likely lead to larger degrees of change for New Zealand's climate and its various facets, including means, extremes, frequencies, and shifts in patterns. As a result uncertainty, risks, and vulnerabilities will likely scale with radiative forcing.

The enhanced resolution of the NZ-RCM, especially the ability to model on a daily time step, also shows that the nature of the changes will be complex, such that different locations will experience different impacts and implications resulting from the combined changes to daily, seasonal and annual weather patterns. For example, drought intensity shows the strongest increases over the northern and eastern North Island and the lee of the main divide over the South Island under the strongest forcing.

Uncertainty in Ecological Effects – Banded Kōkopu Distribution Modelling

Impacts

When fitted to each year of observed data, the linear and Mohseni models were both able to describe broad patterns of independently observed water temperatures (Fig. 22). There was not a strong relationship between overall model performance and difference between the observed and predicted periods. This indicates that, within the observed range of conditions, models fitted to cooler periods were able to predict to warm periods and vice versa. However, predictions were not unbiased when inspected over the range of observed water temperatures (Fig. 23). The Mohseni models tended to over-predict minimum temperatures and under-predict maximum temperatures regardless of differences between observed and fitted periods. This was because New Zealand's temperate climate resulted in a narrow range of water temperatures that did not encompass the complicating effects of freezing and evaporation on water temperature. The linear models tended to under-predict maximum temperatures, but this was not consistent across sites. Some patterns were present between a model's tendencies to over or under-predict and difference in temperature regime between the observed and predicted periods, but these were not consistent across sites.

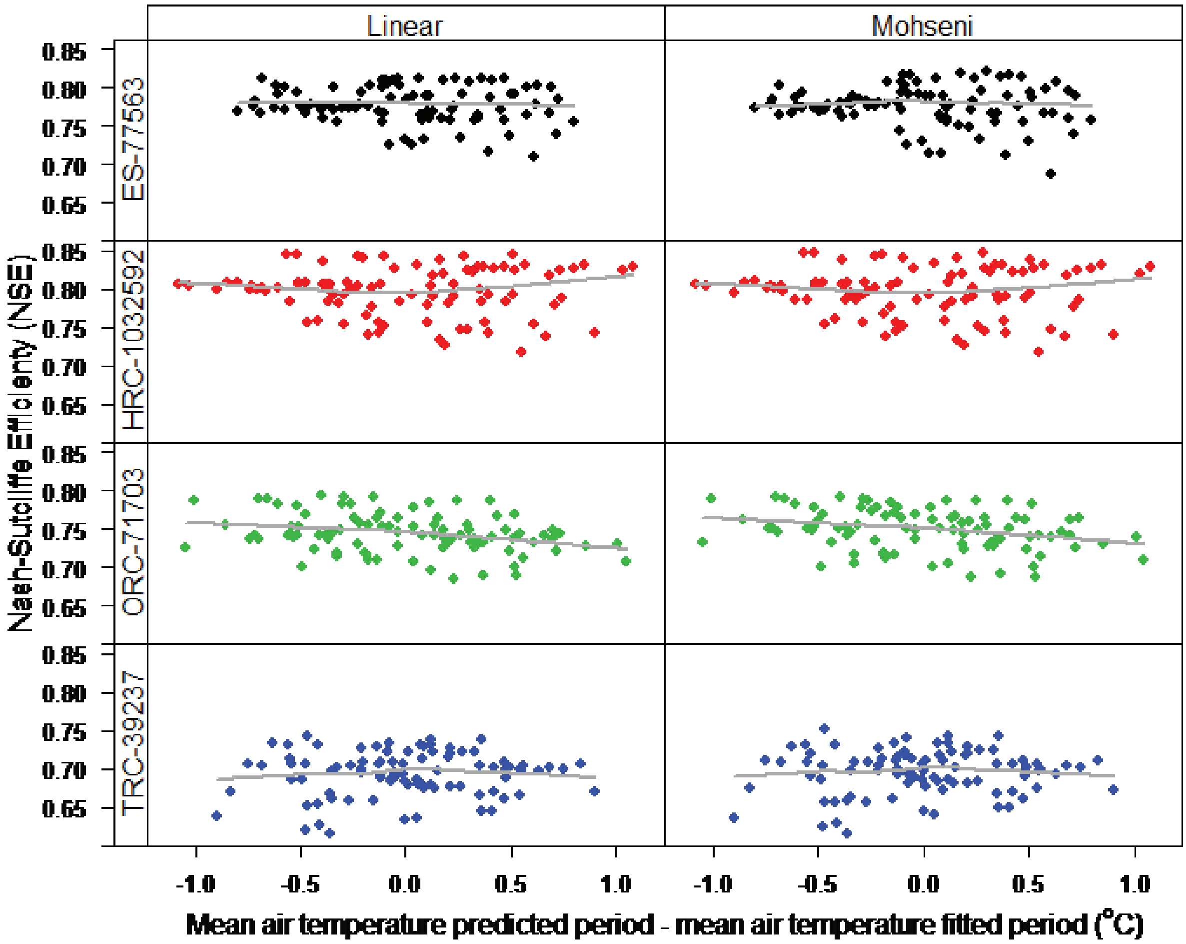


Figure 22 Prediction performance against mean difference between fitting period and predicting period (high values indicate fitting period is cooler than predicting period). Higher NSE values represent better performance (a value of 1 indicates perfect predictions).

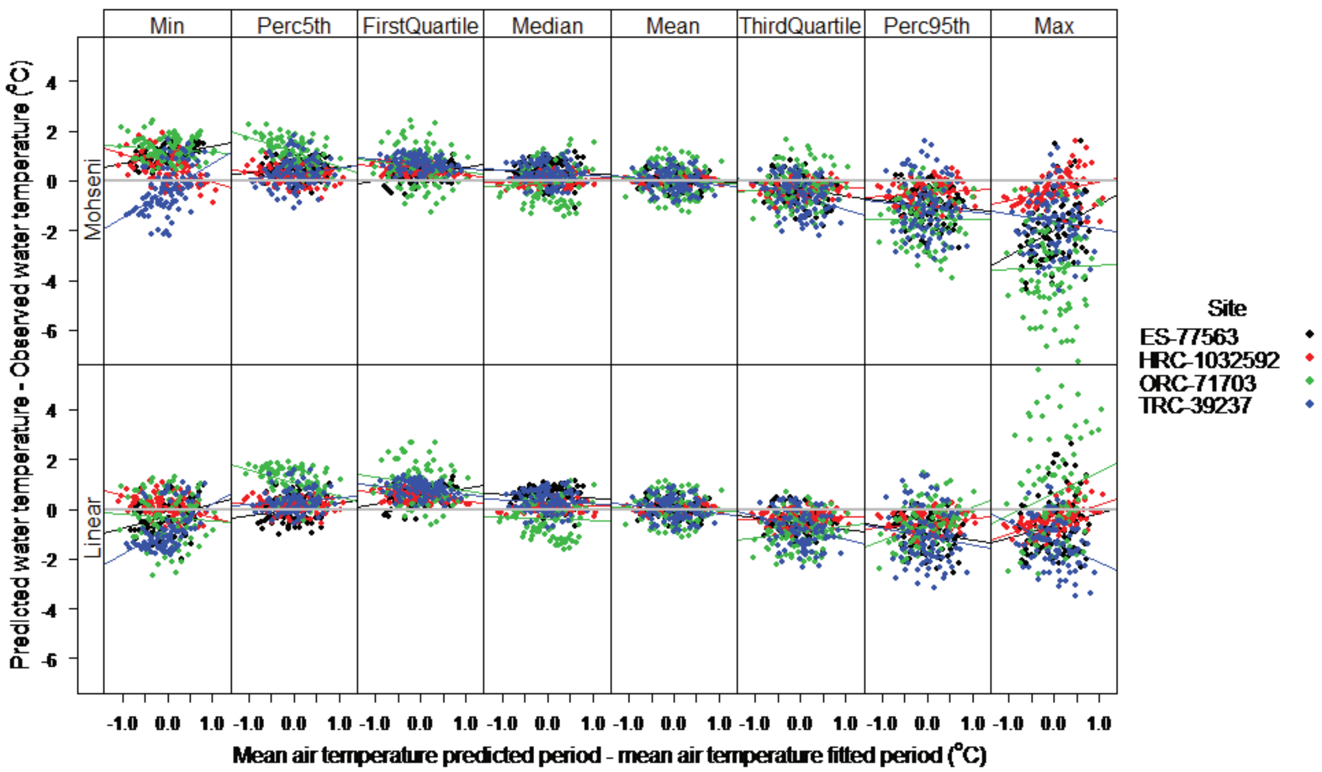


Figure 23 Residuals of water temperature annual summary statistics (high values indicate over prediction) against difference between fitting period and predicting period (high values indicate fitting period is cooler than predicting period). Coloured lines are linear regressions.

Mean annual water temperatures were assessed as being within the range of any of the observed 10 years (i.e. interpolation), or being either warmer or cooler than any of the observed 10 years as represented by the colours in Figure 24. The likelihood that future water temperatures will fall outside the 10-year observed range was predicted to increase through time and with intensity of RCP. Under RCP 8.5, by 2125 all river water temperatures were predicted to be warmer than any of the 10 observed years at all four sites, as indicated by red in Figure 24.

There were strong differences in the suitability of water temperatures between sites as represented by differences between box-and-whiskers and coloured lines in Figure 25. For all sites, the majority of 2015 simulations fell inside the temperature range that 90% of fish preferred. Future increases in water temperatures caused shifts in the likelihood that future temperatures will fall within the various percentiles of temperature preferences. The severity of these shifts was related to the RCP and the water temperatures relative to those preferred by the fish. The most detrimental changes in water temperature suitability were predicted at the warmest site for RCP 8.5, where all simulations for 2085 and beyond were predicted to be warmer than the temperature that was avoided by 95% of fish (top red line in Figure 25 represents temperatures avoided by 95% of fish). The most beneficial changes in water temperature suitability (ideal temperatures fall at orange line in Figure 25) were predicted for the coolest site for RCP 8.5, where all 2015 simulations were predicted to be cooler than that preferred by 95% of fish, but nearly all 2125 simulations fell within the inter-quartile range of preferred temperatures.

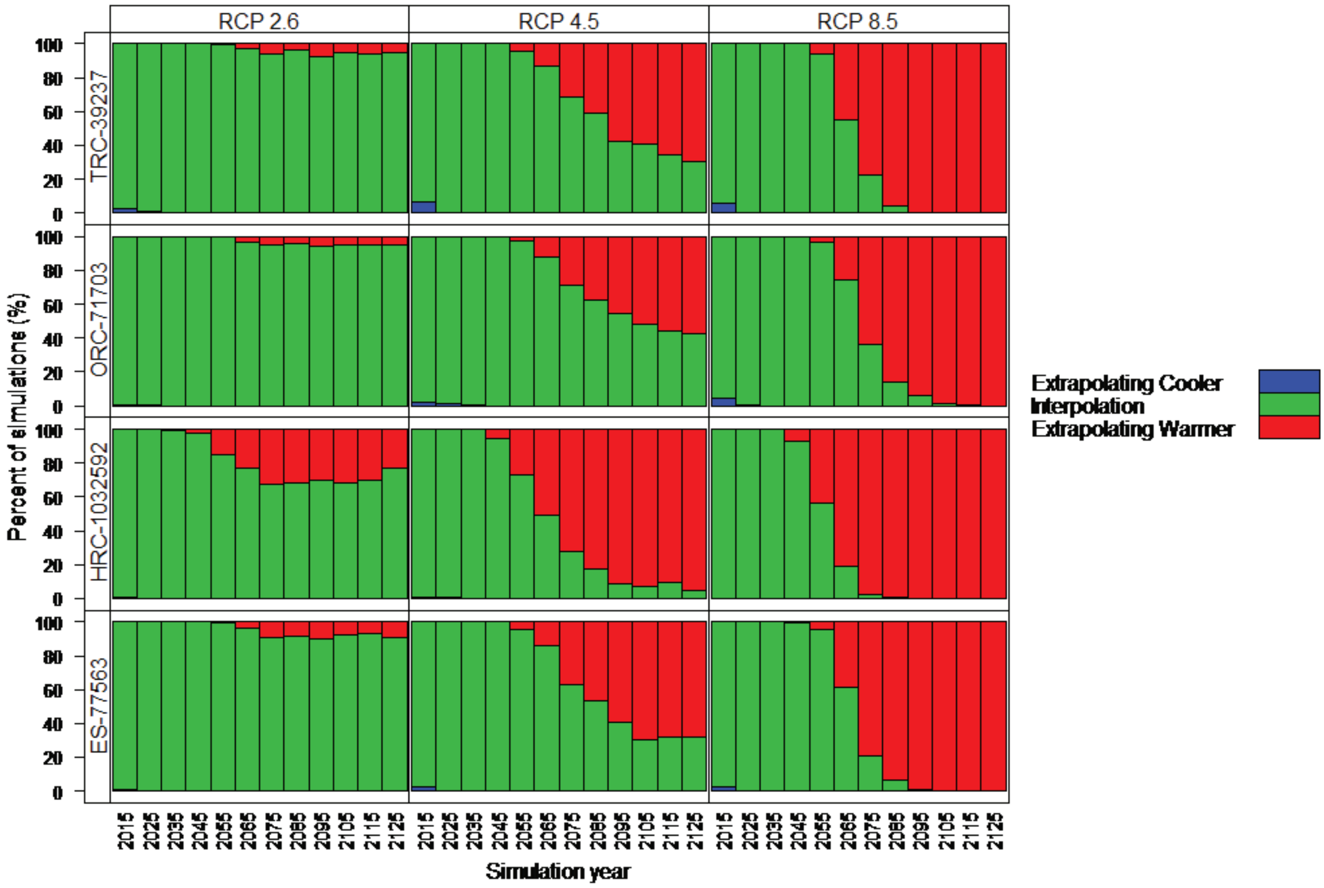


Figure 24 Predicted mean air temperatures derived from multiple (190) simulations of three RCPs in comparison to observations from 10 years.

Implications

The approach was applied to objectively express mathematical uncertainty when assessing the effects of climate change on suitability of river water temperatures for banded kōkopu (whitebait). The method was able to assess uncertainty in the air-water temperature relationships, the fish temperature preferences and the air temperature predictions. The steps described could be applied to many other situations where the ecological effects of climate change are being predicted.

It should be noted that some arbitrary decisions were applied such as use of mean daily temperature for the 10th hottest day. The method could be applied using any index of temperature for any day of the year or summarised over the entire daily time-series. The influence of climate change on other life-stages (spawning, oceanic phase) and possibility for regional evolutionary adaptation were not considered.

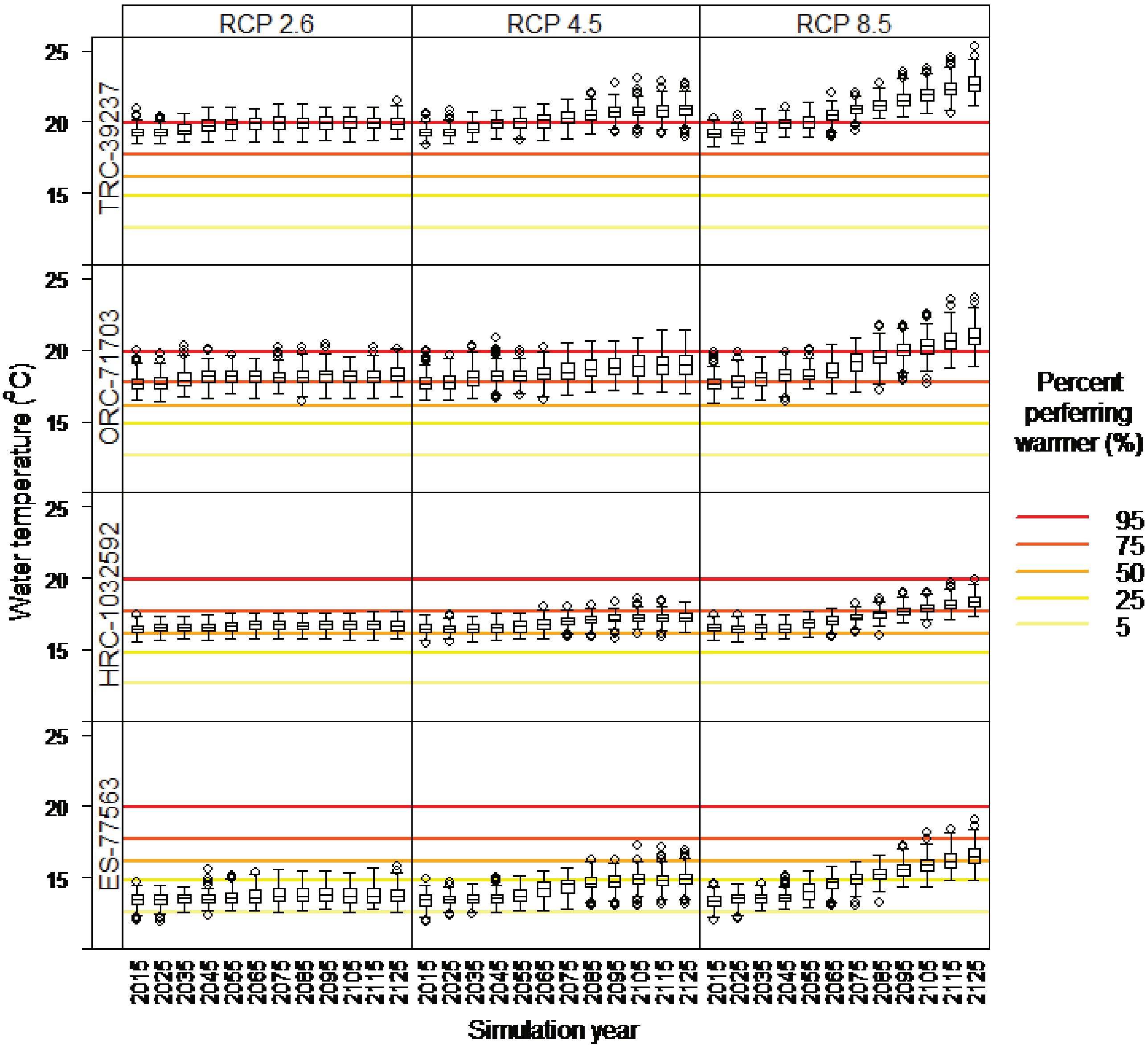


Figure 25 Predicted 10th hottest day of river water temperatures derived from multiple (190) simulations of three RCPs in comparison to temperature preferences of banded kōkopu whitebait.

Crop Productivity (Maize) – APSIM

Impacts

For historical climate, a consistent north-south pattern of climate suitability for maize growth emerged (Fig. 26). Silage yield estimates ranged from 7 tonnes of dry matter per hectare (t DM/ha) in southern regions to 27 t DM/ha in northern regions.

Silage quality, represented by the percentage of grains in total biomass (i.e. harvest index), also declined from 46% in the warmer regions of the North Island to 17% in NZ's cooler southern regions. These differences were mainly due to the period available for grain growth.

