Modelling to identify direct risks for New Zealand agriculture due to climate change

Linda Lilburne[a]*, Anne-Gaelle Ausseil[b], Abha Sood[c], Jing Guo[a], Edmar Teixeira[d], Indrakumar Vetharaniam[d], Tony van der Weerden[e], Hugh Smith[a], Andrew Neverman[a], Rogerio Cichota[d], Craig Phillips[e], Patricia Johnson[e], Steve Thomas[d], Robyn Dynes[e]

[a*]*Manaaki Whenua – Landcare Research, New Zealand;* [b]*Ministry for the Environment, New Zealand;* [c]*NIWA, New Zealand;* [d]*Plant & Food Research, New Zealand;* [e]*AgResearch, New Zealand.*

e-mail for the *corresponding author: lilburnel@landcareresearch.co.nz

Modelling to identify direct risks for New Zealand agriculture due to climate change

Climate change will affect New Zealand's diverse range of climatic systems in different ways. The impacts on agriculture are expected to vary with geographical location and the specific biophysical requirements of different crops and agricultural systems. To improve our understanding of these impacts, key biophysical vulnerabilities for the main farming systems in New Zealand were identified and modelled using the daily projected climate scenario data. Results show high spatial variability but a general pattern of suitability ranges for crops moving south, and animal health issues intensifying and also moving south. Sediment loads are projected to increase, particularly in soft-rock hill country areas in the North Island. The modelling approach offers opportunities for analysing the temporal significance of projected changes, such as the timing and duration of drought, the effect on timing of phenological stages, the timing of pasture growth, and the effect on animal farm systems.

Keywords: hazards; vulnerabilities; arable; horticulture; pastoral

Introduction

Background

New Zealand's primary sector is vulnerable to a range of weather-related risks, and this could be exacerbated by climate change, with the prospect of declining yields and profitability, and adverse socio-economic impacts as a consequence of unfavourable changes to temperature and rainfall patterns (Hopkins et al. 2015; Ausseil, Daigneault, et al. 2019; Cradock-Henry et al. 2019). However, climate change could also provide new opportunities to diversify agricultural activities as the climate warms. Although projected temperature warming for New Zealand is less than the global average, change is still expected to have significant impacts because of our mild climate (Manning et al. 2015; Lawrence et al. 2022). These changes could affect agricultural production systems directly through:

- temperature regulation of crop growth and development (Hatfield & Prueger 2015) as well as soil-based processes that support plant growth (Orwin et al. 2015),
- altering rainfall patterns (Snyder 2017), and
- more acutely by modulating the virulence of pests and disease (Jones 2016; Trębicki et al. 2017; Wakelin et al. 2018; Mansfield et al. 2021).

Climate change will affect New Zealand's diverse range of climatic systems in different ways, with impacts on agriculture expected to vary with geographical location and the specific requirements of different crops and agricultural systems (Warrick et al. 2001; Clark et al. 2012). Under climate change some areas may become less suitable for certain crops or farm systems, but new opportunities may arise elsewhere where low temperatures currently limit crop growth. Given the large spatial variability and crop specificity of impacts, farm systems may need to adopt locally tailored adaptation strategies to minimise risks and become more resilient. Information on the projected effects of climate change is essential for timely adaptation, including the option of land-use change (Clark et al. 2012).

We use the Intergovernmental Panel on Climate Change risk framework and definitions of hazard, vulnerability, exposure and risk (Fig. 1; Openheimer et al. 2014) to help ensure a comprehensive assessment of the effects of climate change on agriculture. There are interactions between the various physical climate *hazards* (events and trends) and the *vulnerability* of the range of agricultural crops and farm systems in New

Zealand. For example, the climate *hazard* of changing patterns in rainfall may be more or less risky depending on the *vulnerability* or sensitivity of a cropping system to the intensity or timing of drought or excess moisture. Similarly, changing rainfall patterns may alter *exposure* in locations where access to irrigation water is not reliable, thus increasing the risk of drought. Interactions between hazard, vulnerability, and exposure, the spatial and temporal variability of the climate response, and the uncertainty in the projections mean that modelling approaches are needed to gain an understanding of climate change impacts on agriculture in New Zealand.

Risk framework

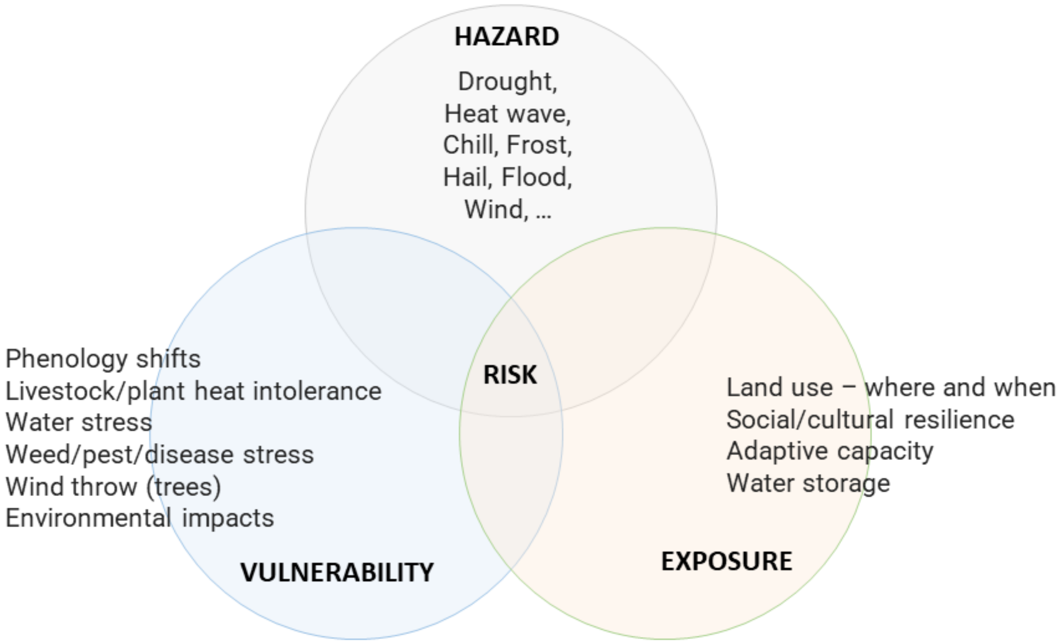

Figure 1. Risk framework (adapted from Oppenheimer et al. 2014)

Because our focus is on understanding future land-use suitability, we have limited our work to the hazard and vulnerability components. We have not considered the exposure component because that would imply understanding actual current (and future) land uses and infrastructure, as well as the socio-economic-cultural context in New Zealand. We identified a set of hazards affecting vulnerabilities relevant to New Zealand agriculture, which functioned as an assessment of potential risks and opportunities (Table 1). These have been identified through consultation with experts and stakeholders (Ausseil, Weerden, et al. 2019).

The risks focused on the physical impacts of climate change and were categorised according to the Task Force on Climate-related Financial Disclosures (TCFD[1]) into chronic risks (based on long-term shifts in climate patterns) and acute risks (event-driven risks such as extreme events). A biophysical modelling approach was then used to quantify these risks. Note that we focused on direct risks rather than indirect risks such as damage to infrastructure, regulations, or change to markets. Although this paper presents a selection of model outputs, we have also pointed to some other research outputs for New Zealand that have been published in the last 15 years.