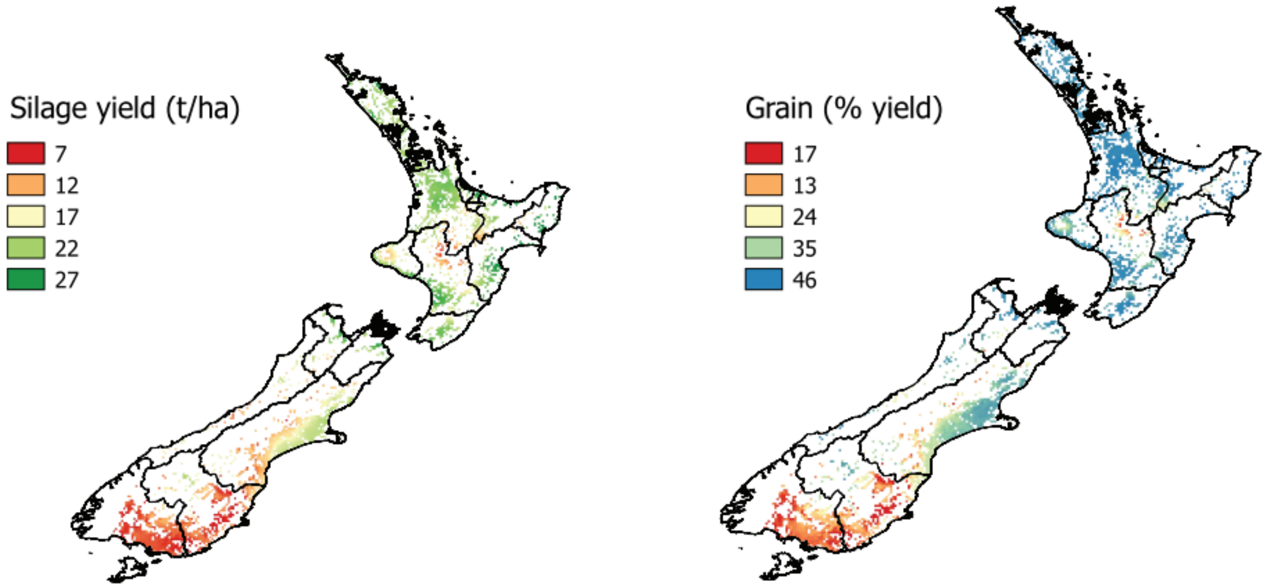


Figure 26 Simulated total biomass yield of silage maize (t dry matter DM)/ha) and grain content (% yield) of silage maize in arable lands for the period 1971–2000 (ERA-40 historical climate) using the Agricultural Production Systems sIMulator (APSIM).

The North Island showed more negative yield (Fig. 27). Southern regions showed potential for an increase in climatic suitability for maize growth. Adaptation of sowing dates and maize genotypes partially counteracted negative impacts. In northern and central regions, negative yield changes were reduced or even converted to positive changes. In southern regions, adaptation further increased positive yield changes.

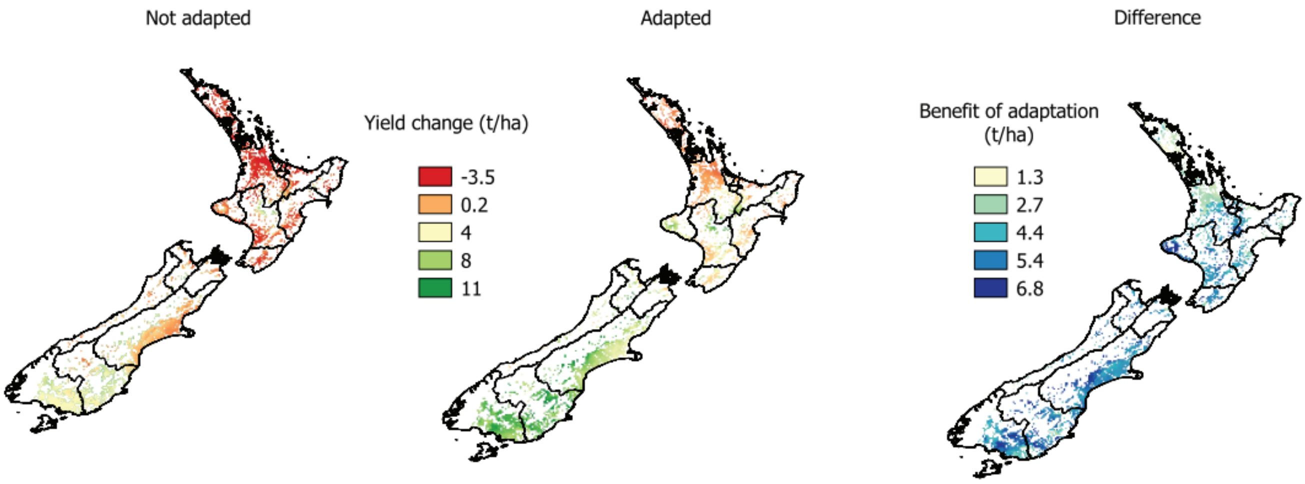


Figure 27 Simulated climate change impact on silage maize yields for end-of-century climate (2080–2099, Representative Concentration Pathway RCP 8.5 using the HadGEM2-ES climate model) and the effect of adapting genotypes and sowing dates across New Zealand's arable lands.

Implications

Depending on logistical and economic limitations, adaptation to climate change is possible through a shift or expansion of cropping areas to regions with more favourable climatic suitability within the country.

Adaptation of current agronomic practices (e.g. sowing dates and genotypes used) is likely to be required to maintain yields under climate change, and in some cases may increase them.

The magnitude of adaptation benefits is spatially variable across NZ. A case-by-case study of possible adaptive interventions considering local conditions (e.g. micro-climate, soils, relief, resources and markets) is necessary to select those adaptive measures that maximise productivity and enterprise viability and resilience.

Forestry Productivity (*Pinus radiata*) – CenW

Impacts

On average across the country for simulations with constant CO_2, there were minor changes in productivity under all RCPs at 2040 as well as for all RCPs other than RCP 8.5 for 2085 (Table 10), although there was a small decrease overall within increasing RCP. For simulations with increasing CO2, trends were reversed, with productivity increasing with increasing CO2 concentration.

Table 10: Ratio of P. radiata productivity between 1990 and 2040 and 2085 assuming constant and increasing CO_2 under the four different RCPs. Data show means +/– standard deviations

RCP	2040	2085	2040	2085
	Constant CO_2		Increasing CO_2	
2.6	1.00 +/– 0.05	1.00 +/– 0.05	1.12 +/– 0.05	1.10 +/– 0.05
4.5	0.98 +/– 0.05	0.99 +/– 0.09	1.13 +/– 0.06	1.23 +/– 0.10
6.0	1.00 +/– 0.05	0.99 +/– 0.11	1.14 +/– 0.06	1.31 +/– 0.14
8.5	0.99 +/– 0.07	0.92 +/– 0.15	1.18 +/– 0.08	1.40 +/– 0.21

Changes in productivity also showed substantial spatial variability. Assuming constant CO_2 concentrations, *P. radiata* productivity decreased overall with increasing RCP (Fig. 28). Under RCP 2.6 (Fig. 28a), responses were only slight, with growth responses nearly everywhere being within the range of –10% to +10%, with the North Island being mainly in the 0 to –10% range, and the South Island within the 0 to +10% range. The only consistent deviation from that pattern of little change was for the west coast of the South Island, for which there were significant growth reductions even under RCP 2.6.

Under RCP 4.5 (Fig. 28b), the pattern intensified, with growth reductions by 10–20% for parts of Northland the east coast of the North Island and isolated parts of the South Island, while isolated other parts of both islands also show significant growth increases by 10-20%. That pattern was similar under RCP 6.0 (Fig. 28c), with only the negative impact on Northland noticeably intensifying and becoming more universally widespread. Some other, more distributed regions, shows slight growth increases compared to simulations under RCP 4.5.

Under RCP 8.5, however (Fig. 28d), growth responses became significantly worse, with growth reductions of 20-30% for most of Northland and the east coast of the North Island, and 10–20% growth reductions for parts of Canterbury and a large region in central Otago, while the areas with positive responses became restricted to parts of Southland and isolated small areas in both islands. While large parts of the country had growth reductions of 0–10% or even 10–20%, there were also other, but smaller, parts of the country with growth gains of up to 10–20%.

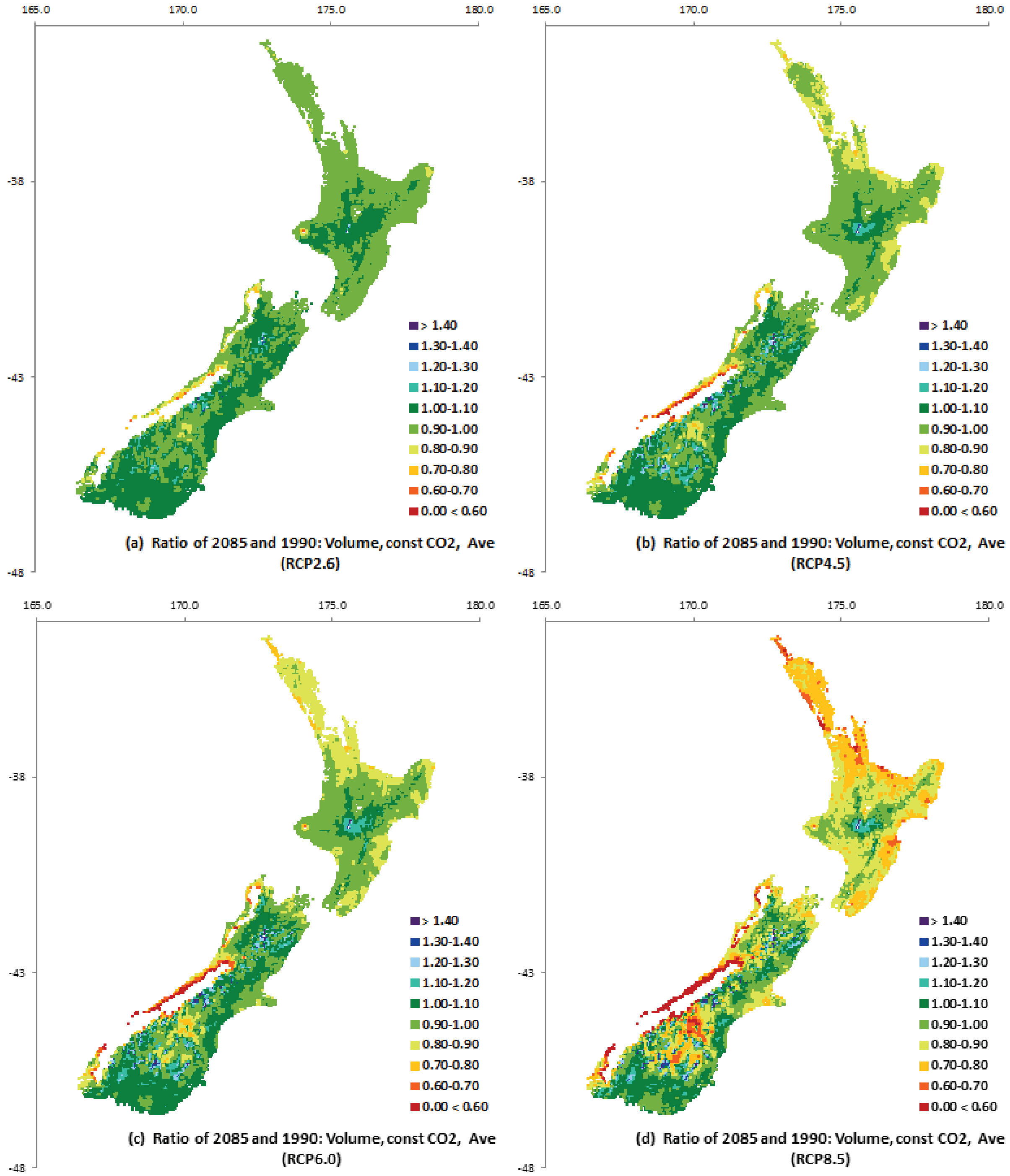


Figure 28 Ratio of 2085 to 1990 productivity modelled with constant CO_2 under the four RCPs.

Assuming increasing CO_2 concentrations, climate change impacts reversed. *P. radiata* productivity increased for nearly all of New Zealand under all RCPs (Fig. 29), with RCP2.6 showing the lowest overall increase and RCP8.5 the highest. The only exception to that were regions that already receive excess rainfall for optimal pine growth, essentially restricted to the very wet west coast of the South Island, where further increased rainfall, coupled with reduced water use under elevated CO_2, led to adverse effects on productivity. These responses were restricted to small parts of the country and to regions already very marginal for pine productivity.

For most of New Zealand, the simulations suggested growth enhancement. Under RCP 2.6 (Fig. 29a), they were in the range of 0–10% for most of the North Island and 10–20% for most of the South Island, where increasing temperature added to the beneficial effect of increasing CO_2 concentration. In the North Island, with warmer current temperatures, any further temperature increases did not convey similar benefits.

Growth enhancements strengthened under RCP 4.5 (Fig. 29b), with enhancements of 10–20% for most of the North Island, increasing to 20–30% for most of the South Island, and substantially greater enhancements in isolated pockets. The pattern strengthened further going to RCP 6.0 (Fig. 29c), with growth enhancements for most of the North Island increasing further to 20–30%, and to 30–40% for most of the South Island. It is interesting to note that there were only minor differences between RCP 4.5 and RCP 6.0 based simulations when CO_2 was kept constant, yet large differences emerged with increasing CO_2. It presumably means that the significant differences in CO_2 concentrations between the RCPs were reflected in much less pronounced differences in resultant temperature and rainfall changes for New Zealand.

The strongest growth responses were seen under RCP 8.5 (Fig. 29d), with a further strengthening of growth responses across the North Island, and growth responses of more than 50% for most of the South Island. In some areas, growth responses exceeded 70%, mainly confined to areas that were both dry, where increasing CO_2 had the greatest stimulating effect, and cold, where warming had the greatest effect. These strong growth responses were consequently seen for areas like Otago and Canterbury. Growth responses were more muted for wetter regions like Southland and most of the North Island.

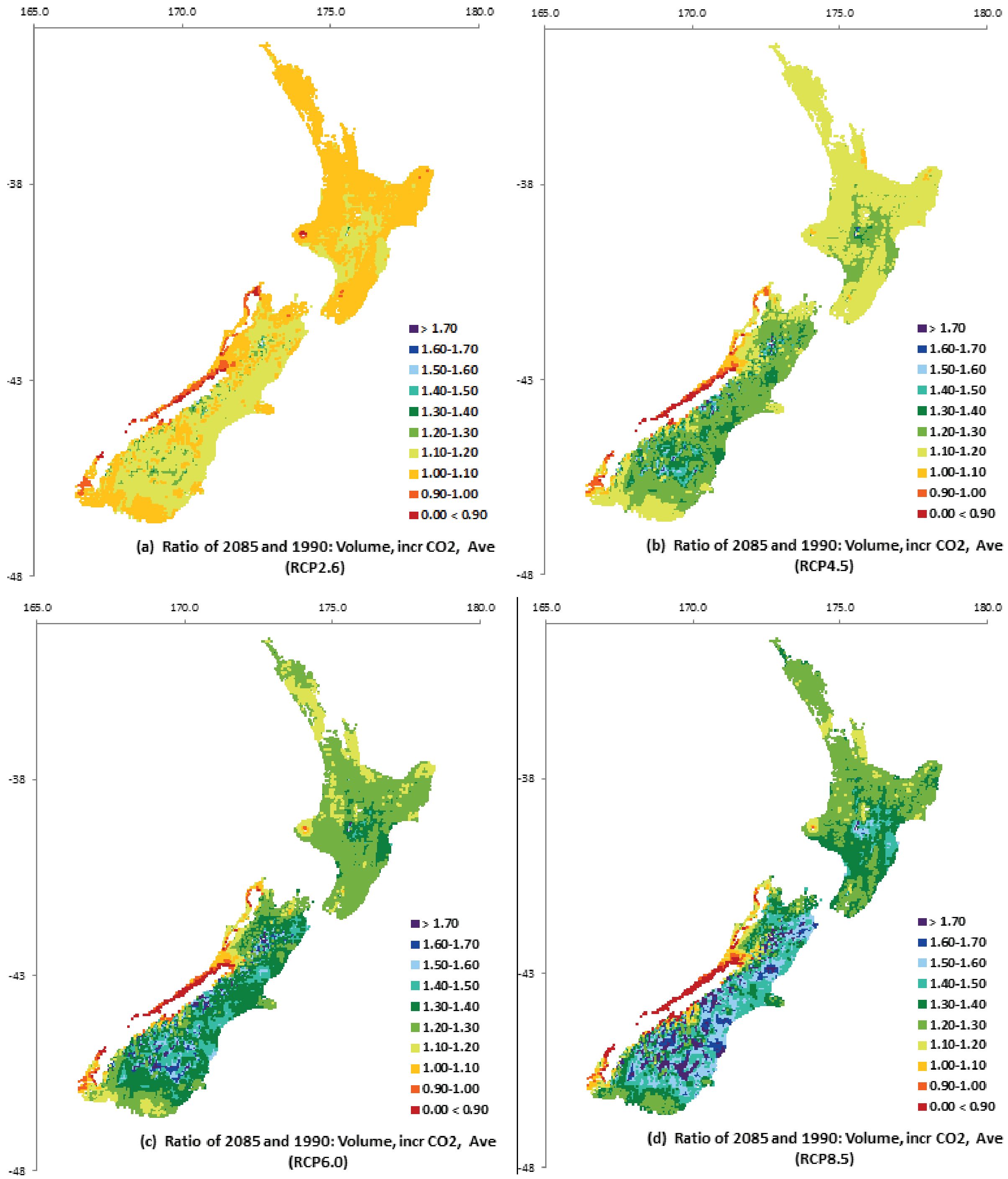


Figure 29 Ratio of 2085 to 1990 P. radiata *productivity, modelled with increasing CO_2 under the four RCPs.*

Implications

Results from CenW modelling indicate that climate change will have a positive impact on *P. radiata* productivity. Increased atmospheric CO_2 enhances growth and helps compensate for other potentially negative aspects of climate change. This suggests that New Zealand may be well-placed to take advantage of the increased productivity from the standpoint of both primary productivity and possibly also via climate change mitigation via such mechanisms including forest sinks and biomass with carbon capture and storage.

Pasture Productivity – Biome-BGC

Impacts

Biome-BGC modelled positive changes in pasture production for both Sheep & Beef and Dairy pasture (Fig. 30). Although some regions and scenarios show negative changes in production by 2046–2065, by 2100 almost all have recovered. Sheep & Beef pasture under scenarios RCP 6.0 and 8.5 shows a small decline of 1–5% around mid-century across the central North Island and the top of the South Island, but by the end of the century, there are increases of 1–10% over much of the country. For Dairy pasture, the change is positive at both time slices for most regions. An increase of 1–10% is projected for the majority of the country regardless of scenario. For RCPs 6.0 and 8.5, larger gains on the order of 10–30% are projected along parts of the coast and at higher elevations.

To analyse the relative influence of a few model inputs on the results, we tested model sensitivity to CO_2 concentrations by running Biome-BGC using NZ-RCM projections based on outputs from one GCM (UK HadGEM2-ES) using RCP8.5, i.e. the RCP with the CO_2 concentrations that differ the most from the past. In the first test, we ran the model with RCP 8.5-based climate projections but kept CO_2 atmospheric concentrations constant at 2005 levels. In the second test, we kept climate constant and increased CO_2 according to the RCP 8.5 projection (Fig. 31).

Without any increase in atmospheric CO_2 concentration, average pasture production declines by 5–10% over much of the North Island and by 0–5% over the South Island for Sheep & Beef by 2100 (Fig. 31a). The climate has somewhat more of an adverse effect around mid-century over parts of the North Island than at the end of the century and could be partially responsible for the relative improvement in yields at the end of the century in the full simulation. The impact of projected climate on Dairy pasture is milder, with smaller negative changes and a slight increase in production for the majority of the South Island.

With increasing atmospheric CO_2 concentration, average pasture production increases by 4–10% over much of the country by mid-century and 8–14% at the end of the century under the RCP8.5 scenario, which corresponds to atmospheric CO_2 of 570 ppm (52% increase) at 2055, and 845 ppm (125% increase) at 2090, respectively. The increase is of similar magnitude for both Dairy and Sheep & Beef pastures. There is more of an increase in the areas that are projected to be drier and warmer (e.g. the East Coast and Northland), demonstrating the importance of the reduction in water loss with elevated atmospheric CO_2.

Given these results, the increase in production in the full simulations can be largely attributed to CO_2 fertilization. The amount of increase follows the trends in CO_2 atmospheric concentrations, with the largest (smallest) increase in production occurring in RCP 8.5 (2.6) at 2100, in which the CO_2 atmospheric concentration is highest (lowest). This offsets any adverse climate effects on production, leaving an overall net gain in total annual production in most locations in New Zealand.