[1] https://www.tcfdhub.org/Downloads/pdfs/E06%20-%20Climate%20related%20risks%20and%20opportunities.pdf

Table 1. Model outputs for some hazard and vulnerability risks to New Zealand agriculture (: discussed in this paper; yellow cells: available from https://landuseopportunities.nz/; italics: other research outputs). ap = apple, av = avocado, bl = blueberry, ch = cherry, cn = chestnut, ki = kiwifruit, ma = maize, on = onions, pe = peas, po = potatoes, wh = wheat, wi = wine grape.*

			VULNERABILITY				
CHRONIC RISKS (long-term shifts)	HAZARD	Sub-category	Arable	Horticulture	Pastoral: sheep	Pastoral: dairy	forestry
Water quality	Changes in magnitude/frequency of rainfall	Sediment loss	*Change in sediment yields (NZ and case study)				
	Changes in temperature and rainfall	Nutrient loss			*Nutrient (case study) (Ausseil, Weerden et al. 2019)*		
Changes in yield & timing	Changes in seasonal temperature & variability in precipitation		*Change in phenological stages (NZ)(ma) *Crop rotations (Teixeira et al. 2018)*	*Change in crop suitability (ap, av, bl, ch, cn, ki) Change in phenological stages (wi)	*Change in pasture production (ryegrass/white clover)		*Change in wood biomass (NZ) (Kirschbaum et al. 2012)*
					Change in perennial ryegrass (Babylon et al. 2023)		
Water availability	Changes in water supply		*Change in mean annual flow (Collins & Zammit 2016)*				
	Changes in precipitation					*Change in soil moisture (Garcia et al. 2021)*	
Sea-level rise	Changes in ocean temperature		*Sea-level rise projection maps (www.searise.nz)*				
Pests and disease	Changes in humidity and temperature		*Change in plant diseases (Wakelin et al. 2018)*		*Change in facial eczema, barber's pole worm risks	*Effect on biological systems (Gerard et al. 2013) Effect on grass endophytes (Hewitt et al. 2021)*	*Disease damage (Wakelin et al. 2018; Watt et al. 2019)*
ACUTE RISKS (event - based)	HAZARD	Sub-category	Arable	Horticulture	Pastoral: sheep	Pastoral: dairy	forestry
Heat stress	Changes in extreme temperature	Duration	*Heat stress indices (ma, on, pe, po, wh)			*Dairy cattle heat stress	
Frost	Changes in seasonal temperature	Timing	*Frost risk indices (on, pe, po)	*Frost risk indices (ch)			
Extreme rainfall	Changes in extreme rainfall	Timing	*Extreme rainfall risk (on)				
Drought	Changes in rainfall and evapotranspiration demand	Timing, magnitude	*Change in monthly water demands (ma)		*Change in monthly water demand (pasture)		
Wildfire	Changes in dry conditions						Forest fire danger
Wind	Changes in extreme wind						*Wind damage (Watt et al. 2019)*

Methods

Climate projections

Climate projections for New Zealand were dynamically downscaled from the best-performing global general circulation models (GCMs) of the Coupled Model Intercomparison Project Phase 5 (CMIP-5) archive generated for the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC-AR5, IPCC 2014). The six best-performing representative models for the New Zealand region were chosen for use in impact studies (Ministry for the Environment 2018). They are: HadGEM2-ES (UK), CESM1-CAM5 (USA), NorESM1-M (Norway), GFDL-CM3 (USA), GISSE2-R (USA), and BCC-CSM1.1 (China). Each model was bias-corrected and downscaled to the National Institute of Water and Atmospheric Research (NIWA) 5 km Virtual Climate Station Network grid (Sood 2014; Ministry for the Environment 2018). The downscaled data, including uncertainties, have been comprehensively analysed by the Ministry for the Environment (2018). For computational reasons, the sheep facial eczema analysis described in this paper used one GCM (HadGEM2-ES), and the pasture production analysis used three GCMs. The horticultural analyses in this work used a different bias correction approach, as described by Vetharaniam, Timar et al. (2022).

In line with IPCC-AR5, four scenarios of future greenhouse gas (GHG) emissions, or representative concentration pathways (RCPs), were selected. They are (in order of increasing atmospheric GHG concentrations) RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. RCP 2.6 is a low-end scenario consisting of aggressive emissions reductions and/or CO_2 removal from the atmosphere. On the other end of the spectrum, RCP 8.5 is a high-end, worst-case scenario, with no mitigation of global GHG emissions, which would result in a global mean temperature increase of as much as +4°C by 2100 (IPCC 2014). RCP 4.5 and

6.0 are in between these two extremes. The RCP 8.5 scenario, though not very likely under current socio-economic and no-policy assumptions, is a good illustration for a worst-case scenario that, given the high amount of uncertainty in carbon cycle feedbacks and socio-economic conditions, policy makers and farmers should consider when planning for future change (Kemp et al. 2022). We aim to provide results for all four RCPs. Projections of minimum and maximum temperature, precipitation, solar radiation, relative humidity, mean sea-level pressure, and average wind speed are available at a daily time-step.

Models

Different modelling approaches of contrasting complexity were selected to address identified risks, reflecting the available data and knowledge to assess specific climate change impacts (Table 2). We used six types of models with various degrees of complexity. The low complexity types (1 and 2) are quick to run in response to average climate inputs. Low-to-medium complexity models (types 3 and 4) involve expert knowledge and more spatially explicit data inputs. More complex models (types 5 and 6) involved mechanistic models (simplified dynamic to detailed, respectively) that can be challenging to run when simulating crop-soil-water processes on a daily time-step. Complex models are more likely to be able to represent the interactions between plants, soils, and the environment. They can also inform more detailed quantitative outputs, such as yield, timing of phenological stages or water deficit, contingent on accurate specification of the model parameters. Most of the models were run on the high-performance computer (HPC) infrastructure for computational and/or climate data storage reasons.

The models were applied to all of New Zealand using the climate projection data described above and soil information from S-map (Manaaki Whenua – Landcare Research 2020b) and the Fundamental Soil Layers (Manaaki Whenua – Landcare Research 2020a), as required. The 5 km grid underpinning the climate data means that the risk estimates are limited in spatial detail. They can be used at the district scale and above, but further information would be needed for use at the farm scale.

Table 2 Types of models used in the climate change assessments.

Complexity	Type	Description	Risks/impact	Type of risk
Low	1. Simple climate attribute metrics	Uses knowledge of temperature thresholds for specific crops	Crop heat stress; grow degree days (GDD); frost risk	Chronic, acute
Low	2. Data-driven empirical model	Uses available data to derive an equation for current day, which future climate is then applied to	Sheep facial eczema; barber's pole worm; dairy cattle heat stress	Chronic, acute
Low-medium	3. Rule-based model	Uses expert knowledge to derive suitability indices based on rules	Change in suitability, yields	Chronic
Low-medium	4. Conceptual/ empirical model	Combines empirical models with expert knowledge	Water quality – sediment; change in wine phenological stages	Chronic
Medium	5. Simplified dynamic model	Combines knowledge to create simple mechanistic models where change in the timing of phenology stages due to temperature is also accounted for	Change in timing; drought	Acute
High	6. Mechanistic model	Uses a complex mechanistic model (APSIM[a]) with future climate data	Ryegrass/white clover pasture yield	Chronic

[a] https://www.apsim.info/

Results

Results from the modelling are presented below, by sector. All of the GIS layers mentioned below (and more) can be accessed from the Whitiwhiti Ora Data Supermarket at https://landuseopportunities.nz/.

Arable sector

Using the simple type 1 model, thresholds and sensitive periods were identified for up to three hazards (heat stress, frost risk, extreme rainfall) for six crops: maize, wheat, onions, peas, potatoes, and chestnuts, based on defined date ranges in a simplified representation of the sensitive period. Heat stress is becoming more of an issue (Figure 2). For example, on the Canterbury plains there is projected to be a mean increase of approximately six extra days per annum in which loss of yield could occur. Conversely, the lowering risk from frost damage means there will be new opportunities in some areas to plant crops such as onions, peas, and potatoes.

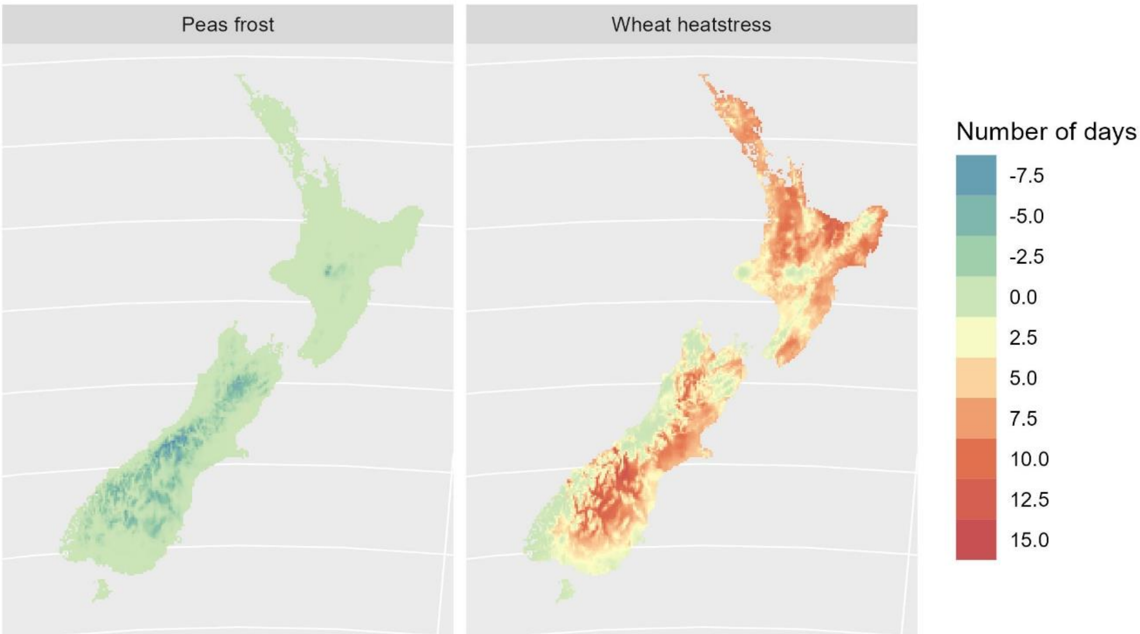

Figure 2. Change in risk of frost (peas) and heat stress (wheat) from a baseline (1985–2005) to a future climate (RCP 4.5, 2040–2060). Note that these risk maps must be used in conjunction with crop suitability maps that account for other climatic and soil requirements (see https://landuseopportunities.nz/).

A more mechanistic representation of the response of plants or animals to increasing temperature (model type 5) enables the development of risk indices where changes in the timing of key phenological stages can be included. For example, crops may mature sooner, leading to a change in the period when rainfall or irrigation water is critical (Figure 3). This figure indicates that maize grain cropping may become more viable in southern regions as temperatures increase. Previous work with mechanistic models (model type 6) has shown similar patterns (Rutledge et al. 2017), with the crop also becoming more suitable at higher altitudes (Teixeira et al. 2018). This is a result of an increase in the growing season length as well as increases in daily temperature, with a reduction in the proportion of years with failed crops due to insufficient thermal units to complete the productive cycle, reflected in reduced inter-annual variability.

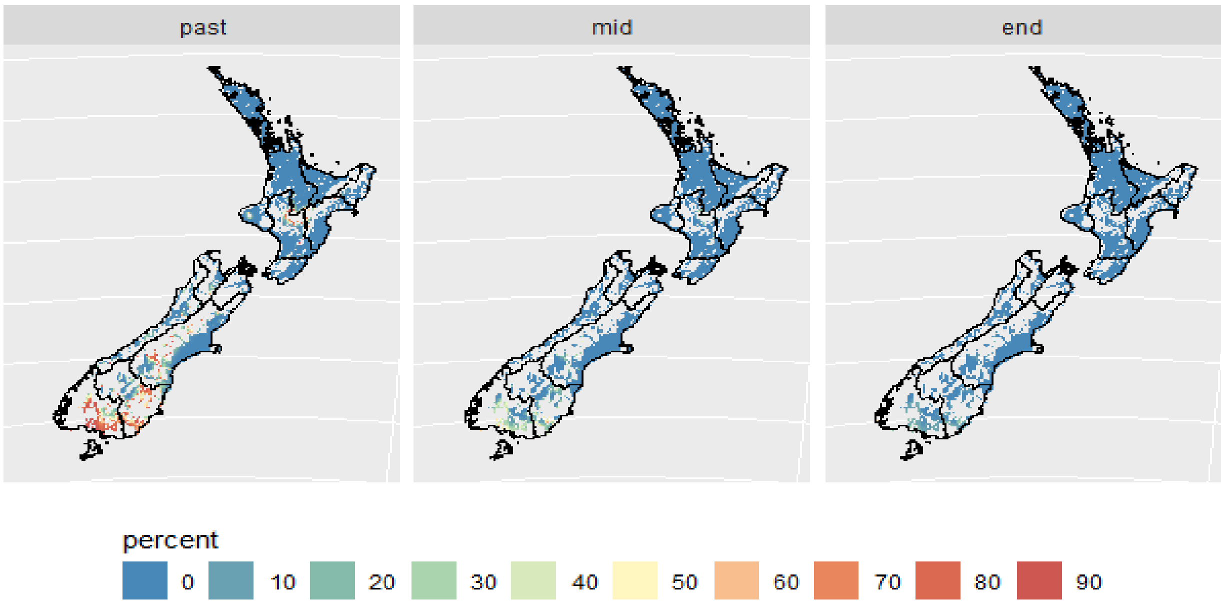

Figure 3 The percentage of 20 years where the maize silage crop did not reach maturity under baseline past (1981–2000), mid-(2041–2060), and late century (2080–2099) under RCP 4.5.

Sood et al (in prep.) describe how they modified a simple Food and Agriculture Organization (FAO) water balance model to estimate water deficit (potential evapotranspiration deficit – PED) in maize crops and accumulate the water deficit over the period of growth and water demand, which varies according to the timing of the phenological stage. Figure 4 shows how the peak period of water demand by maize crops occurs earlier in the season for more intense warming scenarios and late time-slices in the century (e.g. more demand in December for RCP 4.5 than in the past).

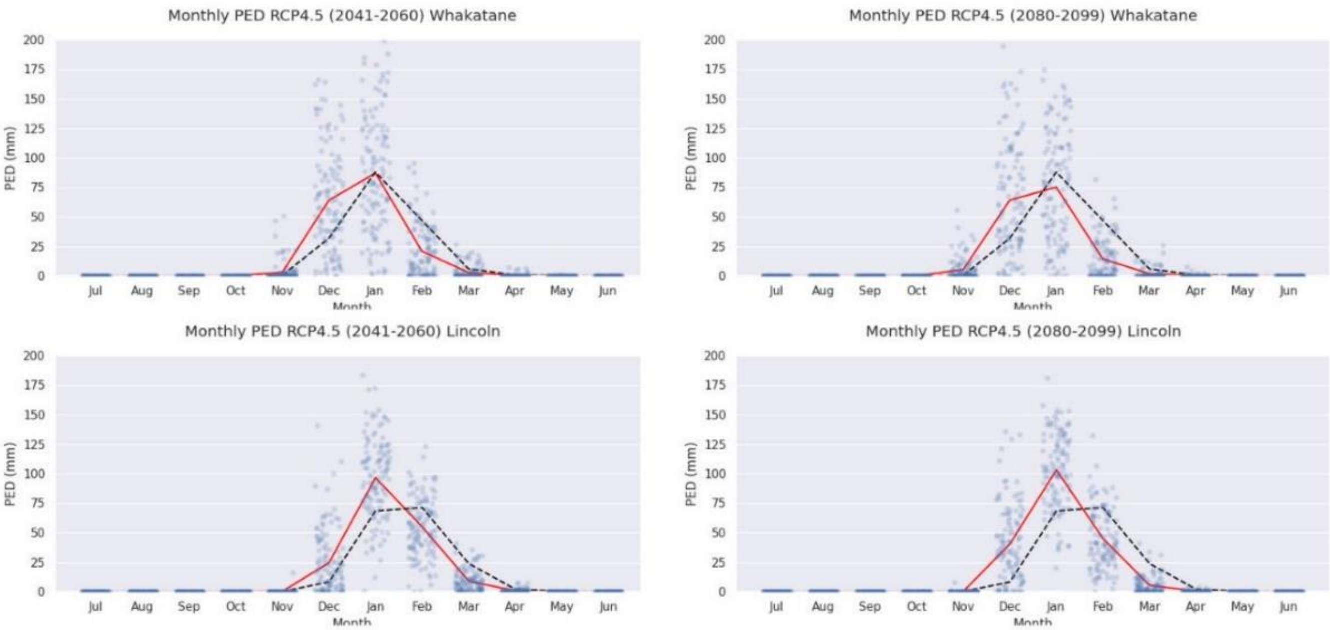

Figure 4 Monthly demand of maize crops for water at two locations (Whakatane RCP 4.5 and Lincoln RCP 4.5), and two time-slices (mid- and end of century). The dashed black line is the demand in the baseline past (1981–2000); the red line is the mean demand under RCP 4.5. The grey dots indicate the variability across the 20 yr period and the six climate models.