Seasonal average growth rates show consistent, large increases in winter (JJA) and spring (SON), as expected under warmer conditions and an extended growing season (Figs 32 & 33). Autumn (MAM) shows small increases in the majority of scenarios, while hotter, drier summers (DJF) result in a steep decline in growth, which is as large as −20% to −30% in some regions at mid-century, particularly for RCP 8.5. By the end of the century, the increased atmospheric CO_2 in the high emissions scenarios somewhat lessens the impacts of summer drought, but declines of 5–15% are still apparent over much of the country.

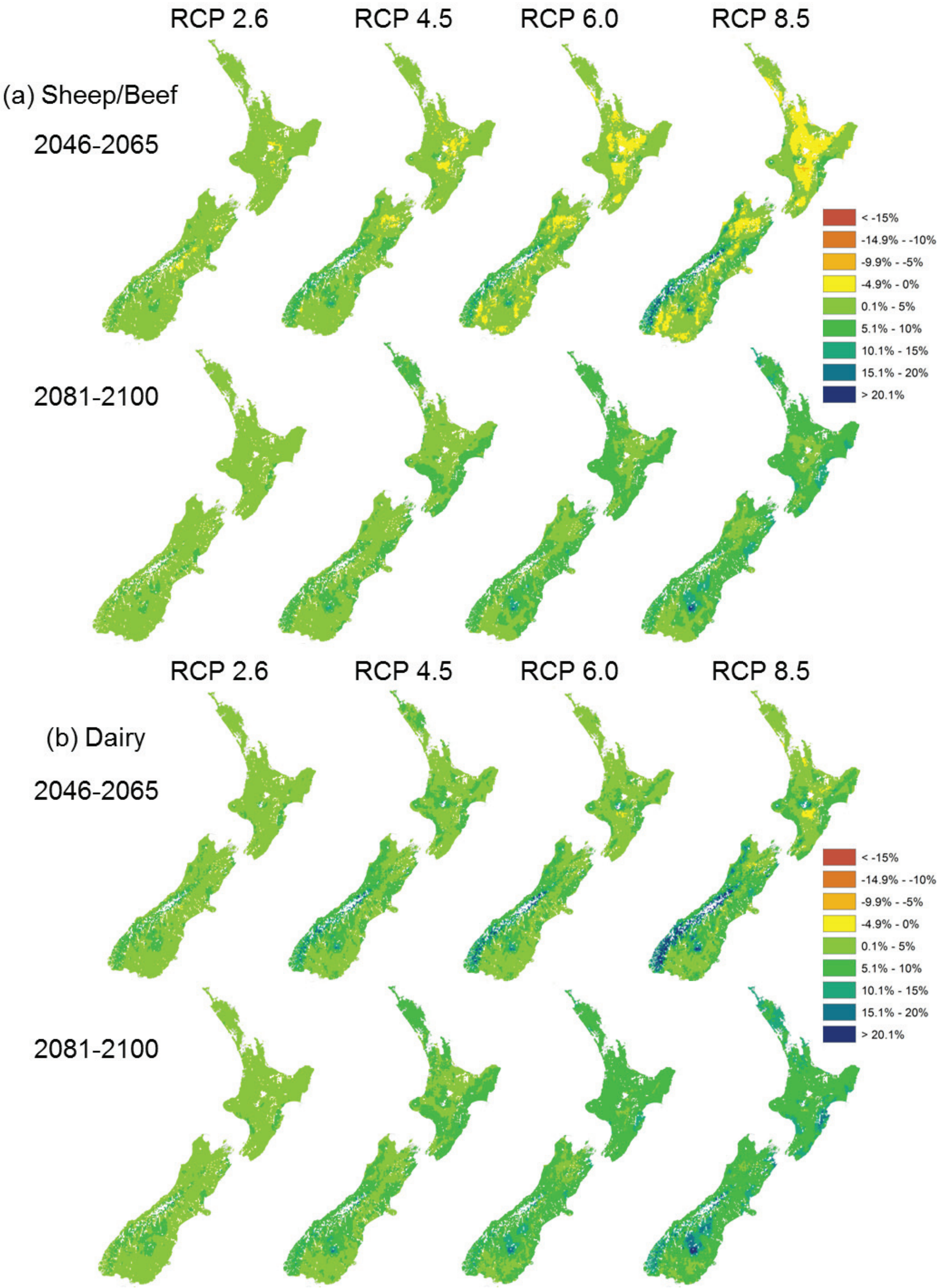


Figure 30 Biome-BGC model ensemble for percent change in annual average total pasture production for (a) Sheep & Beef and (b) Dairy between RCP-past (1981–2005) and the four RCPs at mid- (2046–2065) and end-century (2081–2100).

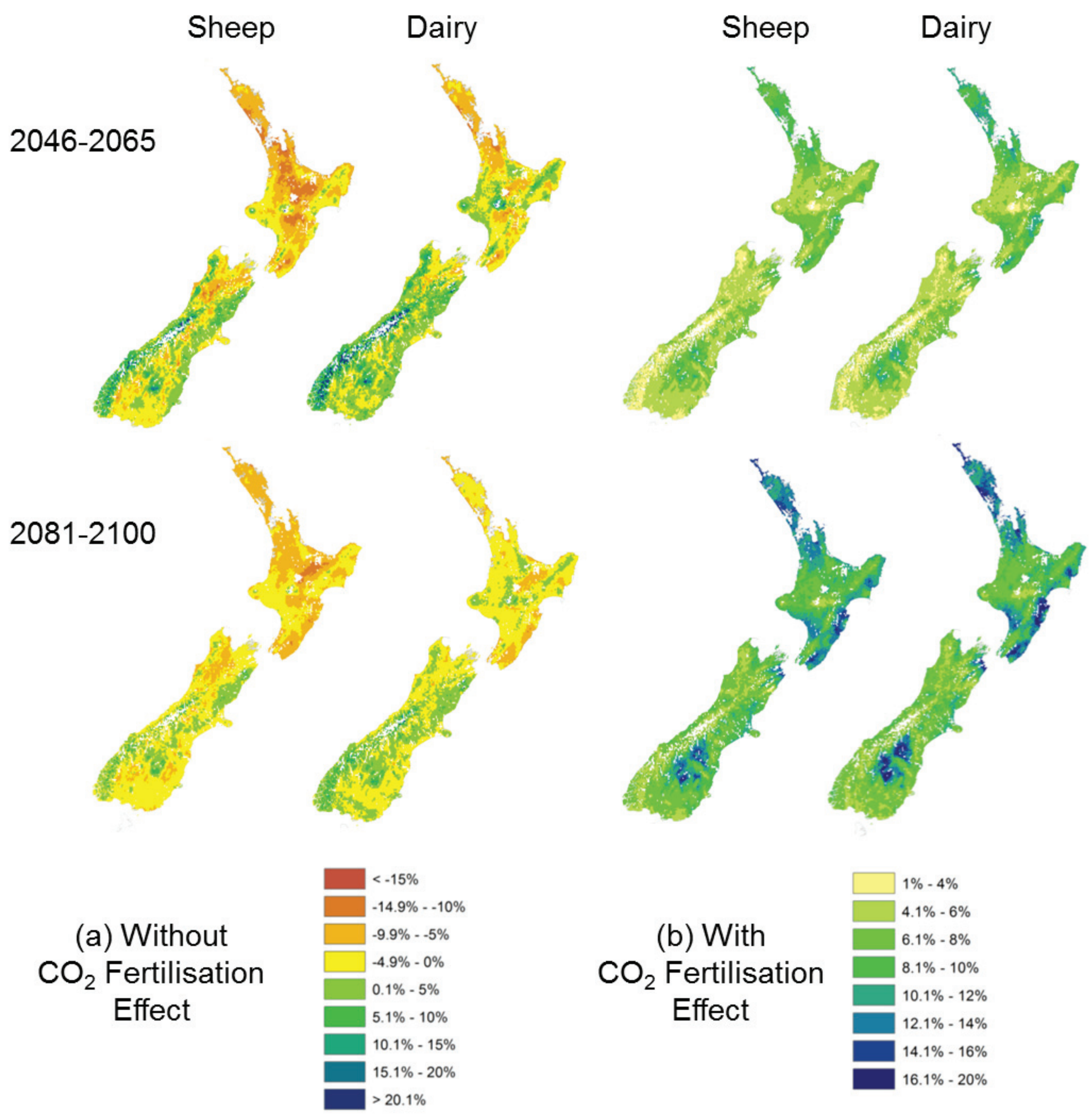


Figure 31 Biome-BGC model ensemble for percent change in annual average total pasture production with constant (a) and variable (i.e. increasing) CO2 concentration for Sheep & Beef and Dairy between RCP-past (1981–2005) and RCP8.5 at mid- (2046–2065) and end-century (2081–2100).

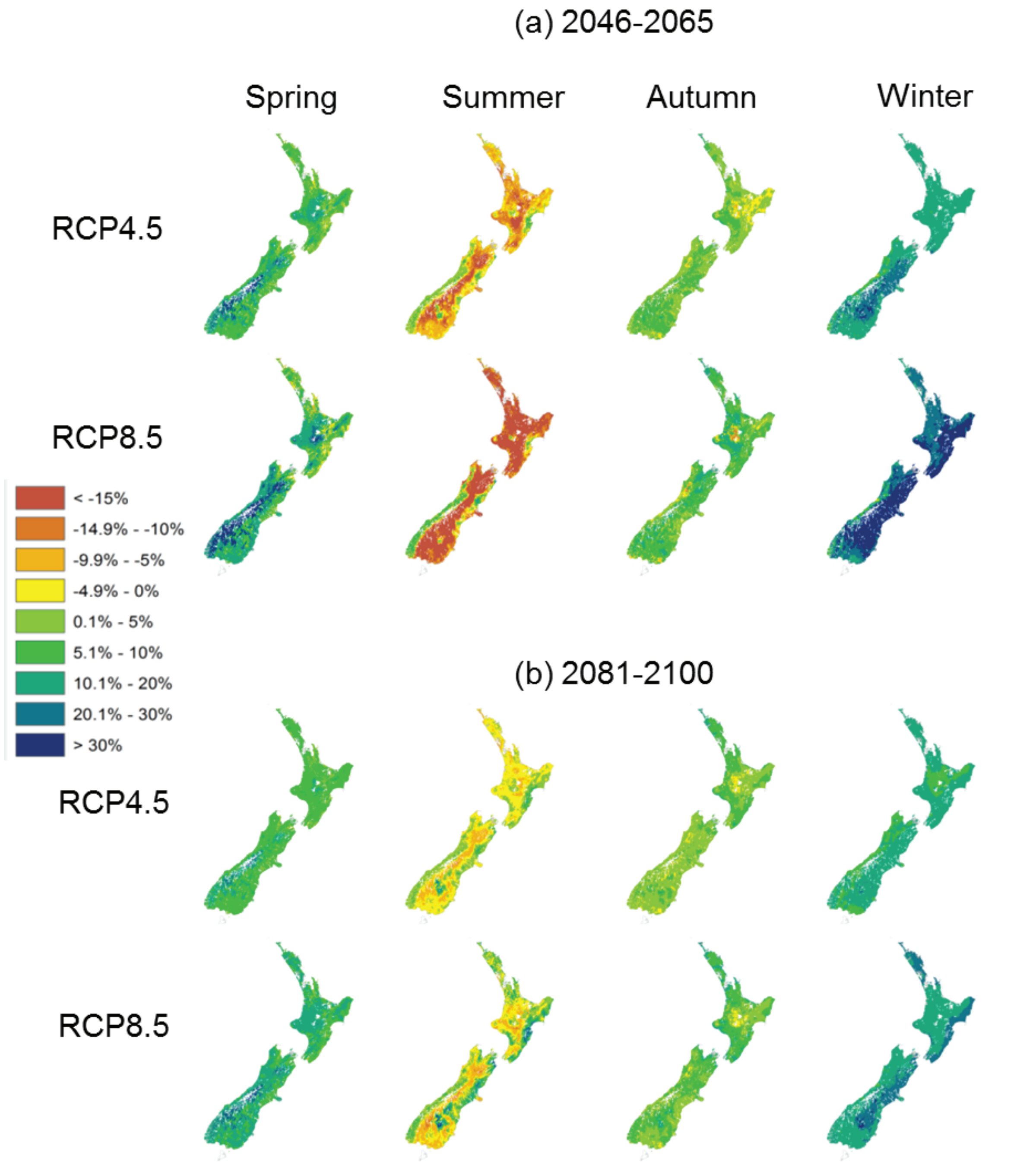


Figure 32 Percent change in average seasonal changes in pasture production rate for Sheep & Beef pasture between RCP-past (1986–2005) and RCP4.5 and RCP8.5. From top to bottom: (a) mid-century (2046–2065) shown in top two rows; (b) end century (2081–2100) shown in bottom two rows. From left to right: Spring = September–October–November; Summer = December–January–February; Autumn = March–April–May; Winter = June–July–August. RCP2.6 and RCP6.0 (not shown) show similar trends.

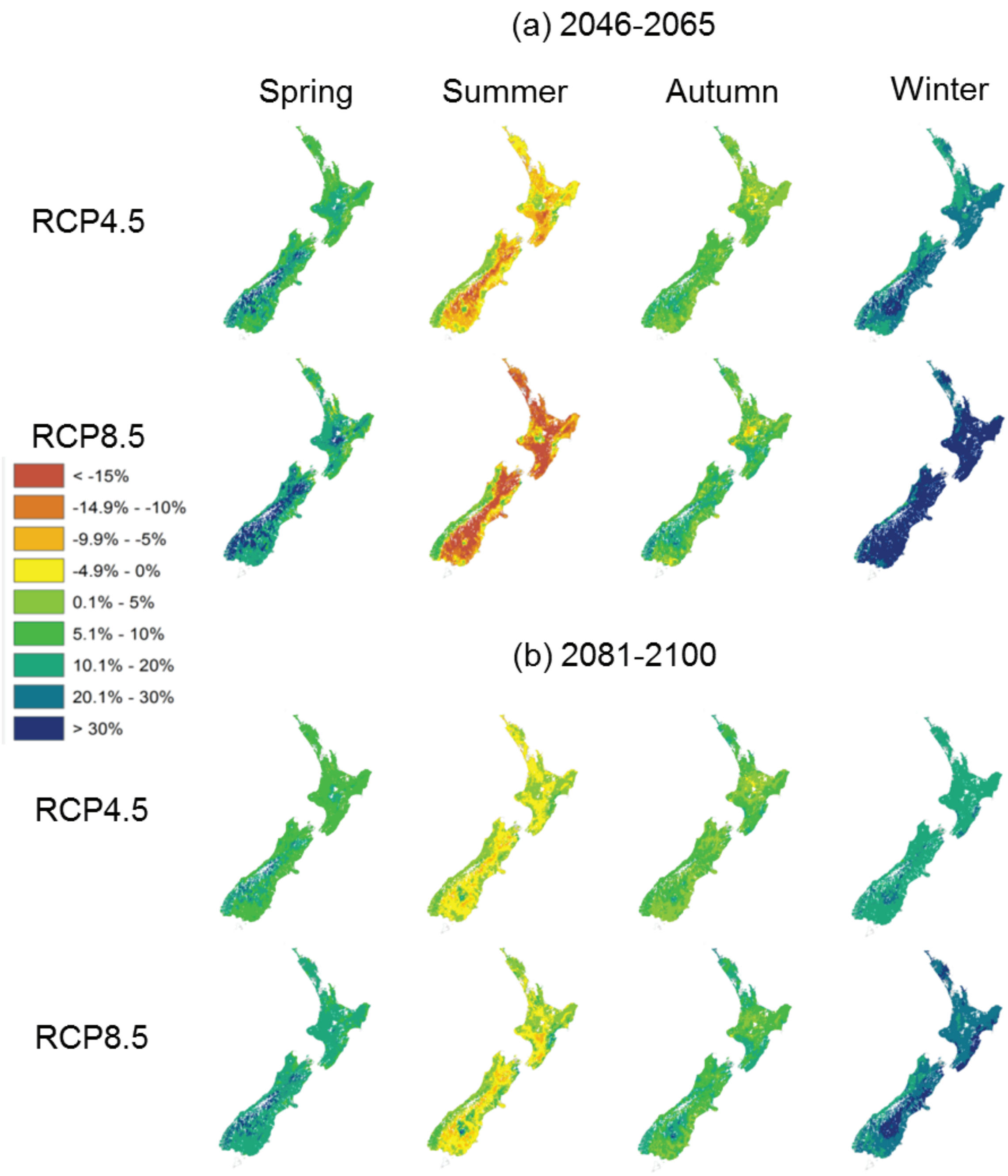


Figure 33 Percent change in average seasonal changes in pasture production rate for Dairy pasture between RCP-past (1986–2005) and RCP4.5 and RCP8.5. From top to bottom: (a) mid-century (2046–2065) shown in top two rows; (b) end century (2081–2100) shown in bottom two rows. From left to right: Spring = September–October–November; Summer = December–January–February; Autumn = March–April–May; Winter = June–July–August. RCP2.6 and RCP6.0 (not shown) show similar trends.

Implications

Despite the net positive gain in total annual production, seasonal shifts in pasture yields are likely to cause disruption and/or require adaptation. Dry summers can be mitigated by irrigation or using stored and imported feed, but come at an additional cost to the farmer. On the other hand, increased production in winter might make winter grazing more viable in the coldest parts of the country, and suggest that adaptive changes in winter farm system management deserve consideration.

We note that the relative increase in production at 2081–2100 compared with 2046–2065 is somewhat unexpected, and has not been a feature of previous modelling such as Keller et al. (2014). The reduction in impacts at the end of the century could be explained by the steep rise in atmospheric CO_2 at the end of the century in the higher emissions scenarios, or a relative improvement in climate between the two time slices.

An alternative but more complex explanation is an enhancement of the CO_2 fertilisation effect resulting from enhanced nitrogen levels in soil and plants. Neither sheep nor dairy pasture appears to be nitrogen-limited in our model, and the difference between Sheep & Beef and Dairy systems is somewhat muted as a result. This could be a result of enabling transient simulations, which are more realistic than equilibrium simulations employed previously (Keller et al. 2014) and which allow for nitrogen to accumulate (or to become depleted) during the model run and feed back to plant growth. In real systems, nitrogen limitation would likely reduce the increased rate of photosynthesis from CO_2 fertilization. In the modelled Sheep & Beef and Dairy systems, nitrogen inputs via clover and fertiliser are fixed, but in reality might vary due to self-regulation in the grass-clover system or overall farm system management. If nitrogen inputs are reduced relative to the values we have modelled, our results likely overestimate the benefits of CO_2 fertilization. Similarly, in farm systems with lower nitrogen inputs than modelled, such as extensive tussock grasslands and unimproved pastures, our model is likely to overestimate the benefits of CO_2 fertilization and therefore overestimate production.

Hydrology & Water Resources – National TopNet

National TopNet modelling produced a substantial range of detailed results modelling future hydrological dynamics under each of the four RCPs across New Zealand. Assessing projected trends of key indicators, both individually and collectively, provides insights into how the hydrological system will evolve across space and over time. Through those insights we can better understand the potential impacts and implications for water resources (e.g. water supply, water quality) and water resources management (e.g. hazards such as flooding) under different magnitudes of radiative forcing and evaluate outcomes from different strategies implementing mitigation and/or adaptation tactics.

Below we summarise results for five key indicators based on a related report prepared for the Ministry for Primary Industries (Collins & Zammit 2016): 1) mean annual flow; 2) magnitude and timing of mean annual low flows; 3) mean annual flood; 4) flow reliability; and 5) summer soil moisture deficit.

Impacts

National TopNet modelling showed that climate change will impact hydrology in complex ways by differentially changing the amount, timing, and spatial distribution of water flows throughout New Zealand's river and stream network. Despite the complexity, some patterns emerged that provide some broad insights regarding the potential impacts and implications of climate change on New Zealand's water resources.

Perhaps most importantly, the magnitude of the change, whether positive or negative, tends to increase with higher radiative forcing. For example, under RCP2.6 changes in mean annual flow range from +/– 40%, whereas under RCP8.5 changes range from –60% to >100%.