Horticultural sector

Rule-based models (type 3) using a continuous or fuzzy logic approach (Vetharaniam, Müller et al. 2022) that could be discretised were linked to the climate change projection information cover the following crops: apple, avocado, blueberry, cherry, kiwifruit, and two wine grapes. Phenology was modelled (type 5 approach) for some crops depending on data availability to establish risk windows and how they might change. The model outcomes indicate a similar pattern of crop suitability moving south with time, while some previously suited land becomes less suited or unsuited (

Figure 5).

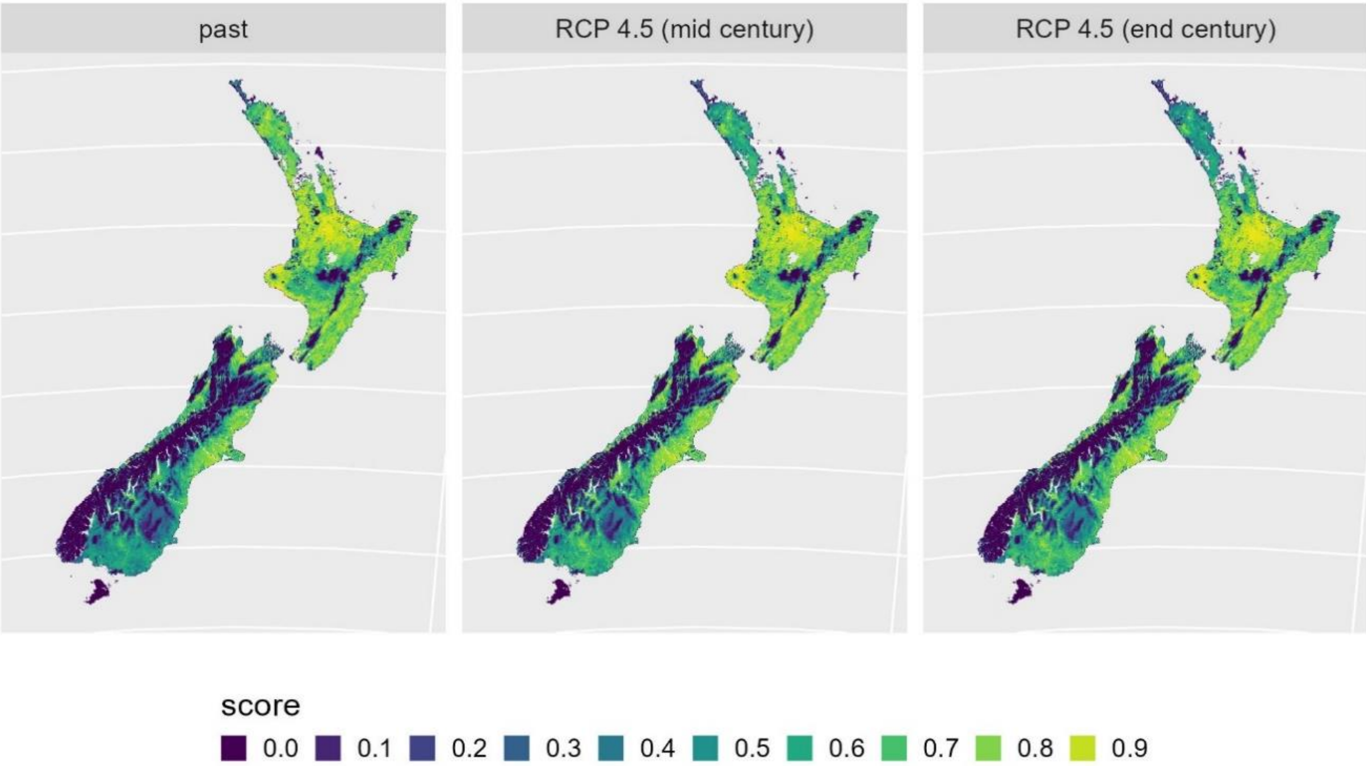

Figure 5. Suitability scores (0 = poor, 1 = good) for apples at the baseline period (1972–2004), mid-century (2028–2058), and end of century (2068–2098) under RCP 4.5.

In another study on the impacts for viticulture, empirical models were combined with an expert assessment of the dominant process (type 4). For instance, expert knowledge about the influence of temperature on phenological stages was used to create an empirical model that helped project future flowering times for wine cultivars (Ausseil et al. 2021). This work showed that the phenological timing of bud burst and ripening was likely to advance, and that the timing between these stages varied among cultivars. This implies that different regional cultivars might ripen within a smaller window of time, complicating harvesting schedules across the country. It also suggested that New Zealand could consider either moving cool-climate cultivars further south (e.g., Sauvignon Blanc, Pinot Noir, and Merlot), or using more late-ripening cultivars (although this would change the nature of the wine produced).

Pastoral sector

Phillips et al. (2023) describe the empirical work for the type 2 model developed for predicting the risk of *Pseudopithomyces chartarum* sporulation in pastures, which can cause facial eczema in sheep (Figure 6). The historical occurrence of facial eczema was related to temperature and rainfall, then predictions were made. Even under RCP 2.6 the suitability for *P. chartarum* sporulation will increase with time in most regions, particularly in the North Island. The suitability for *Haemonchosis contortus*, a highly pathogenic intestinal nematode that affects sheep and cattle health, is similarly predicted to increase in the North Island and extend further south with time (Sauermann et al. in prep).

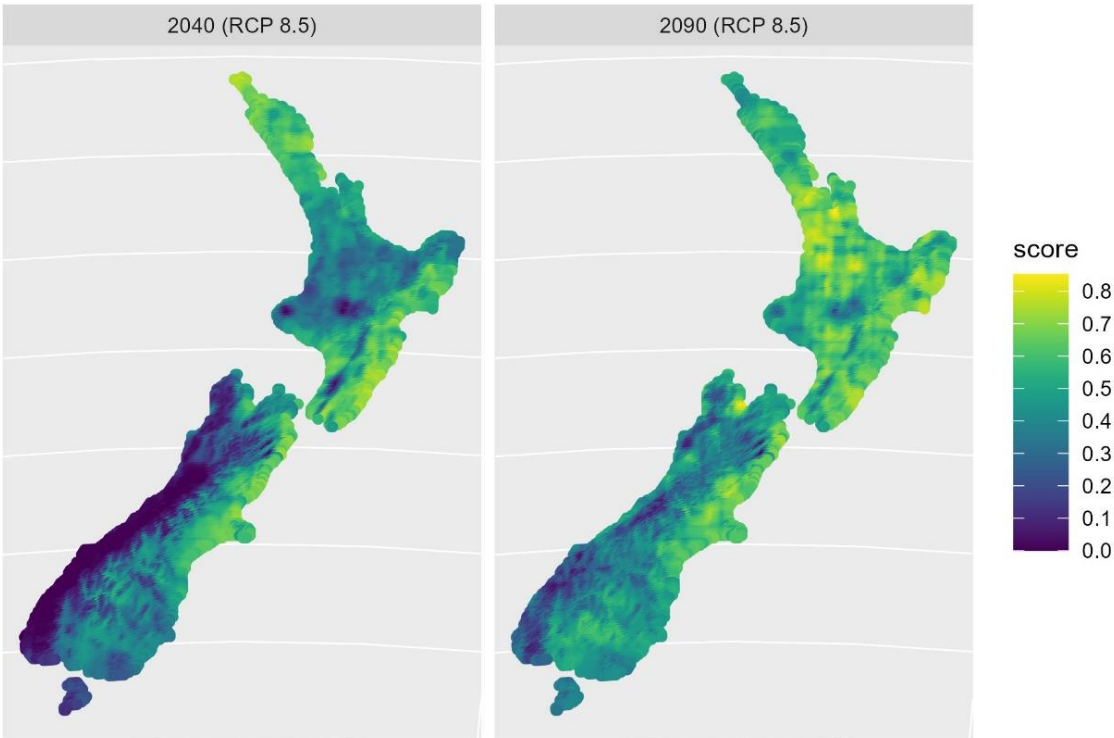

Figure 6. Predicted climate suitability for facial eczema in 2040 and 2080 under HADGEM2 emissions scenario RCP 8.5.

A simple temperature humidity index (Davis al. 2003) was generated, indicating increasing risk of heat stress for dairy cows for all RCPs. Another research project is developing a more specific model of the impact of heat stress on dairy production and economics.[2]

As with maize, above, we have run our simple mechanistic FAO model with pasture to assess the changes in drought conditions. The rainfed simulation shows increasing drought in the North Island in the summer, but spatially more variable impacts in the spring and autumn.

APSIM (model type 6) was set up to simulate a ryegrass/white clover sward with and without fertiliser and irrigation (N fertiliser varied with plant demand and was capped at 200 kg N/ha/yr and near-optimal irrigation). All RCPs have been run, but only for three GCMs (due to the computation demand). The output consisted of estimates of average potential yield over 20 yr periods (Figure 7). The simulations used the standard AgPasture model set-up (with default parameters) describing a rotational defoliation (triggered by pasture biomass), with no management limitations and minimal inefficiencies. The simulations assumed no nutritional deficiencies other than N and neither the occurrence of any pest or disease. The model has been tested under New Zealand conditions and including climate variations (Li et al. 2014; Vogeler & Cichota 2016; Cichota et al. 2018), but the simulations run for this work did not include changes in pasture species and may have underestimated the effects of increased temperature. Also, no adjustments were made to account for the effects of topography (slope and aspect) and thus the predictions for hilly areas have greater uncertainties.

[2] https://deepsouthchallenge.co.nz/resource/dairy-nz-matamata-piako/.

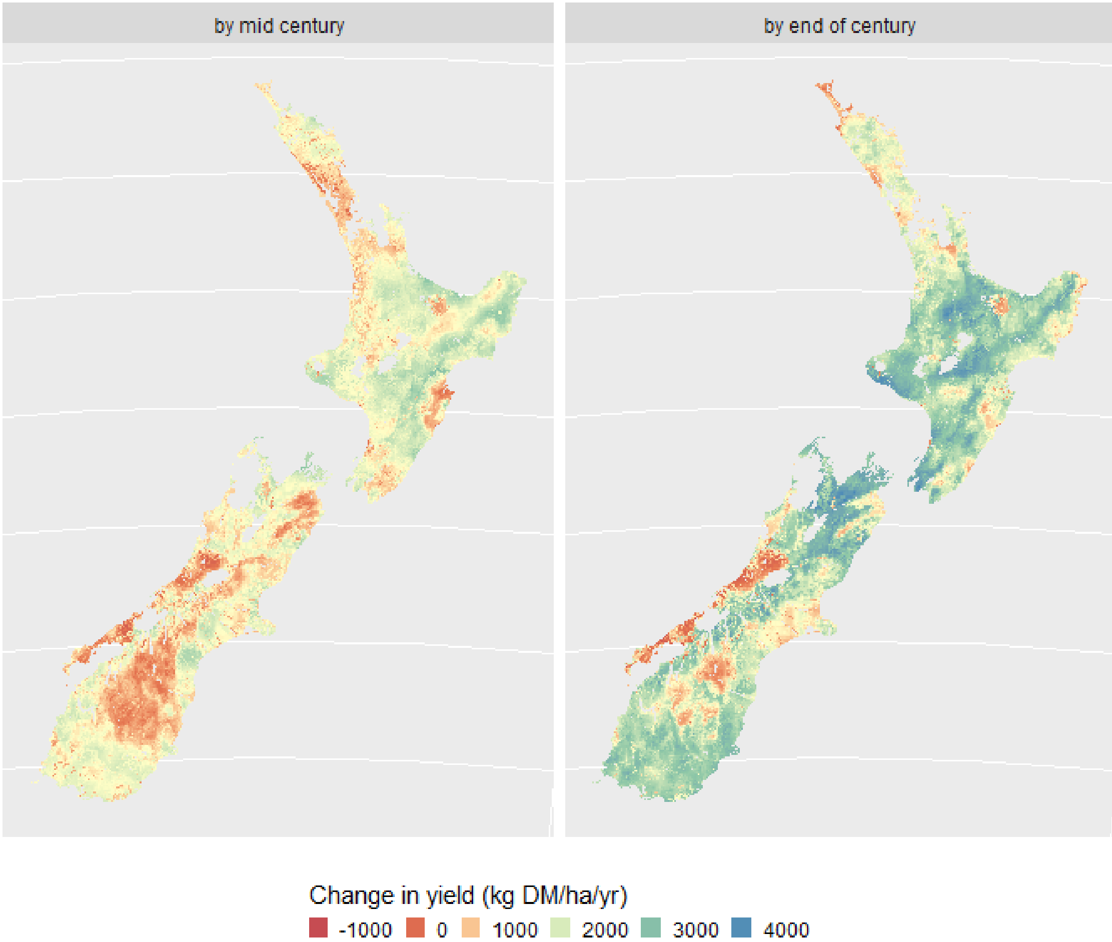

Figure 7. Projected changes in pasture yield (rainfed, no fertiliser) under RCP 6.0.

Dominant erosion processes were modelled in a type 4 approach to predict the changes in sediment yields (Neverman et al. 2023). The study demonstrated a disproportionate increase in mass movement erosion expected in soft-rock hill country (Figure 8), with <1–28% of North Island watersheds and <1–8% of South Island watersheds estimated to experience a 100% increase in sediment yield by end of century, primarily driven by the impact of increasing storm magnitude frequency on mass movement erosion. This results in regional increases in sediment load delivered to the coast, ranging from 1 to 233%.