In terms of the dynamics of the hydrological system, the broad pattern nationally is for an increased variability (Table 11). The total range of flows (low to high=flood) increases overall, with lower mean annual low flows and higher mean annual floods. Flow reliability also decreases overall in most areas of the country.

Within the trend of overall increasing variability, mean annual flows show a more complicated pattern of increases and decreases (Table 11). Western areas of both the North and South Islands and the south of the South Island tend to experience increases in mean annual flows, primarily due to the projected increases in precipitation interacting with typical west-east airflows and orographic effects. Eastern uplands and lowlands of both islands located in the rain shadows tend to experience decreases in mean annual flows, some eastern coastal areas in Bay of Plenty and Canterbury being noticeable exceptions.

Nationally, timing of low occurs earlier, except for the West Coast (Table 11), and the magnitude of the shift increases both over time and with increasing radiative forcing.

Summer soil moisture deficits intensify such that soils become drier except in a few areas of the South Island (Table 11).

Table 11: Regional trends for six key hydrological indicators under RCP8.5 from National TopNet modelling based on Collins and Zammit (2016). Coloured arrows: ↑ = positive trends; ↓ = negative trends; ↑↓ = mixed trends. Pluses + minuses: ++ = earlier low flow timing; -- = later low flow timing

	MEAN ANNUAL FLOWS			FLOW RELIABILITY	SUMMER SOIL MOISTURE DEFICIT
REGION	LOW	MEAN DISCHARGE	FLOOD		
NORTHLAND	↓++	↓	↑	↓	↓
AUCKLAND	↓++	↓North ↑West Coast & South	↑	↓	↓
WAIKATO	↓++	↑West Coast & Volcanoes ↓Coromandel & Central Plateau	↑ ↓Central Plateau	↓	↓
BAY OF PLENTY	↓++	↓ ↑Central Coast	↑	↓	↓
GISBORNE	↓++	↓	↓ ↑West Hill Country	↓	↓
TARANAKI	↓++	↑ ↓Mt Taranaki	↑	↓	↓
MANAWATU-WANGANUI	↓++	↑North & West Coast ↓Central & East Coast	↑	↓	↓
HAWKE'S BAY	↓++	↓	↑	↓	↓
WELLINGTON	↓++	↓	↑	↓	↓
TASMAN	↓++	↑	↑	↓	↓
NELSON CITY	↓++	↑	↑	↓	↓
MARLBOROUGH	↓++	↑North & Sounds ↓South & East Coast	↑ ↓southern Uplands	↓	↓
WEST COAST	- -↑	↑	↑	-	-
CANTERBURY	↓++ ↑some East Coast	↑Lowlands & East Coast ↓Mountains & Uplands	↑	↓ ↑some East Coast	↓ ↑some Lowlands & East Coast
OTAGO	↓++ ↑some Uplands & East Coast	↑ ↓northern Uplands	↑	↓ ↑some East Coast	↓ ↑some Uplands & East Coast
SOUTHLAND	↓++	↑	↑	↓	↓

Global-NZ Socioeconomic Co-Development – CliMAT-DGE

As discussed earlier, CliMAT-DGE provides the ability to represent New Zealand independently in the broader global context. In the SSP framework and the global scenario study, New Zealand's broad socioeconomic development follows a predetermined, SSP-based pathway and other New Zealand developments follow appropriate regional (i.e. OECD) assumptions.

For RA3 scenario evaluation, CliMAT-DGE modelled two global regions, New Zealand and the rest of the world, subject to three primary constraints: 1) the global coupled population-GDP pathway should follow the SSP-specified pathway; 2) New Zealand's population pathway should follow the SSP-specified pathway; and 3) global GHG emissions should be in line with concentrations required to achieve a specific RCP. Within those constraints, New Zealand could develop independently from standard SSP and/or SPA assumptions.

Impacts

SSP3-based scenarios showed the best fit with the fixed coupled global population-GDP trajectories (Fig. 34). In SSP1- and SSP5-based scenarios, projected global GDP at 2100 from CliMAT-DGE was about half the target SSP3 value. That large discrepancy makes comparing SSP1- and SSP5-based scenario results from the global scenario study and CliMAT-DGE problematic. We therefore limit discussion of impacts and implications to SSP3-based scenarios: Unspecific Pacific (SSP3-RCP8.5-SPA3-SPANZ_A) and Kicking, Screaming (SSP3-RCP4.5-SPA0-SPANZ_A).

Unspecific Pacific

In Unspecific Pacific, New Zealand's development parallels the SSP-specified pathway with some differences (Table 12). Population mirrors SSP projections, both in magnitude and timing, such that total population at 2097 is 3.8 million, or 600,000 less than at 2007. Labour force as a percentage of the total population grows to ~60% of the total population by 2037 and remains more-or-less constant thereafter, even as total population declines.

Economically, New Zealand fares slightly better than SSP-projections, with GDP at 2097 of \$296 billion USD_{2007}, versus \$283 billion USD_{2005} (Table 12). The main difference is the pattern of change, as the SSP-specified projection shows constant, albeit relatively low growth as would be expected for SSP3, whereas CliMAT-DGE has New Zealand GDP growing more quickly and then peaking and declining slightly by the end of the century. NZ household consumption as a percentage of GDP increases to 92% by 2097.

Imports and exports also grow continuously over the period 2007–2097 (Table 12). Exports grow at a slightly faster rate, resulting in a shift from a trade deficit of –\$4.6 billion in 2007 to +\$23.4 billion USD_{2007} in 2097.

New Zealand greenhouse gas emissions increase from 75.9 to 112.0 megatons of CO_2-equivalent per year (Table 12). As specified for all non-mitigation scenarios, no climate mitigation policies operate such that no carbon market(s) operate and the assumed price of carbon is \$0 per tonne of CO2-equivalent throughout the simulation.

Kicking, Screaming

In Kicking, Screaming, New Zealand's development also broadly parallels the SSP-specified pathway (Table 12). Population mirrors SSP projections, both in magnitude and timing, such that total population at 2097 is 3.8 million, or 600,000 less than at 2007. Labour force as a percentage of the total population grows to ~60% of the total population by 2037 and remains more-or-less constant thereafter, even as total population declines.

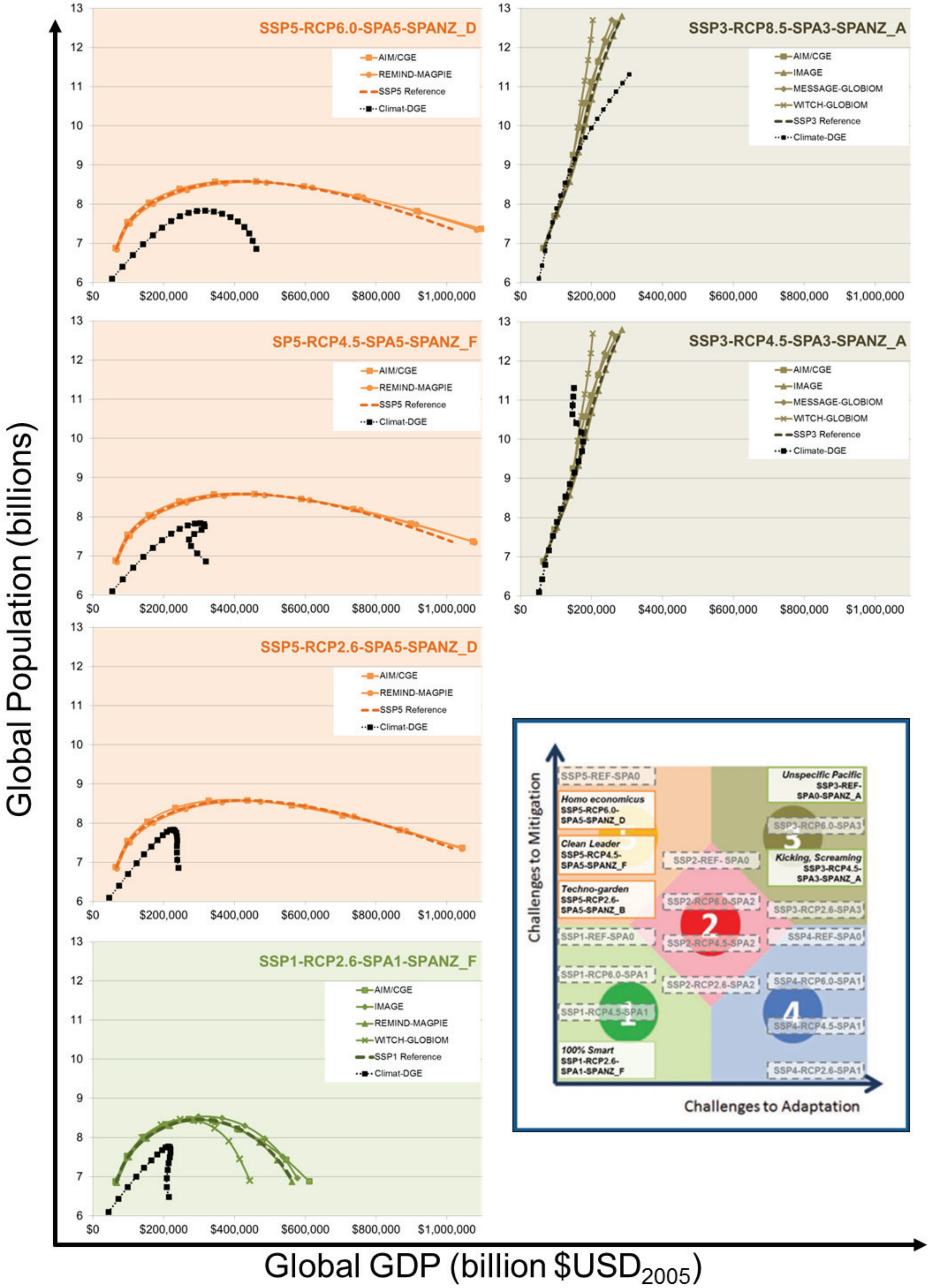


Figure 34 Modelled global Population-GDP trajectories for the six CCII scenarios. Scenarios arranged according to their relative location as shown in the inset CCII scenario diagram. Reference trajectory = bold dotted lines; global modelling results = coloured lines; CliMAT-DGE results = black dotted line.

Table 12: CliMAT-DGE projections for selected indicators for New Zealand for SSP3 scenarios with selected comparisons to global scenario study marker scenario projections (brown italics). Note: global models and CliMAT-DGE use slightly different reference monetary values and time steps that together account for a small but unquantified proportion of any differences between them. Global scenario study data from the SSP Public Database Version 1.1

		Kicking, Screaming (SSP3-RCP4.5-SPA3-SPANZ_A)				*Unspecific Pacific* (SSP3-RCP8.5-SPA0-SPANZ_A)			
		2007	2037	2067	2097	2007	2037	2067	2097
POPULATION (Million)									
Total	SSP*	*4.4 (2010)*	*5.0 (2040)*	*4.7 (2070)*	*3.6 (2100)*	*4.4 (2010)*	*5.0 (2040)*	*4.7 (2070)*	*3.6 (2100)*
	CliMAT-DGE	4.2	4.8	4.5	3.7	4.2	4.8	4.5	3.7
Labour Force	Total	2.3	2.9	2.8	2.3	2.3	2.9	2.8	2.3
	% of Total Population	54%	59%	61%	61%	54%	59%	61%	61%
NEW ZEALAND GDP & HOUSEHOLD CONSUMPTION (Billion $US2007)									
GDP	*SSP**	*$111 (2010)*	*$177 (2040)*	*$241 (2070)*	*$283 (2100)*	*$111 (2010)*	*$177 (2040)*	*$241 (2070)*	*$283 (2100)*
	CliMAT-DGE	$125	$227	$286	$247	$ 125	$219	$299	$296
	△CliMAT-DGE – SSP	+14	+50	+45	-36	+14	+42	+57	+13
Household Consumption	Total	$76	$138	$185	$129	$101	$187	$254	$272
	%GDP	61%	61%	65%	52%	81%	85%	85%	92%
IMPORTS & EXPORTS (Million $US2007)									
Exports		$42,783	$88,560	$131,909	$138,593	$33,529	$61,541	$104,416	$134,529
Imports		$22,195	$38,878	$48,039	$20,009	$38,132	$66,907	$92,478	$111,095
	△Exports – Imports	+$20,588	+$49,682	+$83,869	+$118,584	-$4,603	-$5,367	+$11,938	+$23,434
GREENHOUSE GAS EMISSIONS (Megatons CO2-equivalent)									
CH_4		29.2	66.6	103.9	105.0	26.8	47.4	64.6	60.9
CO_2		35.0	32.1	20.2	12.8	34.9	21.5	23.1	19.6
Fluorinated Gases		1.2	1.1	0.7	0.4	1.1	0.8	0.9	0.7
N_2O		14.2	31.8	49.5	49.3	13.0	23.1	32.1	30.8
	TOTAL	79.6	131.6	174.4	167.6	75.9	92.8	120.7	112.0

Economically, New Zealand fares slightly worse than SSP-projections, with GDP at 2097 of $247 billion USD_{2007}, versus $283 billion USD_{2005} (Table 12). As with Unspecific Pacific, the Kicking, Screaming trajectory is similar to the CliMAT-DGE projections where New Zealand GDP will grow more quickly than the SSP3-specified pathway to ~2070 and then peak and decline by the end of the century. NZ household consumption as a percentage of GDP decreases from 61% in 2007 to 52% by 2097.

Imports and exports show different trends. Exports grow monotonically over the modelled period Imports first grow, then peak around 2067, and then substantially decline by 2097 to $20 billion USD_{2007}, or $2 billion less than imports in 2007. As a result, New Zealand's trade surplus grows by a factor of 6, from $20.6 billion in 2007 to $118.6 billion USD_{2007} in 2097.

New Zealand's greenhouse gas emissions increase from 79.6 to 167.6 megatons of CO_2-equivalent per year (Table 12). As specified for mitigation scenarios, climate mitigation policies operate, as reflected in rising carbon prices.

In the Kicking, Screaming scenario, global greenhouse gas mitigation policies follow SPA3, which assumes that carbon markets remain fragmented until 2050 for fossil fuel & industry (F3) and have limited inclusion of emissions from land use (LN) (Fig. 6). In the global scenario study, global carbon prices begin at $0 in 2010 and increase to between $138.27 and $661.09 USD_{2005} per tonne by 2100 (Table 13). Per SPA3 assumptions, regional carbon price projections remain fragmented until converging to the same price at 2050 and thereafter.

CliMAT-DGE projected global and New Zealand carbon prices to increase from $0 USD_{2007} per tonne in 2007 to $12,203.48 and $8,334.05 USD_{2007}, respectively, in 2100 (Table 13). New Zealand carbon prices increase more quickly than global carbon prices to 2087, after which global carbon prices become higher. Comparatively, CliMAT-DGE's projected global carbon price parallels global scenario study projections until ~2060–2070 and diverges to higher prices such that CliMAT-DGE's global carbon price is 27 times larger than the marker scenario global carbon price in 2100.

Implications

Assumptions about future global and socioeconomic development, as embodied in the SSPs, account for most of the difference among possible realisations of New Zealand's future socioeconomic development (Fig. 5). Among the five SSPs, New Zealand's prospects differ markedly, although on a relative basis New Zealand always fares better than the rest of the (non-OECD) world (Fig. 14).

Climate change, by contrast, will have smaller but still significant impacts, as evidenced by comparing CliMAT-DGE results for the two SSP3-based scenarios (Table 12). NZ GDP in 2100 decreases by 16.6% (–$49 billion USD_{2007}) in Kicking, Screaming (RCP4.5) versus Unspecific Pacific (RCP8.5), implying that mitigation in the SSP3 world comes at some economic cost.

More substantially, the pathways of development under the two scenarios differ dramatically. In both scenarios, exports remain an important component of New Zealand's economy. In Unspecific Pacific, household consumption increases from 81% to 92% of GDP and balance of trade becomes positive. These projections suggest that New Zealand adapts by successfully leveraging positive impacts of climate change, e.g. projected increases in primary productivity, to bolster strategic trading relationships and exports in an increasingly fragmented world and offset increasing internal demand (i.e. household consumption).

In Kicking, Screaming, New Zealand household consumption declines to 52% of GDP by 2100. Imports also decline substantially causing the balance of trade to becomes substantially positive (+$118,584 billion US_{2007} or 48% of GDP) by 2100 (Table 12). Somewhat unexpectedly, New Zealand's annual greenhouse gas emissions in 2100 are 50% higher for Kicking, Screaming (167.6 megatons CO_2-equivalent) than Unspecific Pacific (112.0 megatons CO_2-equivalent) despite the assumed operation of global climate policies and carbon market (Table 13).

Taken together, the projections for Kicking, Screaming suggest that New Zealand adopts an outward-looking approach to adapt to a fragmented world that still attempts to mitigate climate change (i.e. RCP4.5). The approach maintains a strong focus on exports while reducing internal demand. New Zealand GHG emissions increase as a consequence of the increased focus on exports, but the increases are offset globally by decreases elsewhere via a range of mechanisms.

Table 13 Global scenario study and CliMAT-DGE decadal projections for carbon price ($ per tonne of CO2-equivalent) for the Kicking, Screaming scenario (SSP3-RCP4.5-SPA3-SPANZ_A). Marker scenario results shown in brown italics. Note: Global models and CliMAT-DGE use slightly different reference monetary values and time steps that together account for a small but unquantified proportion of any differences between them. Global scenario study data from the SSP Public Database Version 1.1

GLOBAL SCENARIO STUDY										
YEAR	*2010*	*2020*	*2030*	*2040*	*2050*	*2060*	*2070*	*2080*	*2090*	*2100*
GLOBAL– ALL MODELS ($US2005)										
MESSAGE-GLOBIOM	$0	$28.60	$31.99	$35.39	$57.65	$93.91	$152.96	$249.16	$405.85	$661.09
WITCH-GLOBIOM	$0	$8.08	$29.74	$43.79	$68.29	$126.40	$198.45	$299.89	$438.94	$625.04
AIM/CGE	***$2.46***	***$15.57***	***$23.43***	***$40.66***	***$64.58***	***$120.95***	***$160.15***	***$212.90***	***$297.62***	***$446.92***
IMAGE	$0	$0	$0	$0	$55.10	$57.98	$68.50	$138.69	$196.36	$138.27
REGIONS ($US2005) – MARKER SCENARIO (AIM/CGE)										
Asia	$0	$0	$0	$36.77	$64.58	$120.95	$160.15	$212.90	$297.62	$446.92
Latin America & Mexico	$0	$0	$0	$36.77	$64.58	$120.95	$160.15	$212.90	$297.62	$446.92
Middle East & Africa	$0	$0	$0	$36.77	$64.58	$120.95	$160.15	$212.90	$297.62	$446.92
OECD (incl. NZ)	$8.40	$25.96	$28.89	$52.29	$64.58	$120.95	$160.15	$212.90	$297.62	$446.92
Former Soviet Union	$0	$0	$0	$36.77	$64.58	$120.95	$160.15	$212.90	$297.62	$446.92
CliMAT-DGE ($US2007)										
YEAR	*2007*	*2017*	*2027*	*2037*	*2047*	*2057*	*2067*	*2077*	*2087*	*2097*
Global	$0	$0	$0	$4.12	$25.20	$68.46	$403.37	$3,115.19	$10,155.19	$12,203.48
NZ	$0	$0	$0	$17.61	$33.10	$144.94	$1,372.37	$5,326.98	$7,374.13	$8,334.05

Rural Land Use – LURNZ

Impacts

LURNZ simulates outcomes at the national level for five land uses: dairy, sheep & beef, forestry, scrub and horticulture. For the Unspecific Pacific scenario (SSP3-RCP8.5-SPA0-SPANZ_A), dairy and forestry expand into current sheep & beef areas under a baseline assuming no climate change and no price changes beyond 2019, which are both consistent with recent historical trends (Fig. 35).