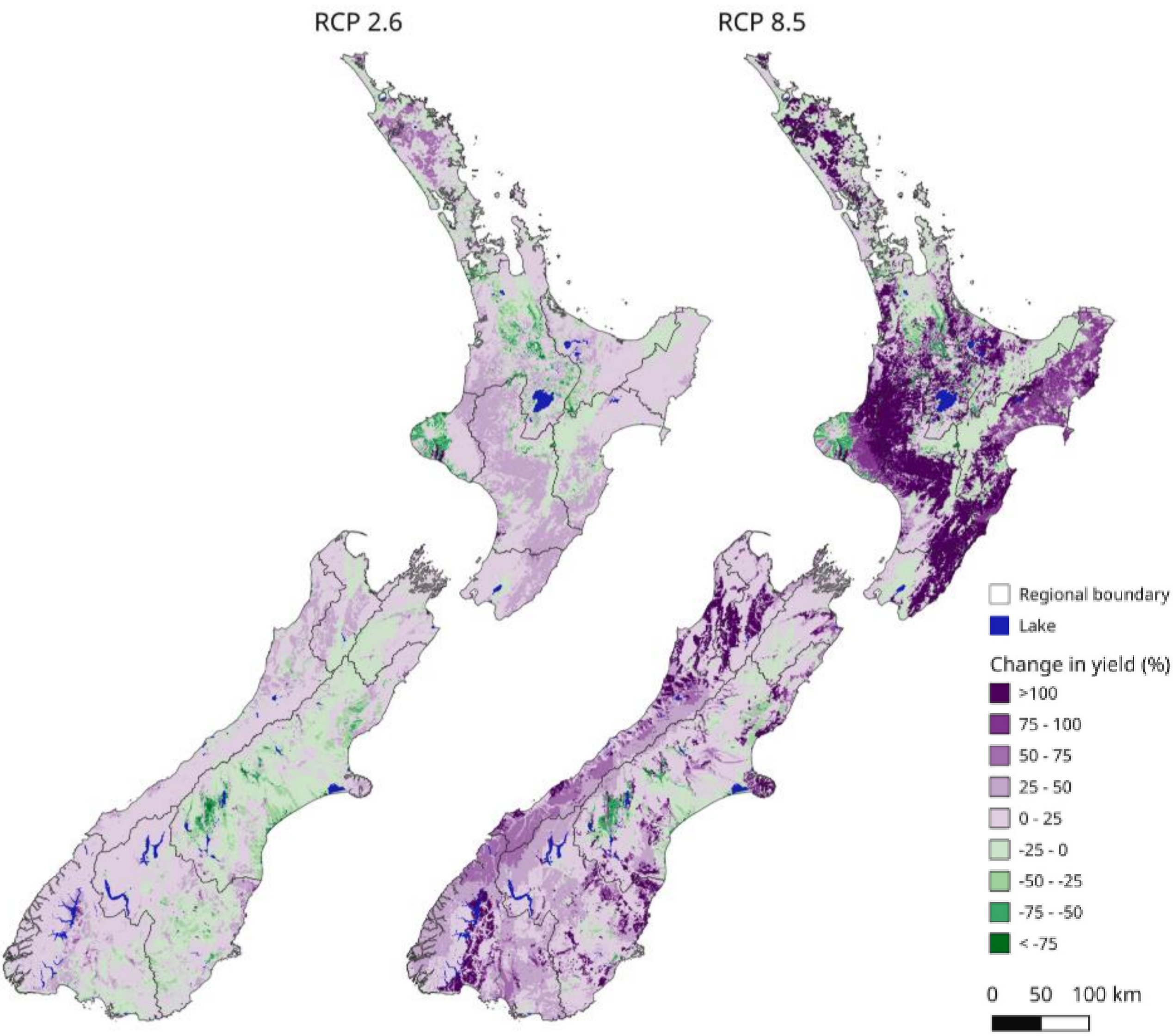

Figure 8. Median proportional change in total sediment yields across the six GCMs for the North Island and the South Island under RCP 2.6 and RCP 8.5 by 2090.

Discussion

Climate projections

A key advance described in this study is to use spatially resolved daily time series in the modelling. The high-resolution climate change maps of the climatological averages of key climate variables (e.g. temperature, precipitation) based on CMIP-5 future climate projections are available from the NIWA websites.3 These climatological averages are not suitable for generating more comprehensive information on the crop life-cycle changes, such as shifts in flowering and subsequent impacts on yields. Even though these maps represent extreme events (e.g., climatological changes in drought frequency and intensity, 99-percentile rainfall, and heatwaves), they are not informative enough to comprehensively determine event-driven risks such as heatwaves, cold spells, or floods. Note, however, that even in the daily time series we have only a limited representation of the extreme events that are, by their nature, exceedingly rare in the short (20 yr) time slices of non-stationary climate and a small ensemble of six models. For example, the probability of a rare event (such as 1 in 100 yr) occurring in a 20 yr time slice is low, and a more reliable estimate will require a considerably larger model simulation ensemble.

Our models used all four RCPs from 2.6 to 8.5. While most research publications tend to present results for the worst-case scenarios, we intentionally chose to show results from a range of RCPs. Debate in the science community is still ongoing on the likelihood of following either the RCP 2.6 or the RCP 8.5 pathway (Sanderson et al. 2016; Hausfather & Peters 2020). Our results show that even under middle-of-the-range scenarios (RCP 4.5 and 6.0), impacts are likely to be significant and therefore need to be considered seriously.

Even though the next generation of CMIP-6-based climate projections are now becoming available, the main results derived in this study are likely to remain robust. For a start, the key climate variables were validated, and bias corrected with respect to observation-based data (Virtual Climate Station Network). Though some features and details of the analysis may change, the climate change signal over model generations is likely to remain mostly

[3] For example, https://ofcnz.niwa.co.nz/#/nationalMaps, https://niwa.co.nz/our-science/climate/information-and-resources/clivar/scenarios#ourfutureclimate

qualitatively stable. Secondly, the CMIP-6 model generation has a higher-than-expected temperature response with the doubling of CO_2, and requires further careful evaluation before being applied to climate impact studies.

Model types

Simple models can be sufficient to answer more general questions related to climate change. Expert knowledge can be elicited to support immediate decision-making by farmers and industry professionals. For instance, the simple crop suitability and hazard indices can help the farming industry to understand future land-use change opportunities across the country. However, for more specific questions, such as "What would be the projected changes in yield at a given location?", more sophisticated models are required.

When model maturity is good enough to trust predictability, these models can inform potential variations in yield under given specific climate change scenarios. However, models vary in how they account for different processes, so it is important to ensure that outputs are accompanied by metadata on fitness for purpose and limitations (as described in the data supermarket: see metadata). The development of mechanistic models relies heavily on the level of understanding of specific biophysical processes, and then on implementing them within the model. Accurate parameterisation is another key challenge. This is labour-intensive, necessitating calibration with in-field measurements to ensure they have sufficient credibility in their predictive capacity to project into the future. Further research is still needed, for instance, to better understand the impacts of climate change on crop phenology, the dynamics of pests and diseases, or the magnitude of impact of increased CO_2 on plant physiology (fertilisation effect, water demand, etc.).

Although simple models may not be suitable for some questions, more complex models also have drawbacks in terms of their computational power requirements, reliance on experts to run them, uncertainty of the parameterisation, and level of data inputs needed. Articulating the right questions and objectives, and assessing data availability and the appropriateness of existing models to evaluate climate change impacts are all necessary steps to enable informed decision-making (Vannier et al. 2022). Note that the model 5 type is a compromise approach that seeks to employ the advantages of a mechanistic model without the computational requirements and need for hard-to-obtain parameters.

Modelling results

The modelled effects of climate change varied spatially across all crops and impact metrics. Some risks are significant for large areas; for example, the expected increase in sediment yield from the soft-rock hill country in the North Island could offset any land management improvements linked to water quality standards. Drought looks to be an increasing issue for rainfed pasture in the North Island. Drought risk for crops, such as maize, may be less significant than for pasture under climate change because crop sowing dates can be advanced under warmer climates, thus taking advantage of the spring rainfall and winter soil water storage. Other impacts are more localised to specific microclimates. For example, under climate change some locations will be less affected by the risk of frost, potentially reducing the probability of crop failure and offering new opportunities to grow some arable or horticultural crops.

The various work streams have tried to address both chronic and acute risk questions. The results should inform discussions on land use and the balance with climatic risks in New Zealand. This will be helpful to policy makers, regulators, and land stewards, guiding decision-making on adaptation options (tactical, strategic, or transformational) for long-term shifts in risks (e.g. change in cultivars) or the mitigation of risks (e.g. investment in water storage, breeding) (Ausseil, Daigneault et al. 2019).

Future work

Although summary information like that presented here and available at the data supermarket (e.g., mean annual maps) can show the trends that can be expected as the climate changes, there is much to be gained from extending the analyses to inspect the inter-annual variability of risk as well as the temporal patterns of duration and frequency. For example, is the length of drought periods or their timing changing? What is the likelihood of multi-regional and consecutive-years droughts, and how are they going to affect the agricultural sector? Are the probabilities of adverse events changing? The information can also be used to investigate more farm-type specific questions (e.g., does an increase in pasture production mean that high-country farms will have more potential to finish their lambs?). Uncertainty could be more explicitly presented. A more temporally detailed analysis would allow separation and analysis of the various drivers, including the negative effects of drought in the summer vs the positive effects of CO_2 fertilisation and warmer winters.

We suggest that the next steps should include an iterative process of working with farm systems scientists and agricultural experts to identify sets of questions about the future that relate to a range of different farm types, locations, and commercial interests, which modellers can then seek to answer. Each iteration would enable the group to devise new questions, ensure the relevance of the answers, and help the agricultural sector to engage with the information

Although there is uncertainty in both the climate projections themselves and in the accuracy of the modelled responses to climate change (Mackay et al. 2023), the information is still valuable for considering how to take advantage of the projected changes as well as identifying adaptative pathways for more resilient farms, especially those, such as land-use change, that will take time and investment to implement.

Adaptation to climate change is critical given the significance of the economic and social importance of the agricultural sector in New Zealand. Having quantitative information on potential risks and opportunities and implications can inform adaptation pathways for communities and avoid risks of maladaptation (Lawrence et al. 2023). Importantly, the physical impacts of climate change should be integrated and coupled with socio-economic models to assess wider implications to the community and sector. These may require more process-based models that can produce the inputs needed for economic models and respond to feedbacks from them (Ausseil, Daigneault et al. 2019). Moreover, progress is still required to model the socio-economic implications of adaptation measures (Giupponi et al. 2022).

Conclusions

This paper describes the latest research in understanding climate change impacts on New Zealand agriculture. A set of models ranging in complexity were developed and used with spatial data to advance our knowledge of risks and opportunities for arable, horticultural, and pastoral land uses. This information is available on https://landuseopportunities.nz/. A more temporally detailed analysis of this information would allow more specific impact questions to be explored. Finally, more research in partnership with the agricultural sector is needed to help with adaptation planning and developing resilience to climate change.

Table 1. Model outputs for some hazard and vulnerability risks to New Zealand agriculture. (*: discussed in this paper; yellow cells: available from https://landuseopportunities.nz/; italics: other research outputs). ap = apple, av = avocado, bl = blueberry, ch = cherry, cn = chestnut, ki = kiwifruit, ma = maize, on = onions, pe = peas, po = potatoes, wh = wheat, wi = wine grape.

Table 2. Types of models used in the climate change assessments.

Figure 1. Risk framework (adapted from Oppenheimer et al. 2014)

Figure 2. Change in risk of frost (peas) and heat stress (wheat) from a baseline (1985–2005) to a future climate (RCP4.5, 2040–2060).

Figure 3. The percentage of 20 years where the maize silage crop did not reach maturity under baseline past (1981–2000), mid- (2041–2060), and late century (2080–2099) under RCP 4.5.

Figure 4 Monthly demand of maize crops for water at two locations (Whakatane RCP 4.5 and Lincoln RCP 4.5), and two time-slices (mid- and end of century). The dashed black line is the demand in the baseline past (1981□2000); the red line is the mean demand under RCP 4.5. The grey dots indicate the variability across the 20 yr period and the six climate models.

Figure 5. Suitability scores (0 = poor, 1 = good) for apples at the baseline period (1972–2004), mid-century (2028–2058), and end of century (2068–2098) under RCP 4.5.

Figure 9. Predicted climate suitability for facial eczema in 2040 and 2080 under HADGEM2 emissions scenario RCP 8.5.

Figure 7. Projected changes in pasture yield (rainfed, no fertiliser) under RCP 6.0.

Figure 8. Median proportional change in total sediment yields across the six GCMs for the North Island and the South Island under RCP 2.6 and RCP 8.5 by 2090.

Disclosure Statement: The authors report there are no competing interests to declare.

Acknowledgements

This paper was jointly funded by the Deep South and Our Land & Water Science Challenges through the Whitiwhiti Ora Land Use Options programme.

References

Ausseil AGE, Daigneault AJ, Frame B, Teixeira EI. 2019. Towards an integrated assessment of climate and socio-economic change impacts and implications in New Zealand. Environmental Modelling & Software 119:1–20. https://doi.org/10.1016/j.envsoft.2019.05.009.

Ausseil A-GE, Law RM, Parker AK, Teixeira EI, Sood A. 2021. Projected wine grape cultivar shifts due to climate change in New Zealand. Frontiers in Plant Science 12(679). https://doi.org/10.3389/fpls.2021.618039.

Ausseil A-G, Weerden Tvd, Beare M, Teixeira E, Baisden T, Lieffering M, Guo J, Keller L, Law R, Noble A. 2019. Climate change impacts on land use suitability. https://ourlandandwater.nz/wp-content/uploads/2019/11/LUS_Ausseil_Land-Use_Final-Report_FINAL-30-June-2019-1.pdf.

Babylon A, Woodward SJR, Beukes PC. 2022. Summer growth rates and annual yields of perennial ryegrass (Lolium perenne L.) in the Upper North Island are expected to decline as a result of climate change. Journal of New Zealand Grasslands 84. doi: 10.33584/jnzg.2022.84.3565.

Cichota R, Vogeler I, Werner A, Wigley K, Paton B. 2018. Performance of a fertiliser management algorithm to balance yield and nitrogen losses in dairy systems. Agricultural Systems 162:56–65.

Clark AJ, Nottage RAC, Wilcocks L, Lee JM, Burke C, Kalaugher E, Roche J, Beukes P, Lieffering M, Newton PCD, et al. 2012. Impacts of climate change on land-based sectors and adaptation options. Stakeholder Report to the Sustainable Land Management and Climate Change Adaptation Technical Working Group, Ministry for Primary Industries. https://www.mpi.govt.nz/dmsdocument/32-impacts-of-climate-change-on-land-based-sectors-and-adaptation-options-stakeholder-report.

Collins DBG, Zammit C. 2016. Climate change impacts on agricultural water resources and flooding. Client Report No: 2016114CH prepared for the Ministry for Primary Industries.

Cradock-Henry NA, Flood S, Buelow F, Blackett P, Wreford A. 2019. Adaptation knowledge for New Zealand's primary industries: known, not known and needed. Climate Risk Management 25:100190. https://doi.org/10.1016/j.crm.2019.100190.

Davis M, Mader T, Holt S, Parkhurst A 2003. Strategies to reduce feedlot cattle heat stress: effects on tympanic temperature. Journal of Animal Science 81: 649–661.

Garcia SC, Kemp S, Clark C, Ota N, Islam M, Kriticos D. 2021. What's next for the New Zealand dairy feed-base? Learnings from climate analogues. Journal of New Zealand Grasslands 17. doi: 10.33584/rps.17.2021.3486.

Gerard PJ, Barringer JRF, Charles JG, Fowler SV, Kean JM, Phillips CB, Tait AB, Walker GP. 2013. Potential effects of climate change on biological control systems: case studies from New Zealand. BioControl 58(2):149–162. doi: 10.1007/s10526-012-9480-0.

Giupponi C, Ausseil A-G, Balbi S, Cian F, Fekete A, Gain AK, Essenfelder AH, Martinez-Lopez J, Mojtahed V, Norf C, et al. 2022. Integrated modelling of social-ecological systems for climate change adaptation. Socio-Environmental Systems Modelling 3:18161. doi: 10.18174/sesmo.18161.

Hatfield JL, Prueger JH. 2015. Temperature extremes: effect on plant growth and development. Weather and Climate Extremes 10:4–10. https://doi.org/10.1016/j.wace.2015.08.001.

Hausfather Z, Peters GP. 2020. Emissions – the 'business as usual' story is misleading. Nature 577:618–620. doi: 10.1038/d41586-020-00177-3.