Compared with the baseline, climate change (RCP 8.5) is projected to lead to a fall in sheep & beef and a nearly offsetting increase in dairy area in both the mid-century (2065) and end-of-century simulations (2100) (Figs 36 & 37). These changes are consistent with the overall rise in pasture productivity under RCP8.5, which suggests that conditions for dairy farming may become more favourable with climate change.[5] By the end of the century, dairy increases by 605,000 hectares and sheep & beef contracts by 842,000 hectares. Forestry and scrub also increase slightly, but the estimated effect of climate change on other land uses is much smaller (Fig. 37).[6]

[5]Yield projections are based on changes in mean climate. The effects of climate variability and extreme events were not taken into account in the yield modelling.

[6]This seems reasonable, given that only pasture yields are included in LURNZ. 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).

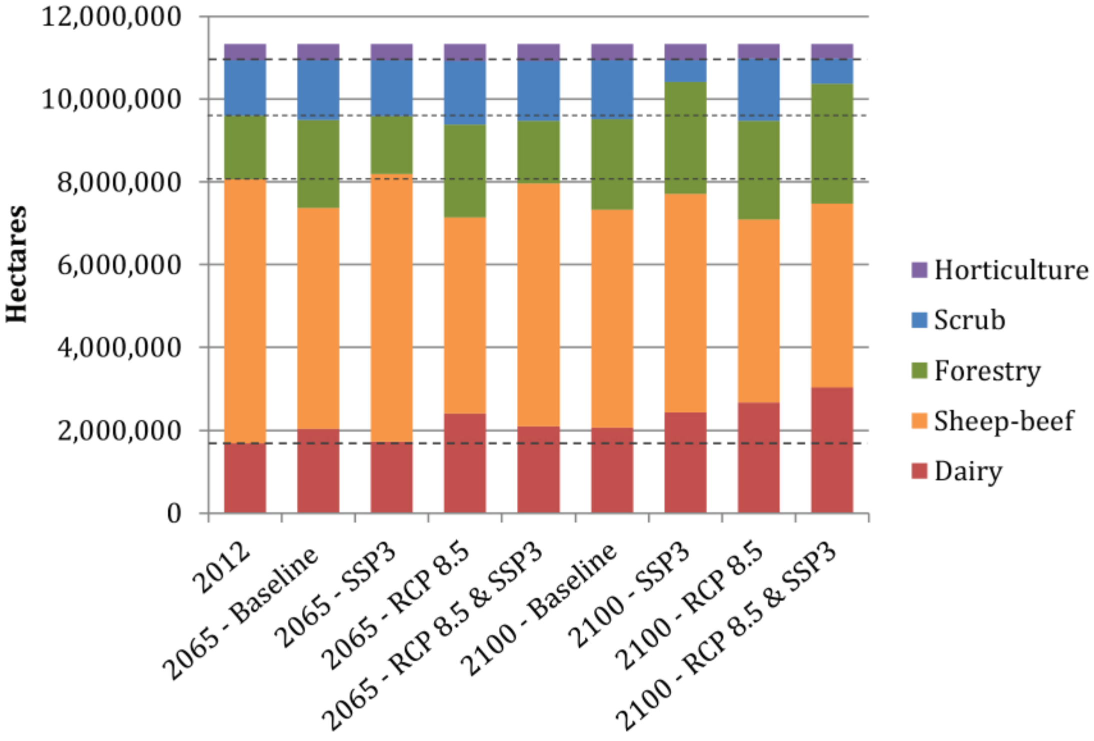


Figure 35 LURNZ projected distribution of land uses (ha) at 2065 and 2100 for different cases in the Unspecific Pacific scenario. All cases involving climate (RCP8.5) use mean pasture production (yield) from Biome-BGC based on the ensemble of NZ-RCM outputs from the six global ESM/GCMs selected in RA1.

The SSP-only and SSP+RCP cases are subject to an important caveat: the economic drivers under SSP3 extend well beyond the observed historical ranges used for LURNZ calibration and validation (Fig. 11). All commodity prices exceed their historical maximums by the end of the century. Sheep & beef shows the largest and fastest change. It exceeds the observed historic maximum by 2031 and increases three-to-five-fold from 2012 values. We do not expect out-of-range projections from LURNZ to be robust under these extreme circumstances as the estimated relationship between prices and land-use areas is unlikely to hold. Nonetheless, we discuss the SSP and combined SSP+RCP cases for completeness.

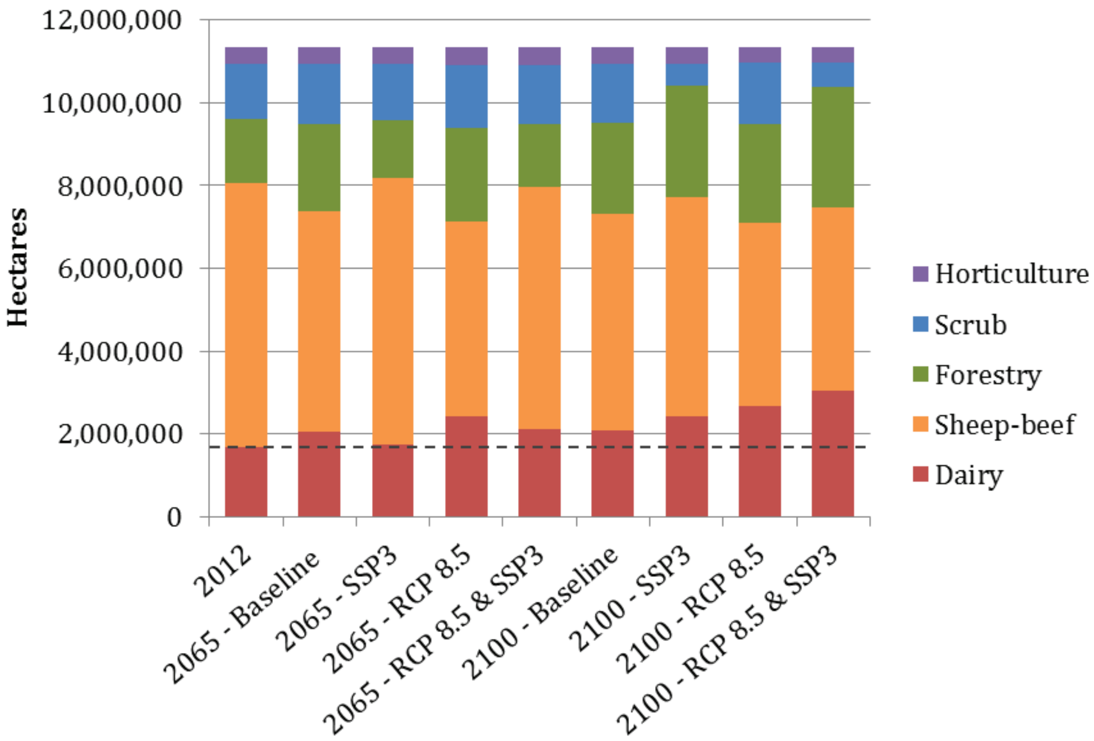


Figure 36 Land-use change (ha) in 2065 between baseline and RCP8.5-only (model ensemble and individual GCM-based NZ-RCM outputs) and SSP3-only cases for the Unspecific Pacific *scenario.*

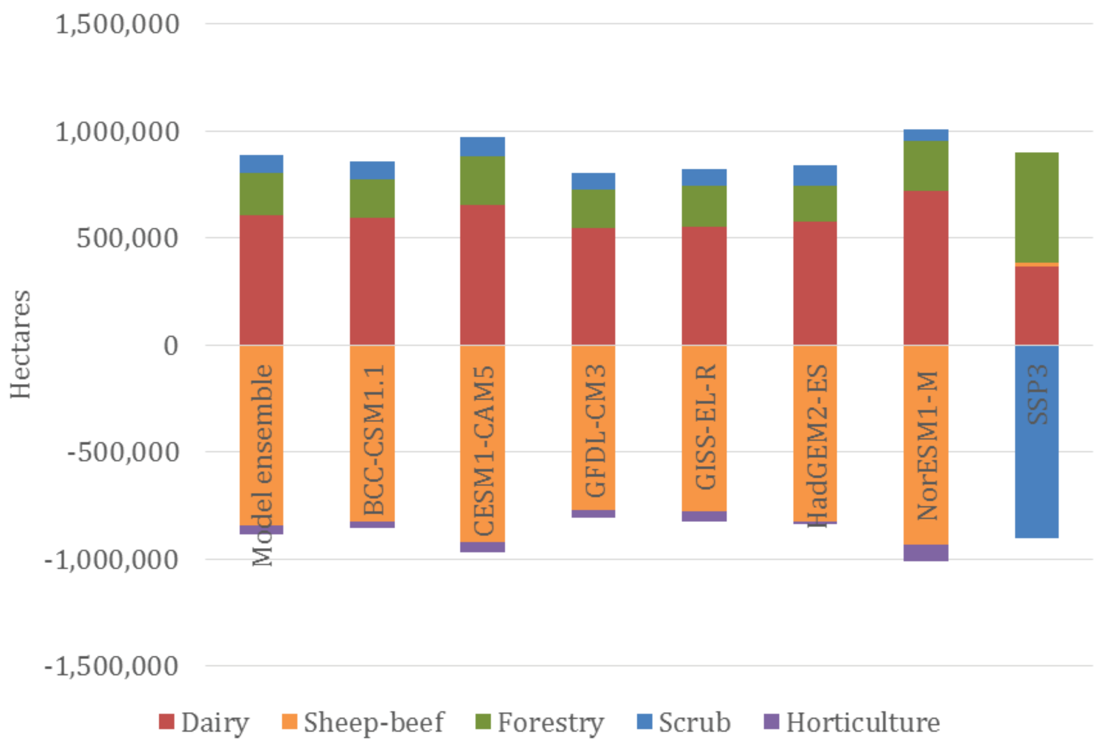


Figure 37 Land-use change (ha) in 2100 between baseline and RCP8.5-only (model ensemble and individual GCM-based NZ-RCM outputs) and SSP3-only cases for the Unspecific Pacific *scenario.*

In SSP3, as sheep & beef prices rapidly increase early in the simulation period, LURNZ projects that the sheep & beef area increases by over 1,100,000 hectares relative to the baseline by 2065 – a 20% increase over the baseline, while forestry, dairy, and scrub contract. With the steady increase in commodity prices, all productive land uses expand beyond baseline levels by the end of the century.[7] Forestry experiences the largest price effect: an increase of over 500,000 hectares. Dairy also increases significantly, while sheep & beef increases marginally. There is an offsetting large decrease in scrub area (see last bars of Figs 36 & 37).

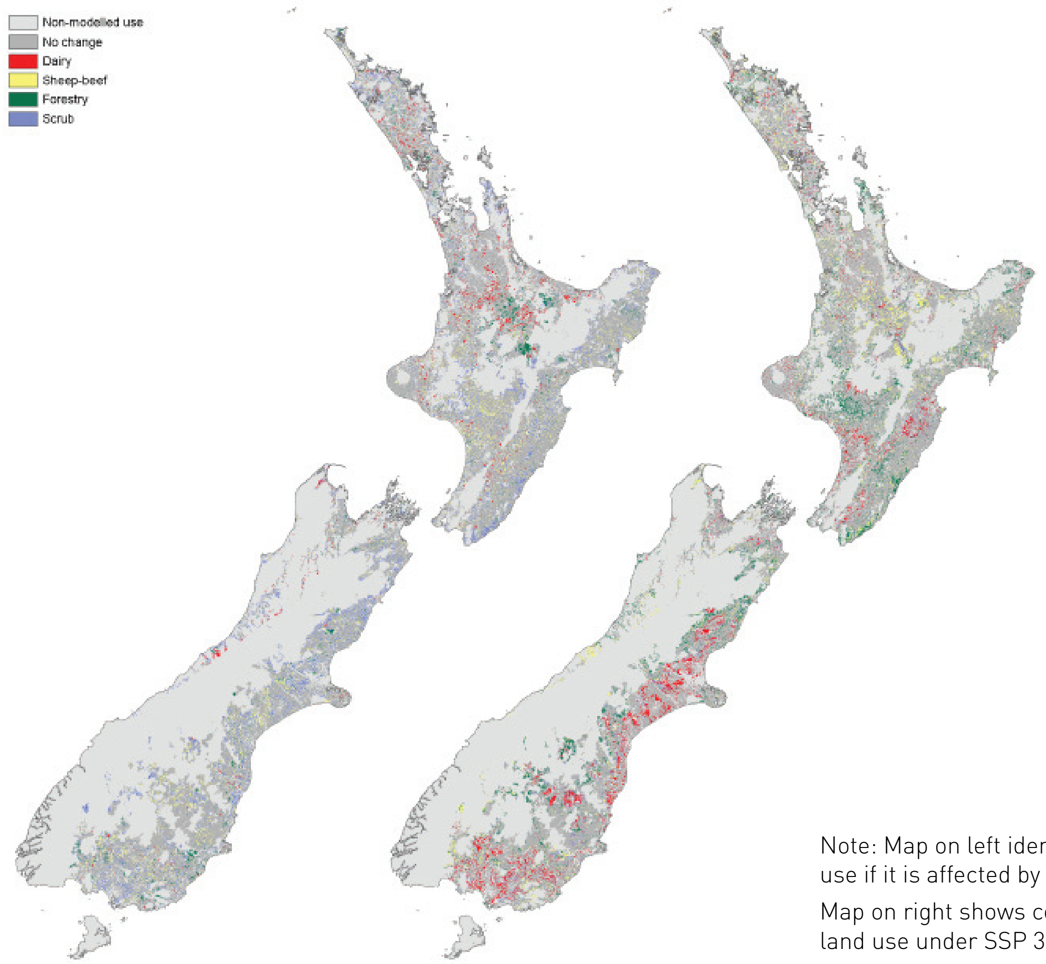
The national land-use impacts under SSP+RCP cases are additive, so land-use change is the sum of individual price effects (SSP) and yield effects (RCP). In the 2065 simulations (Fig. 36), the price and yield effects tend to act in opposing directions. By the end of the century (Fig. 37); however, both climate and economic drivers cause dairy and forestry to expand giving us slightly more confidence in the direction of the long-run combined effects.

In addition to the model ensemble average, Figure 36 and Figure 37 (bars 2–7) also present the RCP-only cases for yield projections using NZ-RCM outputs based on the six GCMs evaluated in RA1. Results are consistent across individual NZ-RCM outputs suggesting that any uncertainty associated with climate modelling has a relatively small bearing on projected economic outcomes.

LURNZ can also model land use at a relatively high spatial resolution. Figure 38 maps the effect of price changes under SSP3 by visualising differences between baseline and SSP3 land uses in 2100. It shows the location and type of land-use change that is likely to occur given the estimated total amount of land-use change. Land-use responses to price changes are modelled in annual steps, so the maps reflect the dynamics of change. For example, they demonstrate that despite the overall growth in forestry area by the end of the century (Fig. 38), some baseline forestry area is nonetheless lost under SSP3 (mainly in the Central North Island). This is because mid-century price changes under SSP3 lead to some deforestation (Fig. 37), and those areas are not afforested again in the simulations.

In a similar manner to Figure 38, Figure 39 shows the land-use effect of yield changes spatially under RCP8.5 in 2100. These maps therefore identify the areas potentially affected by climate change. Comparing Figure 38 and Figure 39 suggests that the distribution of price and yield impacts differs. The increase in

[7] We are unable to model price effects for horticulture in LURNZ, so horticulture area is assumed to remain constant under SSP 3.



Note: Map on left identifies baseline land use if it is affected by price changes.

Map on right shows corresponding new land use under SSP 3.

Figure 38 Simulated land-use impact of price changes under SSP3 by 2100.

pasture yields tends to be larger in the Northern part of the country, so most of the simulated dairy conversions under RCP 85 take place in the North Island. Without the yield changes, however, a greater proportion of the dairy growth is concentrated in the South Island.

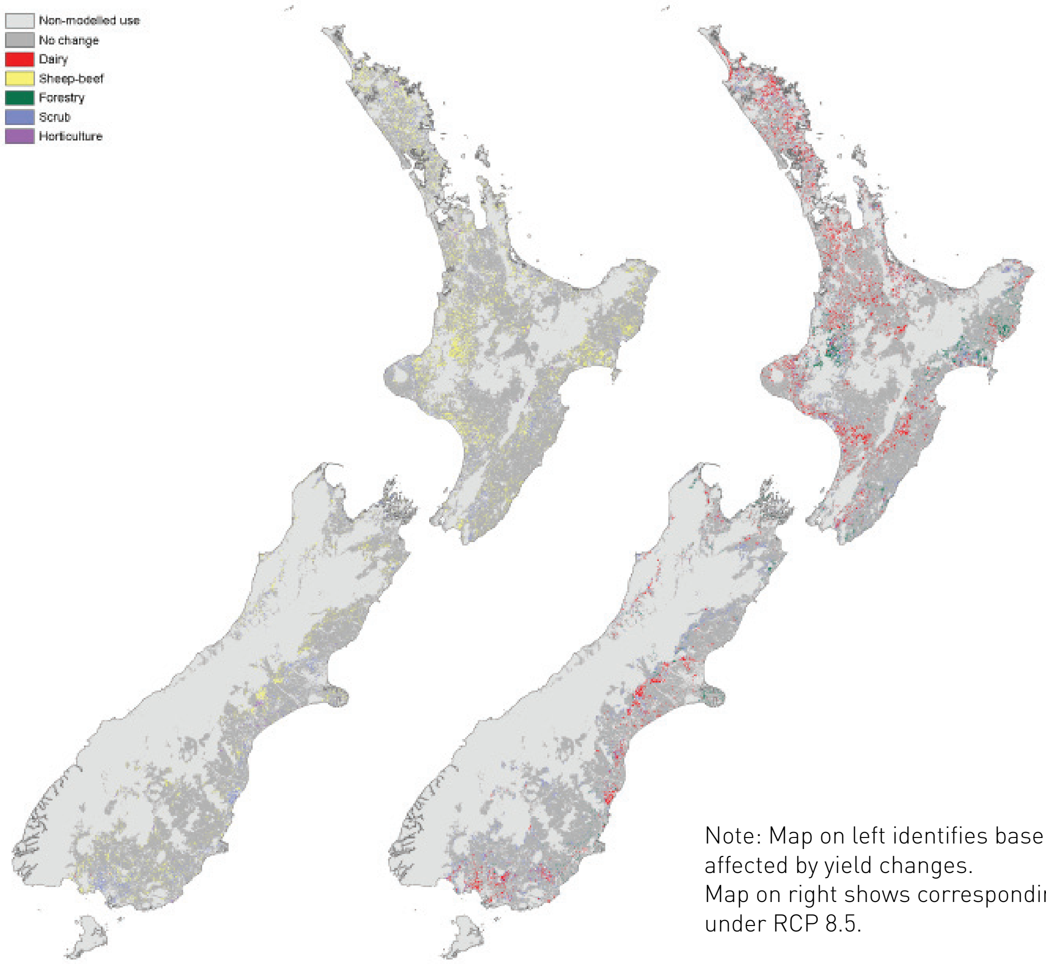
The estimated net price and yield effects may be of comparable magnitude; however, sensitivity testing suggests that economic drivers could be more important in affecting land use. The path of commodity prices under SSP3 causes some of the land-use effects to coincidentally cancel out, but testing shows that the results are sensitive to small changes in prices. We believe the finding on the comparative significance of economic drivers to be robust despite our lack of confidence in the SSP3 simulations.

Implications

Under the baseline, land-use change follows historical trends: dairy and forestry continue to expand, and sheep & beef declines. These projections are driven by SOPI commodity price forecasts.

Climate change under RCP 8.5 further enhances these baseline trends, and the effect grows with time. High sheep & beef prices under SSP3 initially counteract the fall in the sheep & beef area. By the end of the century, however, economic and climate drivers become aligned with both sets of drivers causing dairy and forestry to grow under the combined SSP+RCP case.

The long-term increase in dairy area would put further pressure on New Zealand's water resources and could contribute to increases in the country's atmospheric greenhouse gas emissions. High commodity prices by the end of the century lead to a loss of over half of the New Zealand's scrub area. Some of the potential negative environmental effects could be mitigated by a large increase in forestry area in the second half of the century.



Note: Map on left identifies baseline land use if it is affected by yield changes.
Map on right shows corresponding new land use under RCP 8.5.

Figure 39 Simulated land-use impact of yield changes under RCP8.5 by 2100.

The size of simulated land-use responses is relatively large, but not implausibly large. The adjustment takes place over a long period, and the rate of simulated land use change in LURNZ is in fact much smaller than the rate at which land use in New Zealand has been changing historically.

The choice of climate model seems to be of little consequence to economic outcomes. Land-use change is consistent across (mean) climate projections from the various GCMs.

Forestry & Agriculture – NZ-FARM

Impacts

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 Unspecific Pacific scenario in the following cases: 1) SSP3-only (price effect); 2) RCP8.5-only (yield effect); and 3) combined RCP8.5 and SSP3 (price and yield effect). The model estimated that the greatest change in land use over the different cases is estimated to be between forest plantations and sheep & beef farms. This is because under the RCP 8.5-only case, forest yields increase more than pasture or arable, thereby inducing a shift into pine plantations when all other factors are held equal to the 2015 baseline. However, when the impacts of SSP3 are also accounted for, the large price effects estimated in CliMAT-DGE cause S&B to be relatively more profitable and hence there is a large shift 'back' into that land use, at least for the mid-century estimates. In addition, the large timber price increases over the latter half of the century could potentially reduce the area of dairy in the country. The other land uses tracked in NZFARM, including arable and horticulture, are not estimated to change nearly as much (Figure 40). 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.

The key economic and environmental output estimates for each *Unspecific Pacific* case are summarised in Table 14. These findings indicate that just accounting for the RCP8.5 yield effect results in a relatively small change in aggregate outputs compared with the cases that account for the SSP3 effect. When just accounting for yields, net farm revenue is estimated to increase between 7 and 14%, while reducing freshwater environmental outputs by 1–3%.[8] In all cases when SSP3 is included in the simulation, net farm revenue is estimated to increase dramatically – 259 to 510% over the next century (1.5 to 2.2% per annum) – due to landowners switching to more profitable land uses, producing more output per hectare because of climate-induced yields, and an increase in real commodity prices relative to 2015 (Fig. 40). 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 a result of having a greater number of trees in the country relative to today (and the RCP-only cases). As a result, it could be possible that while environmental outputs increase globally under in the *Unspecific Pacific* scenario, the relative increase in prices and yields could potentially result in local environmental improvements.

SSP-only scenarios (no yield effects)

Yield change estimates were not available for all CCII scenarios, thereby limiting the number of scenarios that could be conducted with NZFARM. However, the potential commodity price impacts were estimated with CliMAT-DGE, including the GHG price required to achieve the global emissions target for each RCP. Based on the findings of the *Unspecific Pacific* scenario (SSP5-RCP8.5-SPA0-SPANZ_A), we hypothesize that model estimates that only incorporate estimated SSP-based price effects are likely much larger than estimates that only include RCP-based yield effects, and also are likely relatively similar to estimates that may have been derived if both SSP and RCP impacts were included in the analysis.

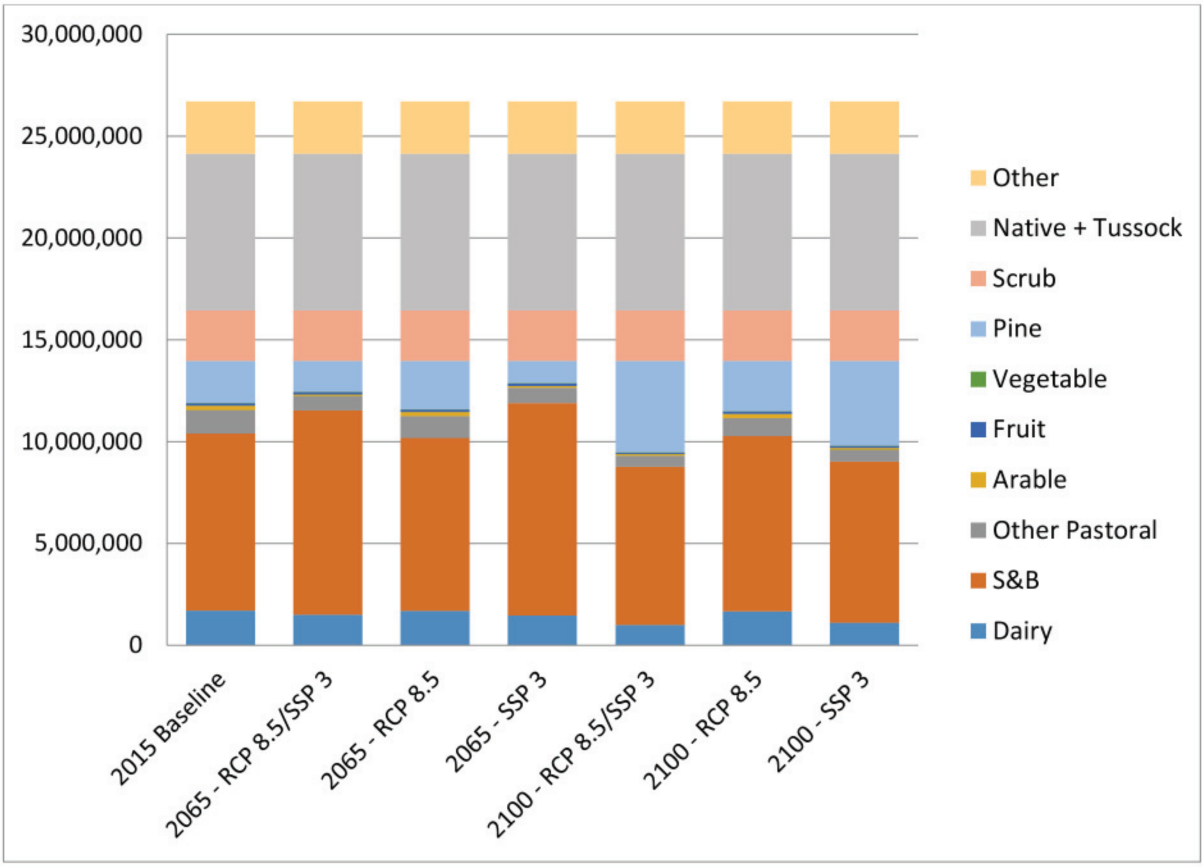


Figure 40 NZFARM estimated land use area (ha) at 2065 and 2100 for the Unspecific Pacific scenario (SSP3-RCP8.5-SPA3-SPANZ_A).

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

Table 14: Summary of key findings for NZFARM analysis (per annum) for the Unspecific Pacific scenario (SSP3-RCP8.5-SPA3-SPANZ_A)

Case	Net Revenue (billion $)	Gross GHG Emissions (megatons)	Net GHG Emissions (megatons)	Nitrogen Leaching (tonnes)	Phosphorus Loss (tonnes)	Soil Erosion (kilotonnes)
2015 Baseline	$11.2	34.4	10.1	215,536	11,780	293,492
			% Change from Baseline			
2065 – SSP3-RCP8.5	271%	12%	93%	−1%	13%	2%
2065 – RCP8.5	7%	-2%	−33%	−1%	−3%	−1%
2065 – SSP3	259%	15%	141%	0%	17%	4%
2100 – SSP3-RCP 8.5	510%	−21%	−276%	−19%	−15%	−4%
2100 – RCP8.5	14%	−2%	-40%	−2%	−3%	−1%
2100 – SSP3	446%	−16%	−232%	−16%	−12%	−4%

The estimated direction of land-use change is relatively consistent across almost all of the cases evaluated for the *Unspecific Pacific* scenario (Figure 41: NZFARM estimated land-use changes (ha) at 2065 and 2100 for the six CCII scenarios arranged by decreasing RCP.). Pine plantations are estimated to increase by 2065 in all but one of the cases (SSP3+RCP 8.5, for reasons discussed above), and by 2100 in all of the scenarios. This is a combination of both an expected increase in timber prices associated with rising global demand. As a result, pastoral enterprises are estimated to experience the largest reduction in area, with sheep & beef often declining by 700,000 ha or more relative to the 2015 baseline area. Dairy is also estimated to be reduced by 500,000 ha or more for most of the scenarios; however, the large increase in the price of milk over the next century potentially results in greater per hectare profits for those farms that continue to operate.

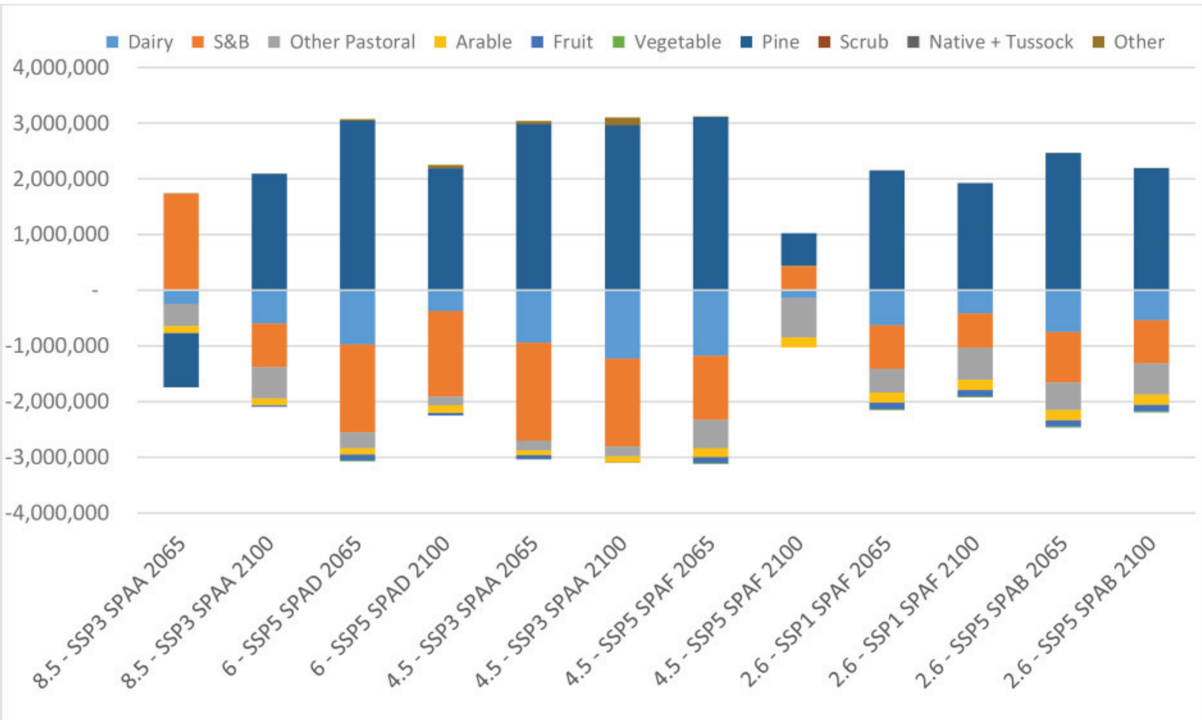


Figure 41 NZFARM estimated land-use changes (ha) at 2065 and 2100 for the six CCII scenarios arranged by decreasing RCP.

The aggregate relative impacts of the price effect relative to the 2015 baseline are estimated to be quite significant, especially in terms of net revenue and GHG emissions (Table 15). Landowners face high commodity prices and thereby adjust their activities accordingly. As a result of the large shift into forestry, NZ's land-use sector becomes a net GHG sink. In addition, the significant increase in pastoral and timber commodity prices results in a net farm revenue increase of 179% or more over the next century relative to 2015, which equates to an annual growth of 0.6 to 4.2%/yr. Further research is needed to assess whether these figures would hold if additional components associated with the scenario narratives developed in RA5 were also incorporated into the model. For example, while we directly incorporated the price estimates from CliMAT-DGE, we did not attempt to model any change in management response that may occur on the New Zealand landscape as a result of living in a SSP3 versus a SSP1 world. One may expect that under SSP3, landowners may be more enthusiastic to plant trees or focus on land-use opportunities that can lower their environmental footprint, especially if there are no clear policy signals being provided by the government.

Table 15: Summary of key findings for NZFARM analysis (per annum), price effect only scenarios ordered by decreasing RCP

Scenario		Net Revenue (billion $)	Gross GHG Emissions (megatons)	Net GHG Emissions (megatons)	Nitrogen Leaching (tonnes)	Phosphorus Loss (tonnes)	Soil Erosion (kilotonnes)
2015 Baseline		$11.2	34.4	10.1	215,536	11,780	293,492
		% Change from Baseline					
Unspecific Pacific (SSP3-RCP8.5-SPA0-SPANZ_A)	2065	259%	15%	141%	0%	17%	4%
	2100	446%	−16%	−232%	−16%	-12%	−4%
Homo economicus (SSP5-RCP8.5-SPA0-SPANZ_D)	2065	179%	−35%	−376%	−26%	−24%	−5%
	2100	944%	−22%	−256%	−14%	−20%	−4%
Kicking, Screaming (SSP3-RCP4.5-SPA3-SPANZ_A)	2065	207%	−35%	−373%	−25%	−25%	−6%
	2100	692%	−39%	−384%	-30%	−26%	−6%
Clean Leader (SSP5-RCP4.5-SPA5-SPANZ_F)	2065	414%	−35%	−382%	−29%	-22%	−5%
	2100	3296%	2%	−40%	−4%	0%	−1%
100% Smart (SSP1-RCP2.6-SPA1-SPANZ_B)	2065	625%	−15%	−231%	−17%	−10%	−4%
	2100	2824%	−11%	−192%	−13%	−9%	-3%
Techno-Garden (SSP5-RCP2.6-SPA5-SPANZ_F)	2065	450%	−21%	−278%	−20%	−13%	−4%
	2100	1878%	−15%	−233%	−16%	−11%	−4%

Implications

Land use in New Zealand is projected to be affected by socio-economic pathways (SSPs), associated policies (SPAs, SPANZs), and climate change pathways (RCP). SSP-SPA-SPANZ effects are likely to cause more dramatic impacts indirectly via price mechanisms operating globally and feeding back to New Zealand via trade and/or mitigation efforts. High log prices cause forestry to increase beyond baseline levels in all six CCII scenarios by 2100 (Fig. 41). The consistent result of an increase in afforestation in NZ by 2100 suggests that environmental outputs such as net GHG emissions and freshwater contaminant loads in New Zealand could be reduced over the next century.

Demographics – National-Regional Cohort Component Model

Impacts

Initial regression modelling identified eight candidate variables for inclusion in the final gravity model specification:

1. Annual precipitation [destination]
2. Mean sea level pressure [destination]
3. Number of days with minimum temperature <0° Celsius [origin and destination]
4. Number of days with maximum temperature >25° Celsius [destination].

5. Potential evapotranspiration [origin and destination]
6. Relative humidity [destination]
7. Surface radiation [origin and destination]
8. Wind speed at 10 metres [origin and destination]

The final parsimonious model included three statistically significant climate variables: 1) mean sea level pressure (MSLP) (destination); 2) surface radiation (SRad) (origin); and 3) wind speed at 10 metres (WS10) (destination). The sign of the effects suggest that MSLP is a positive pull factor, with migrants attracted to areas with higher MSLP. SRad is a negative push factor, with migrants less likely to move away from areas with higher surface radiation (e.g. areas with more sunlight hours). WS10 is a negative pull factor, with migrants preferring to avoid moving to windier areas.

Projecting regional populations to 2100, the model that includes climate variables and the model that excludes climate variables are very consistent for most regions (see Cameron 2017 for full results). The inclusion of climate variables increases the projected populations of Northland, Bay of Plenty, Gisborne, Hawke's Bay, Taranaki, and Nelson.

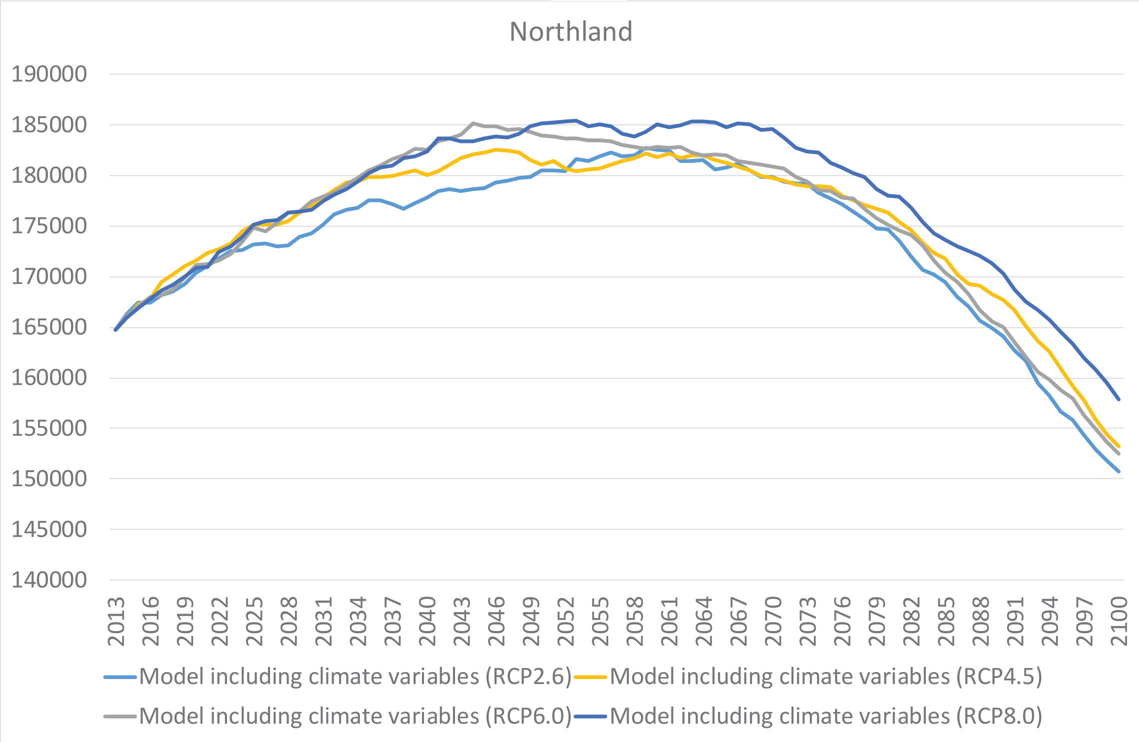
The key results are summarised in Table 16, which shows the 2013 estimated usually resident population (in 000s) for each region, along with the projected populations under the SSP3 scenario for RCP2.6 and RCP8.5. Regardless of RCP, all regions show a similar pattern of initial population growth, followed by later population decline (Table 16). This is a general expected pattern, given that the overall New Zealand population from the IIASA SSP3 projection is projected to follow that pattern, and the projections here are constrained to closely match the IIASA projection in total.

However, there are important differences between the RCP2.6 and RCP8.5 projections. Under the RCP8.5 projections, the projected populations of Northland and Auckland are appreciably higher than under RCP2.6, while the projected populations of Wellington, Canterbury, Otago and Southland are appreciably lower. For other regions, the different RCP scenarios produce projections that are much more similar to each other, illustrating a lack of impact of climate change on the population distribution for these regions.