Hewitt K, Matthew C, McKenzie C, Mace W, Popay A. 2021. The role of Epichloë grass endophytes during pasture renewal. Journal of New Zealand Grasslands 17. doi: 10.33584/rps.17.2021.3446.

Hopkins D, Campbell-Hunt C, Carter L, Higham JES, Rosin C. 2015. Climate change and Aotearoa New Zealand. WIREs Climate Change 6(6):559–583. https://doi.org/10.1002/wcc.355.

IPCC 2014. Fifth assessment report. https://www.ipcc.ch/assessment-report/ar5/

Jones RAC. 2016. Chapter Three: Future Scenarios for plant virus pathogens as climate change progresses. In: Kielian M, Maramorosch K, Mettenleiter TC, editors. Advances in Virus Research. Academic Press; pp. 87–147.

Kemp L, Xu C, Depledge J, Ebi KL, Gibbins G, Kohler TA, Rockström J, Scheffer M, Schellnhuber HJ, Steffen W, et al. 2022. Climate Endgame: exploring catastrophic climate change scenarios. Proceedings of the National Academy of Sciences 119(34):e2108146119. doi:10.1073/pnas.2108146119.

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(4):1342–1356. https://doi.org/10.1111/j.1365-2486.2011.02625.x.

Lawrence J, Mackey B, Chiew F, Costello MJ, Hennessy K, Lansbury N, Nidumolu UB, Pecl G, Rickards L, Tapper N, et al. 2022. Australasia. In: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, et al., editors. Climate change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Lawrence J, Wreford A, Blackett P, Hall D, Woodward A, Awatere S, Livingston ME, Macinnis-Ng C, Walker S, Fountain J, et al. 2023. Climate change adaptation through an integrative lens in Aotearoa New Zealand. Journal of the Royal Society of New Zealand 54:4, 491–522. doi: 10.1080/03036758.2023.2236033.

Li F, Newton P, Lieffering M. 2014. Testing simulations of intra- and inter-annual variation in the plant production response to elevated CO2 against measurements from an 11-year FACE experiment on grazed pasture. Global Change Biology 20:228–239.

Mackay A, Hutchinson K, Moore J, Dodd M, Lin Y, Muir P, Smith C, Vibart R, Bilotto F. 2023. Are observed rates of productivity compared to model predictions indicating negative climate impacts in perennial plants? Journal of New Zealand Grasslands 85:51–60.

Manaaki Whenua – Landcare Research. 2020a. Fundamental Soil Layers. https://doi.org/10.26060/P5S8-CW25.

Manaaki Whenua – Landcare Research. 2020b. S-map – New Zealand's national digital soil map. http://dx.doi.org/10.7931/L1WC7.

Manning MR, Lawrence J, King DN, Chapman R. 2015. Dealing with changing risks: a New Zealand perspective on climate change adaptation. Regional Environmental Change 15:581–594.

Mansfield S, Ferguson C, Gerard P, Hodges D, Kean J, Phillips C, Hardwick S, Zydenbos S. 2021. Climate change impacts on pest ecology and risks to pasture resilience. Journal of New Zealand Grasslands 7:123–138.

Ministry for the Environment. 2018. Climate change projections for New Zealand: atmospheric projections based on simulations undertaken for the IPCC Fifth Assessment. https://environment.govt.nz/assets/Publications/Files/Climate-change-projections-2nd-edition-final.pdf.

Neverman AJ, Donovan M, Smith HG, Ausseil A-G, Zammit C. 2023. Climate change impacts on erosion and suspended sediment loads in New Zealand. Geomorphology 427:108607. https://doi.org/10.1016/j.geomorph.2023.108607.

Openheimer M, Campos M, Warren R, Birkmann J, Luber G, O'Neill B, Takahashi K. 2014. Emergent risks and key vulnerabilities. In: Field C, Barros V, Dokken D, Mach K, Mastrandrea M, Bilir T, Chatterjee M, Ebi K, Estrada Y, Genova R, et al., editors. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press; pp. 1039–1099.

Orwin KH, Stevenson BA, Smaill SJ, Kirschbaum MUF, Dickie IA, Clothier BE, Garrett LG, van der Weerden TJ, Beare MH, Curtin D, et al. 2015. Effects of climate change on the delivery of soil-mediated ecosystem services within the primary sector in temperate ecosystems: a review and New Zealand case study. Global Change Biology 21(8):2844-2860. https://doi.org/10.1111/gcb.12949.

Phillips C, Johnson P, Tomasetto F, McRae K, Van der Weerden T. 2023. Predicting facial eczema risks in a changing New Zealand climate. Journal of New Zealand Grasslands 85: 61-71.

Rutledge DT, Ausseil A-GE, Baisden WT, Bodeker G, Booker D, Cameron MP, Collins DBG, Daignaeult A, Fernandez M, Frame B, et al. 2017. Identifying feedbacks, understanding cumulative impacts and recognising limits: a national integrated assessment. Synthesis Report RA3. Climate Change Impacts and Implications for New Zealand to 2100. https://niwa.co.nz/sites/niwa.co.nz/files/RA3-Synthesis-report.pdf.

Sanderson BM, O'Neill BC, Tebaldi C. 2016. What would it take to achieve the Paris temperature targets? Geophysical Research Letters 43(13):7133–7142, https://doi.org/10.1002/2016GL069563.

Snyder RL. 2017. Climate change impacts on water use in horticulture. Horticulturae 3(2):27.

Sood A. 2014. Improved bias corrected and downscaled regional climate model data for climate impact studies: validation and assessment for New Zealand. https://www.researchgate.net/publication/265510643_Improved_Bias_Corrected_and_Downscaled_Regional_Climate_Model_Data_for_Climate_Impact_Studies_Validation_and_Assessment_for_New_Zealand.

Teixeira EI, de Ruiter J, Ausseil A-G, Daigneault A, Johnstone P, Holmes A, Tait A, Ewert F. 2018. Adapting crop rotations to climate change in regional impact modelling assessments. Science of the Total Environment 616-617:785–795. https://doi.org/10.1016/j.scitotenv.2017.10.247.

Trębicki P, Dáder B, Vassiliadis S, Fereres A. 2017. Insect–plant–pathogen interactions as shaped by future climate: effects on biology, distribution, and implications for agriculture. Insect Science 24(6):975–989. https://doi.org/10.1111/1744-7917.12531.

Vannier C, Cochrane TA, Zawar Reza P, Bellamy L. 2022. An analysis of agricultural systems modelling approaches and examples to support future policy development under disruptive changes in New Zealand. Applied Sciences. doi: 10.3390/app12052746.

Vetharaniam I, Müller K, Stanley C, van den Dijssel C, Timar L, Clothier B. 2022. Modelling continuous location suitability scores and spatial footprint of apple and kiwifruit in New Zealand. Land 11:1528.

Vetharaniam I, Timar L, Stanley C, Müller K, van den Dijssel C, Clothier B. 2022. Modelling climate change impacts on location suitability and spatial footprint of apple and kiwifruit. Land 11(10):1639.

Vogeler I, Cichota R. 2016. Deriving seasonally optimal nitrogen fertilization rates for a ryegrass pasture based on agricultural production systems simulator modelling with a refined AgPasture model. Grass and Forage Science 71:353–365.

Wakelin SA, Gomez-Gallego M, Jones E, Smaill S, Lear G, Lambie S. 2018. Climate change induced drought impacts on plant diseases in New Zealand. Australasian Plant Pathology 47(1):101–114. doi: 10.1007/s13313-018-0541-4.

Warrick RA, Kenny GJ, Harman JJ. 2001. The effects of climate change and variation in New Zealand: an assessment using the CLIMPACTS system. https://docs.niwa.co.nz/library/public/0473079887.pdf.

Watt MS, Kirschbaum MUF, Moore JR, Pearce HG, Bulman LS, Brockerhoff EG, Melia N. 2019. Assessment of multiple climate change effects on plantation forests in New Zealand. Forestry: An International Journal of Forest Research 92(1):1–15. doi: 10.1093/forestry/cpy024.