Table 16: Projected regional populations to 2100 for SSP3-RCP2.6 and SSP3-RCP8.5 scenarios. Regions ordered from north to south. All values in 1,000s of persons

Region		RCP2.6			RCP8.5			△RCP8.5-RCP2.6
	2013	2040	2070	2100	2040	2070	2100	
Northland	164.7	177.9	179.8	150.7	182.4	184.6	157.9	+7.2
Auckland	1493.2	1722.5	1589.1	1279.4	1741.2	1620.7	1309.6	+30.2
Waikato	424.6	491.9	491.2	410.3	492.7	494.5	413.2	+2.9
Bay of Plenty	279.7	331.1	328.6	277.4	331.1	330.8	281.7	+4.3
Gisborne	47.0	53.6	52.8	44.2	53.0	52.8	45.1	+0.9
Hawke's Bay	158.0	174.7	171.1	145.3	170.9	169.3	146.1	+0.8
Taranaki	113.6	120.3	113.2	95.9	120.1	113.9	97.1	+1.2
Manawatū-Wanganui	231.2	257.8	245.8	203.0	253.7	240.5	198.3	-4.7
Wellington	486.7	552.2	502.9	404.4	547.9	490.8	392.6	−11.8
Tasman	48.8	54.4	50.2	41.9	53.0	48.2	40.1	−1.8
Nelson	48.7	56.6	53.2	45.4	55.7	52.7	44.9	−0.5
Marlborough	44.6	51.1	49.2	41.9	50.5	48.1	40.7	−1.2
West Coast	33.0	35.0	32.0	26.8	34.5	31.0	25.8	−1
Canterbury	562.9	630.8	586.1	484.1	626.6	579.8	469.5	−14.6
Otago	208.8	237.7	220.2	176.9	236.1	213.8	170.3	−6.6
Southland	96.0	90.8	74.2	60.6	90.4	70.4	57.0	−3.6

(a)



(b)

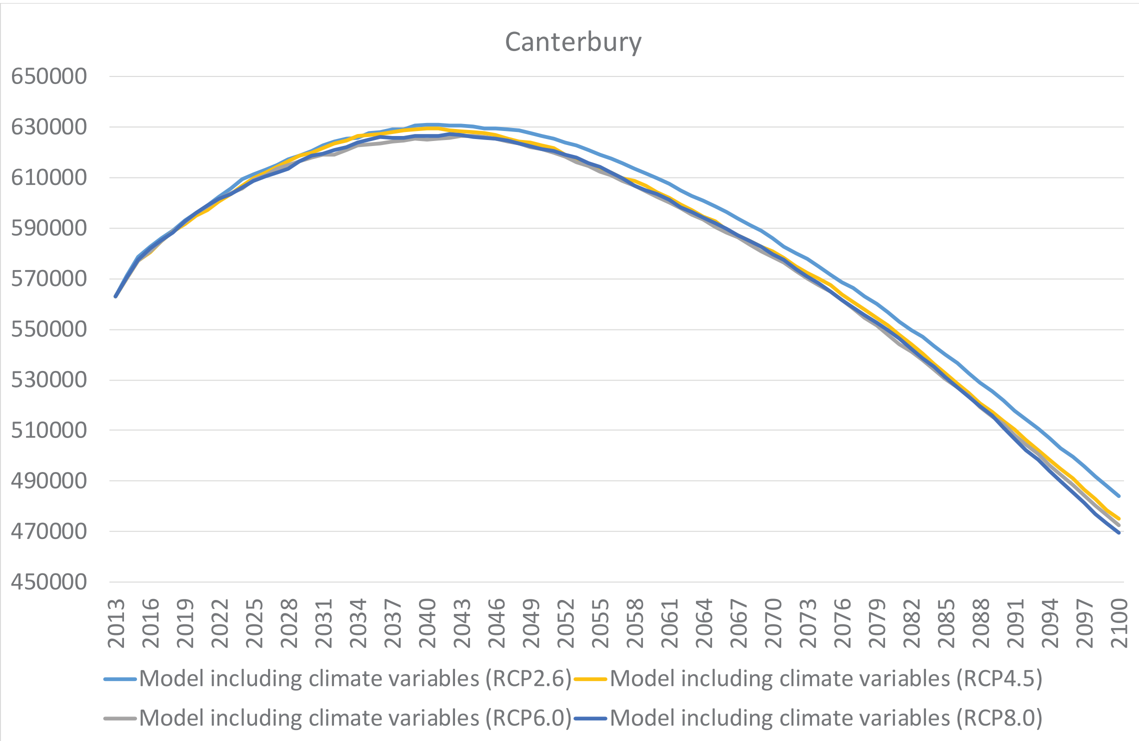


Figure 42 Projections for total population for (a) Northland and () Canterbury under SSP3-based scenarios.

Northland and Canterbury further illustrate the differences in projected populations between all four RCP scenarios (Fig. 42). Differences among the different RCPs are larger in relative terms for Northland than for Canterbury.

Implications

The findings imply that, while climate change will have statistically significant impacts on the population distribution in New Zealand, the size of these impacts at the regional level is small, i.e. ~45,000 out of 3.6 million or ~1.25%.

CONCLUSIONS AND SYNTHESIS

Global Context

This report summarises the results of CCII Research Aim 3, which undertook national loosely-coupled human-natural systems modelling to better understand the potential impacts and implications of climate change for New Zealand's national economy, society and environment out to 2100. RA3 evaluated six scenarios linking global development organised along coupled socioeconomic and representative greenhouse gas concentration pathways with selected aspects of New Zealand development at a national extent.

National systems modelling operated hierarchically. It used global scenario assumptions, including several key quantitative assumptions for New Zealand, as inputs to a suite of New Zealand-based models, added additional New Zealand-specific assumptions, conditions, and considerations, and then modelled resulting future thematic developments both spatially and temporally. Some national system model themes depended only on global assumptions or inputs, while other themes depended upon a mixture of inputs globally and/or via feedbacks from other New Zealand themes/models.

By design, the new global scenario architecture uses a backcasting approach that facilitates formulation of different scenarios by combining one of five socioeconomic pathways (SSPs) and one of four representative concentration pathways (RCPs) (O'Neill et al. 2017). By allowing exploration of different climate change outcomes under different socioeconomic outcomes, the architecture provides more flexibility than the previous (IPCC 4^{th} Assessment Report) generation of global climate change scenarios (Nakicenovic et al. 2000).

The five global SSPs are organised along two broad axes characterising challenges to mitigation and adaptation. Together they paint pictures of five distinct future worlds. SSP1 envisions a world that equitably shares relatively healthy socioeconomic development and can more readily both mitigate and adapt to climate change. SSP2 takes a middle-of-the-road approach in which recent historic global trends more or less continue. SSP3 represents a fragmented world with anaemic economic development and substantial population growth that has trouble both mitigating climate change and adapting to whatever level of climate change eventuates. SSP4 evolves into an unequal world in which poor economic growth among many regions both lowers barriers to mitigation, partly as a by-product of poor economic performance, and challenges adaptive capacity except for an elite few. SSP5's world tends to trade-off climate change for robust economic growth driven by continued reliance on fossil fuels.

Despite their distinctiveness, the five SSPs nonetheless require a degree of similarity and convergence regarding mitigation scenarios with a target RCP of 6.0 or lower. From an energy standpoint, greenhouse gas reduction strategies across mitigation scenarios employ three key tactics in the following order of importance and timing of implementation: 1) reducing total energy use; 2) increasing the proportion of non-fossil fuel sources in the energy mix; and 3) implementing carbon capture and storage.

Regardless of SSP, mitigation scenarios also all assume an operating global carbon market, implemented via SSP-specific shared policy assumptions (SPAs), to help achieve the target RCP (6.0 or lower). While the exact scope of the SPAs vary, the assumption that a global carbon market operates at all (e.g. yes/no) is more plausible for some SSPs than others. For example, an operating global carbon market is more consistent with the broader narratives and assumptions of SSP1's ("Sustainability – Taking the Green Road") inclusive nature and shift towards more sustainable development, but less consistent with those of SSP3's ("Regional Rivalry – A Rocky Road") fragmented, nationalistic nature, lack of global cooperation, and weak global institutions.

Even assuming an operating global carbon market in mitigation scenarios, global scenario study results suggest that achieving a desired mitigation target varies according to broader SSP assumptions and the stringency of the mitigation target i.e. the desired RCP. For example, under SSP1, achieving any mitigation target is highly feasible, given its strong trend towards substantial energy efficiency that reduces total energy demand. SSP3 and SSP5, on the other hand, both have high challenges to mitigation that decrease the feasibility of achieving a more stringent target. SSP3-RCP2.6 and SSP5-RCP2.6 were the only two scenarios evaluated in the global scenario study that had less than a 100% success rate.

From a land-use/cover perspective, cropland area usually increases, and pasture area usually decreases across scenarios. Forest and natural areas show more SSP dependence, largely along lines of challenges to adaptation. Forest area tends to increase for SSP1 and SSP5 (low challenges), decrease for SSP3 and SSP4 (high challenges), and shift from decrease to increase with increasing RCP for SSP2. Other natural land area always decreases under SSP3 and SSP4 (high challenges), almost always decreases under SSP2, and shows both gains and losses for SSP1 and SSP5 (low challenges).

The new global scenario architecture has two key limitations that reflect the design choices. First, it decouples global socioeconomic and climate systems and lacks important feedbacks between them. Impacts and implications of climate change – including for New Zealand – can only be explored indirectly, i.e. by evaluating the feasibility of achieving a particular RCP under a selected SSP. Second, as currently implemented, the new scenario architecture only explores a limited region of the full possible futures space. It specifies a coupled population-economic growth pathway that quantitatively constrains integrated assessment modelling. Other scenarios, such as scenarios with future global economic degrowth achieved either intentionally or unintentionally, remain unexplored.

New Zealand

Within the global context, New Zealand's development trends with the other OECD countries, which broadly track global developments, and always fares economically better than the global average.

New Zealand's economy grows most under SSP5 and least under SSP3, mirroring global trends. Conversely, under SSP5, New Zealand's population becomes highest (nearly 10 million) by 2100 while global population becomes second lowest (~7.5 billion). Under SSP3 global population becomes highest (~12 billion), while for New Zealand it becomes lowest (~3.6 million). For New Zealand, SSP1 and SSP2 show nearly identical trends that rank in the middle both demographically and economically, similar to globally.

Under SSP4, New Zealand becomes relatively better off compared to global circumstances. Whereas global GDP per capita by 2100 for SSP4 ranks fourth among the five SSPs, New Zealand GDP per capita ranks second. New Zealand tracks with the "elites" by virtue of relatively higher (compared with other countries under SSP4) economic growth coupled with relatively lower (compared with other SSPs) national population growth (~5 million by 2100).

Within the assumptions of the broader global context, RA3 loosely coupled human-natural national systems modelling imply that New Zealand has the capacity to anticipate and adapt to a range of variable and uncertain climate outcomes (i.e. RCPs). However, several crucial caveats counterbalance that overall implication and suggest the need for a more cautious interpretation.

We consider RA3 results synthetically following the relationships and flows in the national systems model (Fig. 8), first the climate perspective, i.e. following the flows from the global scenarios along RCPs, and then the socioeconomic perspective along SSPs. We then outline some of the key caveats.

RA1's improved climate modelling, based on the latest round of global climate modelling, reinforces previous findings and refines and enhances others. Overall, New Zealand's climate becomes warmer and more variable, with the magnitude of change increasing with RCP. Other aspects of climate, such as precipitation and wind, show more complex spatial and temporal trends that can vary over finer scales, suggesting they should be considered on a local, catchment or sub-catchment basis rather than on a national or regional basis. Finally, the daily time step of the improved climate projections provide enhanced capabilities for a range of impact modelling, e.g. agricultural productivity.

Nationally, hydrology as modelled by National TopNet responds to climate change by showing overall increased variability (lower low flows, higher floods, lower flow reliability) and some broader spatial and temporal patterns (lower mean flows in the North Island, higher mean flows in the South Island) accentuated with divergent localised trends. Summer soil moisture deficit increases across most of the country, which could have significant impacts for agriculture.

Agricultural productivity showed a broadly positive relationship with climate change due to a combination of the direct impacts of climate combined with possible adaptation. All RA3 models showed a negative impact on productivity due largely to increasing temperature. Crop (maize) modelling (APSIM) demonstrated that adapting sowing dates and new long-cycle genotypes can partly counteract those negative impacts. Forestry (*P. radiata*) (CenW) and pasture (sheep & beef/dairy) (BiomeBGC) productivity modelling suggested that increased CO_2 concentration can induce a fertilisation effect of sufficient magnitude to counteract impacts of rising temperatures and result in a net increase in productivity. Net productivity increases are not necessarily evenly distributed across seasons, e.g. summer feed gaps as modelled by BiomeBGC, which could challenge management when coupled with overall increasing variability.

RA3 also included a novel uncertainty analysis that took advantage of new techniques for producing large climate ensembles developed in RA1 to estimate quantitatively future impacts and implications for fish distributions. The technique shows substantial promise for informing future policy and management by providing more accurate guidance that better quantifies and communicates risk and uncertainty.

Together, the suite of RA3 socioeconomic models (CliMAT-DGE, NZFARM, LURNZ, Demographic Cohort-component) paint a complex picture of how New Zealand might evolve and respond (i.e. SPANZs) under the combined pressures of broader – and, most important, climate change independent – socioeconomic trends (i.e. SSPs) interacting with direct and indirect impacts of climate change (i.e. RCPs) and assumed policy correlates (i.e. SPAs).

From a demographic perspective, population trends for New Zealand are assumed to operate independently of climate change, except for small but significant shifts in internal migration dynamics among regions. Evidence suggests that climate change will not impact either fertility or mortality rates. International migration rates remain the most difficult to model and currently operate free of any influences or impacts of climate change. Internal population distribution shows a northward shift with increasing RCP, although the total effect is small compared to the total population. Under SSP3, RCP8.5 had ~45,000 people from southern regions (Wellington, Manawatū-Wanganui, all of South Island) shifting to northern regions (rest of North Island including ~30,000) re-locating to Auckland) compared with RCP2.6.

CliMAT-DGE modelling provided a critical capability and link between global and New Zealand development. Most important, CliMAT-DGE could model New Zealand developments independently, whereas the global scenario study clustered New Zealand with the broader set of OECD countries. As discussed earlier, while CliMAT-DGE evaluated all six CCII scenarios, only results from the two SSP3-based scenarios (*Unspecific Pacific, Kicking, Screaming*) proved close enough to compare with results from the global scenario study.

For *Unspecific Pacific,* part of the challenge for CliMAT-DGE stemmed from the decision by the CCII team to remain faithful to the original scenario architecture and reproduce the RCP8.5 pathway. That added an additional constraint that was not present in the global scenario study, i.e. global greenhouse gas emissions and therefore radiative forcing in REF-based, non-mitigation scenarios were not required to reproduce the RCP8.5.

Considering those two scenarios, CliMAT-DGE projects a divergent future for New Zealand within the broader constraints and assumptions of SSP3. Both national population and GDP track the prescribed SSP3-based New Zealand trajectory reasonably well. Key differences appear when considering the broad macroeconomic structure and composition. Under *Unspecific Pacific* (SSP3-REF-SPA0-SPANZ_A), New Zealand turns inward, as reflected by the increasing share of domestic household consumption, from 81% in 2007 to 92% in 2097. Both exports and imports increase at about the same rate, with enough of a shift for New Zealand to finish in 2097 with a small positive balance of trade.

In *Kicking, Screaming* (SSP3-RCP4.5-SPA3-SPANZ_A) the New Zealand economy shows a marked structural change. Domestic household consumption declines from 61% to 52%. Exports grow at a similar rate as for *Unspecific Pacific*, but imports decline dramatically after initially rising and finish lower in 2097 ($118.5 million) than in 2007 ($22.5 million). As a result, New

Zealand balance of trade balloons to $118.6 million and represents 48% of GDP by 2097.

NZFARM and LURNZ modelling show that climate change will influence the relative allocations and distribution of rural land uses and farm enterprises directly via climate drivers provided by feedbacks from biophysical models and indirectly via economic drivers that impact future commodity prices and, in turn, relatively profitability among farm enterprises. When considered together, the impact of the indirect economic drivers substantially outweighs the direct climate drivers, implying that the choice of SSP carries more weight than the choice of RCP.

Both NZFARM and LURNZ responded to commodity prices changes by rebalancing the equilibrium among the modelled farm enterprises or rural land uses. In *Unspecific Pacific*, global commodity prices for dairy, sheep/beef, and forestry all increased well beyond their historic range due to increasing demand from a global population of ~12 billion people. Land use responded globally, as evidenced by a noticeable increase in cropland and a small increase in pasture (compared with losses in most other scenarios), and decreases in forest and other natural land.

For New Zealand, LURNZ and NZFARM projections differed somewhat under *Unspecific Pacific*. LURNZ showed gains in dairy and forestry and losses in sheep & beef compared with baseline (2012) values, while NZFARM showed only gains in forestry and losses in dairy, sheep & beef, other pastoral and arable. Both models responded to the large commodity price increases for forestry under *Unspecific Pacific.* Dairy and sheep & beef commodity prices also increased, but not by as large a margin. One potential difference in modelling results could result from LURNZ only taking account of productivity changes to pasture, whereas NZFARM simultaneously takes account of productivity changes to cropping, forestry, and pasture. In particular, NZFARM can take account of the increased P. radiata productivity projected by CenW, whereas LURNZ did not in this analysis. Otherwise LURNZ may have projected even larger gains in forestry area, similar to NZFARM.

Key Caveats

- The RA3 loosely-coupled human-natural systems model lacks important links and feedbacks among the existing components. Examples of critical missing links include:
    - among economic models and productivity models
    - among hydrology modelling (TopNET) and agricultural productivity modelling
    - between demographic modelling and economic modelling
- Modelling did not evaluate or include the availability and feasibility of some potentially important adaptation measures, such as irrigation, which could affect land-use decisions.
- Agricultural productivity modelling did not consider the spatial variability of soils.
- Climate change effects on biotic factors that cause crop damage (insects, pathogens and weeds) were not included in this study.
- Large uncertainties remain regarding crop responses to increasing atmospheric CO_2 (i.e. growth rates and water use) that influence the degree of confidence in the results.
- Nitrogen limitation is also an important aspect of pasture systems that was not fully explored. Nitrogen inputs (fertiliser or clover) vary in time and space, which we were not able to include in this study, and our modelled pasture is not nitrogen-limited. However, if nitrogen levels are depleted or if nitrogen inputs are lower than modelled, our results will likely overestimate production.

FUTURE RESEARCH

Overall

- Develop a strategic national integrated research roadmap outlining: 1) how to improve multi-scale integrated assessment modelling and analysis; and 2) how to plan for, contribute to, and reap the benefits of the next round of global climate change assessment (e.g. IPCC 6th assessment).

- Evaluate technical solutions to improve the coupling and introduce dynamic feedbacks ("strong coupling") where warranted, e.g. evaluate the pros/cons of migrating key models to a common computing platform such as high-performance computing (HPC).

- Improve assessment of uncertainty by via the expanded use of climate ensembles as demonstrated in the fish distribution modelling.

Hydrology

- Incorporate future land-use/land-cover change into TopNet modelling.

- Improve consideration of soil heterogeneity in TopNet.

Socioeconomic including Land-use/Land-Cover Change

- Further develop and refine CliMAT-DGE to improve its performance or the next round of global climate change assessment.

- Incorporate consideration of urban/residential and protected areas land uses in future modelling.

- Enhance feedbacks between NZFARM, LURNZ, and agricultural productivity models.

- Link economic and demographic models.

Agricultural Productivity

- Enhance spatial and temporal representation of agro-ecosystems to take account of heterogeneity of farm enterprises, soils (e.g. via links to Landcare Research's S-map (https://smap.landcareresearch.co.nz/, seasonal variation, water availability including irrigation, etc.

- Enhance understanding and modelling of the feedbacks among the potential CO_2 fertilisation effects, temperature, water availability and nutrient availability, e.g. nitrogen.

- Build modelling capacity that allows flexible incorporation of new knowledge and adaptive capacity such as management interventions in consultation with local stakeholders including farmers, rural communities, iwi, regional councils, etc.

Demographics

- Explore the impacts of extreme weather events on New Zealand population distribution to establish whether increasing incidence or severity of extreme weather events would impact population distribution.

- Re-examine the assumption that that mortality would not be affected by climate change (follow-up research is currently underway).

- Improve the understanding of socioeconomic and climate drivers of international migration and their linkages.

Expansion

In developing the RA3 national systems model, we selected a subset of key models from a much broader range of models that was available from the participating institutions. The next phase of development could expand on the current national coupled human-natural systems model in two ways: 1) identifying and linking additional high-priority models to the suite of existing models, hopefully in a more tightly coupled manner; and 2) allowing more models to contribute to future evaluations and analysis, even if only in a one-way fashion. The recommended national integrated assessment roadmap outlined above can develop the necessary protocols and rules for both expansion pathways.

ACKNOWLEDGEMENTS

The Climate Change Impacts and Implications project was funded by the Ministry for Business, Innovation and Employment under Contract C01X1225 to NIWA and Landcare Research. The authors in particular wish to thank the global integrated assessment and climate change research communities for their on-going efforts to improve our collective understanding and knowledge of the potential impacts and implications of climate change and for striving to make their ideas, methods, data, etc. as transparent and accessible as possible.

REFERENCES

Ausseil A-GE, Bodmin K, Daigneault A, Teixeira E, Keller ED, Baisden T, Kirschbaum MUF, Timar L, Dunningham A, Zammit C, Stephens S, Bell R, Cameron M, Blackett P, Harmsworth G, Frame B, Reisinger A, Tait A, Rutledge DT 2017. Climate change impacts and implications for New Zealand to 2100: Synthesis Report RA2 Lowlands Case Study. Synthesis Report LC2714. Climate change impacts and implications for New Zealand to 2100. MBIE contract C01X1225. 60 p.

Barron MC, Pech RP, Christie JE, Tait A, Byrom A, Elliot G 2016. Climate change impacts and implications: an integrated assessment in the alpine case study. Synthesis Report RA2: Alpine Case Study. The beech forests of New Zealand. Climate change impacts and implications for New Zealand to 2100. MBIE contract C01X1225. 19 p.

Calvin K, Bond-Lamberty B, Clarke L, Edmonds J, Eom J, Hartin C, Kim S, Kyle P, Link R, Moss R, McJeon H, Patela P, Smith S, Waldhoff S, Wise M 2017. The SSP4: a world of deepening inequality. Global Environmental Change 42: 284–296.

Cameron MP 2013. The demographic implications of climate change for Aotearoa New Zealand: a review. New Zealand Population Review 39: 121–142.

Cameron MP, Poot J 2014. Developing a systems-based multi-region stochastic population projections model for New Zealand, presented at the Australia and New Zealand Regional Science Association International 38th Annual Conference, Christchurch, 1–4 December 2014.

Cameron MP 2017. Climate change, internal migration, and the future spatial distribution of population: a case study of New Zealand, Working Paper in Economics 17/03. Hamilton, Department of Economics, University of Waikato.

Clark MP, Woods RA, Zheng X, Ibbitt RP, Slater AG, Rupp DE, Schmidt J, Uddstrom MJ 2008. Hydrological data assimilation with the Ensemble Kalman Filter: use of streamflow observations to update states in a distributed hydrological model. Advances in Water Resources 31(10): 1309–1324.

Collins DBG, Zammit C 2016. Climate change impacts on agricultural water resources and flooding. NIWA Client Report Number 2016114CH prepared for The Ministry for Primary Industries. 71 p.

Daigneault A, Greenhalgh S, Samarasinghe O 2017. Sharing the pie: The dilemma of allocating nutrient leaching between sources. Ecological Economics 131: 449–459.

Dellink R, Chateau J, Lanzi E, Magné B 2017 Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 42: 200–214.

Ebi KL, Kram T, van Vuuren DP, O'Neill BC, Kriegler E (2014) A New Toolkit for Developing Scenarios for Climate Change Research and Policy Analysis. Environment: Science and Policy for Sustainable Development 56, 6–16.

Fæhn T, Isaksen E, Jacobsen K, Strøm B 2013. MSG-TECH: Analysis and documentation of a general equilibrium model with endogenous climate technology adaptations. Statistics Norway Report 47/2013. 48 p.

Fernandez M, Daigneault A 2015. The Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE) model. Landcare Research Contract Report LC2156 prepared for the Ministry for the Environment. 52 p.

Fowler A, Aiken S, Maree K 2008. Vulnerability of New Zealand pastoral farming to the impacts of future climate change on the soil water regime. The University of Auckland Client Report CC MAF POL_2008-21 (128-3)) prepared for the New Zealand Ministry of Forestry and Agriculture. 37 p.

Frame B, Reisinger A 2016. Exploring options for New Zealand under different global climates. Synthesis Report RA5. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. 19 p.

Fricko O, Havlika P, Rogelja J, Klimonta Z, Gustia M, Johnson N, Kolpa P, Strubegger M, Valin H, Amann M, Ermolieva T, Forsell N, Herrero M, Heyes C, Kindermann G, Krey V, McCollum DL, Obsersteiner M, Pachauri S, Rao S, Schid E, Schoepp W, Riahi K 2017. The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. Global Environmental Change 42: 251–267.

Fujimori S, Hasegawa T, Masui T, Takahashi K, Herran DS, Dai H, Hijioka Y, Kainuma M 2017. SSP3: AIM implementation of shared socioeconomic pathways. Global Environmental Change 42: 268–283.

Holzworth DP, Huth NI, Devoil PG, et al. 2014. APSIM – Evolution towards a new generation of agricultural systems simulation. Environmental Modelling & Software, 62: 327–350.

Howden-Chapman P, Chapman R, Hales S, Britton E, Wilson N 2010. Climate change and human health: Impact and adaptation issues for New Zealand. In: Nottage RAC, Wratt DS, Bornman JF, Jones K eds Climate change adaptation in New Zealand: future scenarios and some sectoral perspectives. Wellington: New Zealand Climate Change Centre. Pp. 112–121.

Hurtt GC, Chini LP, Frolking S, Betts RA, Feddema J, Fischer G, Fisk JP, Hibbard K, Houghton RA, Janetos A, Jones CD, Kindermann G, Kinoshita T, Goldewijk KK, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, Vuuren DP, Wang YP 2011. Harmonization of land-use scenarios for the period 1500-2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Climatic Change 109: 117–161.

IPCC 2014. Climate Change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team: RK Pachauri and LA Meyer eds]. Geneva, IPCC. 151 p.

Keller ED, Baisden WT, Timar L, Mullan B, Clark A 2014. Grassland production under global change scenarios for New Zealand pastoral agriculture. Geoscientific Model Development 7: 2359–2391.

Kerr S, Anastasiadis S, Olssen A, Power W, Timar L, Zhang W 2012. Spatial and temporal responses to an emissions trading scheme covering agriculture and forestry: Simulation results from New Zealand. Forests 3: 1133–56.

Kirschbaum MUF, Watt MS 2011. Use of a process-based model to describe spatial variation in Pinus radiata productivity in New Zealand. Forest Ecology and Management 262: 1008–1019.

Kirschbaum MUF, Watt MS, Tait A, Ausseil A-GE 2012. Future wood productivity of Pinus radiata in New Zealand under expected climatic changes. Global Change Biology 18: 1342–1356.

Kriegler E, Edmonds J, Hallegatte S, Ebi K, Kram T, Riahi K, Winkler H, van Vuuren DP 2014. A new scenario framework for climate change research: the concept of shared climate policy assumptions. Climatic Change 122: 401–414.

Kriegler E, Bauer N, Popp A, Humpenöder F, Leimbach M, Strefler J, Baumstark L, Bodirsky BL, Hilaire J, Klein D, Mouratiadou I, Weindl I, Bertram C, Dietrich J-P, Luderer G, Pehl M, Pietzcker R, Piontek F, Lotze-Campen H, Biewald A, Bonsch M, Giannousakis A, Kreidenweisa U, Müller C, Rolinski S, Schultes A, Schwanitz J, Stevanovic M, Calvin K, Emmerling J, Fujimori S, Edenhofer O 2017. Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. Global Environmental Change 42: 297–315.

Law CS, Rickard GJ, Mikaloff-Fletcher SE, Pinkerton MH, Gorman R, Behrens E, Chiswell SM, Bostock HC, Anderson O, Currie K 2016. The New Zealand EEZ and South West Pacific. Synthesis Report RA2: marine case study. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. 41 p.

Lawrence J, Blackett P, Cradock-Henry N, Flood S, Greenaway A, Dunningham A 2016. Synthesis Report RA4: enhancing capacity and increasing coordination to support decision making. Climate Change Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. 74 p.

Ministry for the Environment 2016. Climate change projections for New Zealand: atmosphere projections based on simulations from the IPCC Fifth Assessment. Wellington: Ministry for the Environment. Publication number: ME1247. 127 p.

Ministry for Primary Industry (MPI) 2016. Situation and Outlook for Primary Industries December 2016. Available at: https://www.mpi.govt.nz/about-mpi/corporate-publications/

Mohseni O, Stefan HG, Erickson TR 1998. A nonlinear regression model for weekly stream temperatures. Water

Resources Research 34: 2685–2692.

McBride G, Reeve G, Pritchard M, Lundquist C, Daigneault A, Bell R, Blackett P, Swales A, Wadhwa S, Tait A, Zammit C 2016. The Firth of Thames and Lower Waihou River. Synthesis Report RA2: coastal case study. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. 50 p.

McGlone M, Walker S 2011. Potential effects of climate change on New Zealand's terrestrial biodiversity and policy recommendations for mitigation, adaptation and research. Science for Conservation 312. Wellington, Department of Conservation. 77 p.

Mullan B, Dean S, Stuart S 2013a. How good are the CMIP5 models? Abstract and presentation for New Zealand Climate Change Centre Conference, 4–5 June 2013, Palmerston North. http://www.nzcccconference.org/images/custom/mullan,_bret_-_how_good_are_the_cmip5.pdf.

Mullan B, Dean S, Stuart S 2013b. Validation of 5th assessment global climate models in the New Zealand region. Abstract and presentation for Joint Conference of the NZ Hydrological Society and Meteorological Society of NZ, 19–22 November 2013, Palmerston North. Conference Handbook. Pp. 152–153.

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z 2000. Special report on emission ccenarios. Cambridge University Press. 570 p.

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R, van Vuuren DP 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122: 387–400.

O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Solecki W 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42: 169–180.

PCE 2016 Climate change and agriculture: understanding the biological greenhouse gases. Wellington: New Zealand Parliamentary Commissioner for the Environment. 100 p.

Pomeroy A 2011. Rural community resilience and climate change. University of Otago Center for Sustainability: Agriculture, Food, Energy, Environment prepared for the New Zealand Ministry of Agriculture and Forestry. 101 p.

Popp A, Calvin K, Fujimori S, Havlik P, Humpenöder F, Stehfest E, Bodirsky BL, Dietrich JP, Doelmann JC, Gusti M, Hawegawa T, Kyle P, Obersteiner M, Tabeau A, Takahshi K, Valin H, Waldhoff S, Weindl I, Wise M, Kriegler E, Lotze-Campen H, Fricko O, Riahi K, van Vuuren DP 2017. Land-use futures in the shared socio-economic pathways. Global Environmental Change 42: 331–345.

Riahi K, van Vuuren DP, Kriegler E, Calvin K, Shinichiro Fujimori S, Emmerling J 2015. Integrated assessment modeling of shared socioeconomic pathways – study protocol for IAM runs. 19 p.

Richardson J, Boubee JA, West DW 1994. Thermal tolerance and preference of some native New Zealand freshwater fish. New Zealand Journal of Marine and Freshwater Research 28(4): 399–407.

Rutledge DT, Baisden T, Cradock-Henry N, Keller E, Mason N, Mullan B, Overton JMcC, Palmer D, Sood A, Stuart S, Tait A, Timar T, Vetrova V, Zammit C 2017. Upper Waitaki Catchment/MacKenzie. Synthesis Report RA2: Uplands Case Study. Climate Change Impacts and Implications (CCII) for New Zealand to 2100. MBIE Contract C01X1225.

Samir KC, Lutz W 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42: 181–192.

Samir KC, Potancokova M, Bauer R, Goujon A, Striessnig E 2013. Summary of data, assumptions and methods for new Wittgenstein Centre for Demography and Global Human Capital (WIC) population projections by age, sex and level of education for 195 countries to 2011, IIASA Interim Report IR-13-018. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Tait A, Sood A, Mullan B, Stuart S, Bodeker G, Kremser S, Lewis J 2016. Updated climate change projections for New Zealand for use in impact studies. Synthesis Report RA1. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. 18 p.

Teixeira EI, Brown HE, Sharp J, Meenken ED, Ewert F 2015. Evaluating methods to simulate crop rotations for climate impact assessments – a case study on the Canterbury plains of New Zealand. Environmental Modelling & Software 72: 304–313.

Teixeira EI, Zhao G, Ruiter J, Brown H, Ausseil AG, Meenken E, Ewert F 2016a. The interactions between genotype, management and environment in regional crop modelling. European Journal of Agronomy, http://dx.doi. org/10.1016/j. eja.2016.05.005.

Teixeira EI, Zhao G, Ruiter J, Brown H, Ausseil AG, Meenken E, Ewert F 2016b. Uncertainty due to genotype and management in wide-area maize simulations. International Crop Modelling Symposium, 15–17 March 2016, Berlin.

Thornton PE, Law BE, Gholz HL, Clark KL, Falge E, Ellsworth DS, Goldstein AH, Monson RK, Hollinger DY, Falk M, Chen J, Sparks JP 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. Agriculture and Forest Meteorology 113: 185–222.

Thornton PE, Running SW, Hunt ER 2005. Biome-BGC: Terrestrial Ecosystem Process Model, Version 4.2 Final Release. Missoula, MT, Numerical Terradynamic Simulation Group, School of Forestry, University of Montana, available at: http://www.ntsg.umt.edu/project/biome-bgc (last access: 27 August 2016).

Timar L 2011. Rural land use and land tenure in New Zealand. Motu Working Paper 11–13. Wellington: Motu Economic and Public Policy Research.

Timar L 2016. Yield to change: modelling the land-use response to climate-driven changes in pasture production. Motu Working Paper 16–15. Wellington: Motu Economic and Public Policy Research.

UNPD 2015. World population prospects: the 2015 revision, key findings and advance tables. United Nations, Department of Economic and Social Affairs, Population Division, Working Paper No. ESA/P/WP.241.

van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram V, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith S, Rose SK 2011. The representative concentration pathways: An overview. Climatic Change 109: 5–31.

van Vuuren DP, Riahi K 2017. The shared socio-economic pathways: trajectories for human development and global environmental change. Global Environmental Change 42: 148–152.

van Vuuren DP, Stehfest E, Gernaat DEHJ, Doelman JC, van den Berg M, Harmsen M, de Boer HS, Bouwman LF, Daioglou V, Edelenbosch OY, Girod B, Krama T, Lassaletta L, Lucas PL, van Meijl H, Müllerf C, van Ruijven BJ, van der Sluis S, Tabeaue A 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change 42: 237–250.

Wigley TML, Raper SCB 1992. Implications for climate and sea level of revised IPCC emissions scenarios. Nature 357: 293–300.

Wigley TML, Raper SCB 2002. Reasons for larger warming projections in the IPCC third assessment report. Journal of Climatology 15: 2945–2952.

APPENDIX 1 – CLIMAT-DGE QUANTITATIVE INPUTS

Quantitative inputs used for CliMAT-DGE modelling are provided below, ordered from left to right by decreasing RCP, e.g. from RCP8.5 to RCP2.6 reflecting a gradient of, increasing stringency of the global climate change mitigation target from lowest (RCP8.5 = no mitigation target) to highest (RCP2.6).

GHG Gas Emission Trend

CCII Scenario

Input (Units)	Definition	CCII Implementation	Unspecific Pacific SSP3-RCP8.5-SPA0	Homo economicus SSP5-RCP6.0-SPA5	Clean Leader SSP5-RCP4.5-SPA5	Kicking, Screaming SSP3-RCP4.5-SPA3	Techno-Garden SSP5-RCP2.6-SPA5	100% Smart SSP1-RCP2.6-SPA1
Rate of Global GDP Growth (%)	Rate of GDP growth from one year to another	Specify initial GDP (2007) and annual rate of growth for each region to replicate selected SSP pathway	SSP3 Pathway 1.60% per annum average	SSP5 Pathway 3.07% per annum average	SSP5 Pathway 3.07% per annum average	SSP3 Pathway 1.60% per annum average	SSP5 Pathway 3.07% per annum average	SSP1 Pathway 2.40% per annum average
Rate of Population Change (Number)	Rate of population change in each region/country from one year to another	Specify initial population (2007) and projected rate of change needed to replicate the selected SSP pathway	SSP3 Pathway	SSP5 Pathway	SSP5 Pathway	SSP3 Pathway	SSP5 Pathway	SSP1 Pathway
Economically Active Population (Number)	Number of people supplying labour in a region/country	Specify initial population (2007) and projected rates of change needed to replicate the selected SSP pathway	SSP3 Pathway	SSP5 Pathway	SSP5 Pathway	SSP3 Pathway	SSP5 Pathway	SSP1 Pathway
Productivity – Labour (Ratio-unitless)	Units of sectoral economic output per worker	Specify coefficients to change productivity following SSP, SPA, and SPANZ assumptions	Default	Default	Default	Default	Default	Default
Productivity – Energy (Ratio-unitless)	Units of output by economic sector per unit of energy input (i.e. energy efficiency)	Specify coefficients to change productivity following SSP, SPA, and SPANZ assumptions	Default	Default	Default	Default	Default	Default

GHG Gas Emission Trend

CCII Scenario

Input (Units)	Definition	CCII Implementation	Unspecific Pacific SSP3-RCP8.5-SPA0	Homo economicus SSP5-RCP6.0-SPA5	Clean Leader SSP5-RCP4.5-SPA5	Kicking, Screaming SSP3-RCP4.5-SPA3	Techno-Garden SSP5-RCP2.6-SPA5	100% Smart SSP1-RCP2.6-SPA1
Productivity – Land (Ratio-unitless)	Units of sectoral output per unit of land input	Specify coefficients to change productivity, iteration steps or growth rate following SSP, SPA, and SPANZ assumptions	Default	Default	Default	Default	Default	Default
Productivity – Resource (Ratio-unitless)	Units of sectoral output per unit of resource input over time	Specify coefficients to change productivity, iteration steps or growth rate following SSP, SPA, and SPANZ assumptions	Default	Default	Default	Default	Default	Default
Rate of Technological Change (Ratio-unitless)	Rate of productivity and efficiency change from one year to another	Specify rates of technological change following SSP, SPA, and SPANZ assumptions	Default	Default	Default	Default	Default	Default
GHG Emissions: Output-linked (Ratio-unitless)	GHG emissions per unit of sectoral output over time	Specify coefficients following SSP, SPA, and SPANZ assumptions while replicating the selected RCP	Default	Default	Default	Default	Default	Default
GHG Emissions Factor-linked (Ratio-unitless)	GHG emissions per unit of factor usage over time	Specify coefficients following SSP, SPA, and SPANZ assumptions while replicating the selected RCP	Default	Default	Default	Default	Default	Default
Aggregate Consumption (10 Billion $US2007 Dollars)	Total consumption of goods and services by region over time	Specify 2007 baseline and coefficients to change consumption trajectory over time following SSP, SPA, and SPANZ assumptions	3	3	3	1	3	3
Aggregate Investment (10 Billion $US2007 Dollars)	Total investment on capital formation by region over time	Specify 2007 baseline and coefficients to change investment trajectory over time following SSP, SPA, and SPANZ assumptions	3	3	3	1	3	3

Carbon Market (% below baseline GHG emissions)	Cap on GHG emissions by region over time	RCP8.5 (Carbon Market not operating)	RCP6.0 (Carbon Market Operating)	RCP4.5 (Carbon Market Operating)	RCP4.5 (Carbon Market Operating)	RCP2.6 (Carbon Market Operating)	RCP2.6 (Carbon Market Operating)
Implement GHG mitigation policies following SSP, SPA, and SPANZ assumptions. CliMAT-DGE then endogenously the carbon price needed to replicate the selected RCP							

Agriculture included in Carbon Market (Yes/No)	GHG emissions from agricultural land use included in global carbon market	No	Yes	Yes	No	Yes	Yes
Specify whether to include emissions from agriculture in the global carbon market following SSP, SPA, and SPANZ assumptions							

GHG Mitigation Backstop Technologies (On/Off)	Backstop technologies such as Carbon Capture & Storage (CCS) enter in the model solution if and when they become economically competitive with existing technologies	Off	On	On	Off	On	On
Specify mark-ups, the set of technologies, their timing and their locations where they would be available following SSP, SPA, and SPANZ assumptions.							