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Impacts of climate change on regional economies – Agricultural modelling

Teixeira E, Khaembah E, Yang X, Bristow J, Brown H

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Report prepared by:

Edmar Teixeira
Scientist, Modelling
March 2025

Report approved by:

Penny Tricker
Science Group Leader, Cropping Systems & Environment
March 2025

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Plant & Food Research Lincoln

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As the climate changes, the conditions that determine where crops can grow and how much they can produce will change across the globe. For New Zealand, where agriculture is a key contributor to the national economy, these shifts may bring both challenges and opportunities. Predicting the exact effects of climate change on the yield of specific crop species is very difficult. This is because we cannot know exactly how quickly temperatures will rise, or rainfall patterns will change, across the different agricultural regions in the country. Also, each crop responds differently to the same environmental conditions, and it is uncertain which crops will be most relevant to the New Zealand economy in the future.

To deal with these uncertainties, we simulated yields for a selection of eight crop options under three different climate change scenarios currently projected for New Zealand. The simulations were done by a new crop model, specifically developed for this project, the Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY). The model uses a well-established platform, the Agricultural Production Systems sIMulator (APSIM). The eight crop species were preselected through consultations with the arable and horticultural sectors. These included four annual/arable crops (maize, wheat, hemp and oilseed rape) and four perennial/horticultural crops (grapevine, macadamia, avocado and lemons). Climate change scenarios, used as daily weather input to APSIM-DEROPAPY, were prepared by the National Institute of Water and Atmospheric Research (NIWA) at 5 km resolution across New Zealand.

Our results show that climate change impacts on yields will largely differ across crop species and locations, as shown for selected New Zealand regions in Figure 1S.

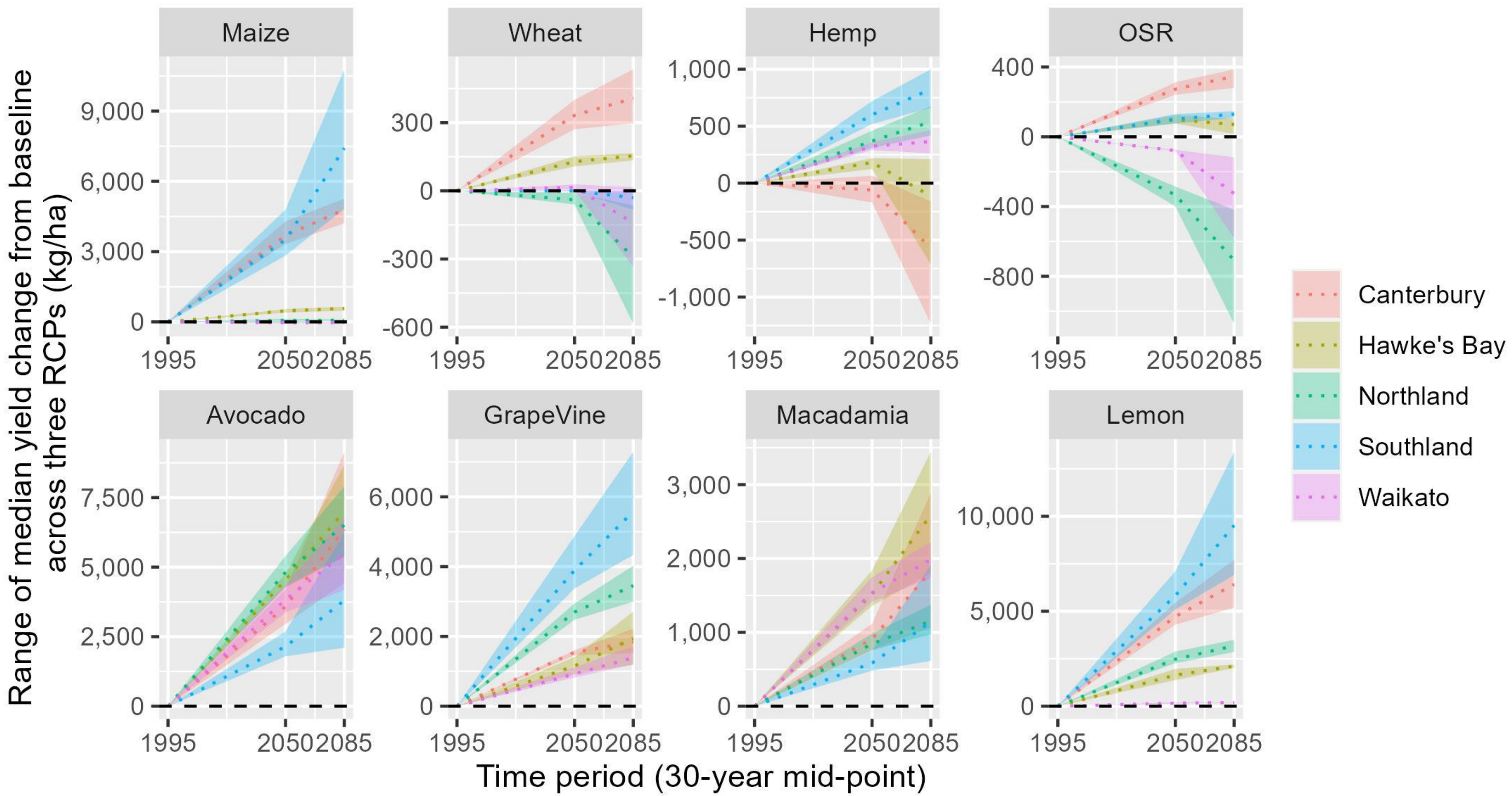

Fig.1S: Range of median yield changes estimated along three Representative Concentration Pathways (RCP4.5, RCP6.0 and RCP8.5). Values are pooled across ~5 km grid-cells within New Zealand regions considering three most prevalent soils per grid, two water regimes (irrigated and rainfed) and climate from five General Circulation Models (GCMs). OSR is oilseed rape crop.

With a few exceptions, yield stagnation or decline was more commonly estimated for northern (warmer) locations. In contrast, highest yield gains were often estimated for southern (cooler) regions. For any given region, different crop species responded differently to climate change. For example, tropical crops such as avocado tended to benefit from warming more broadly across the country than temperate crops such as wheat, which mostly benefited at the more southern locations. Insights for each of the selected crops include:

- **Grapevine**: Yield benefited from warming in mid- and end-century across New Zealand. Highest yield gains were estimated in the South Island. However, some hotspots of yield decline were estimated in the east coast and Nelson region, due to heat stress during flowering.
- **Macadamia**: Yields showed an overall increase across all New Zealand in mid- and end-century, with the highest increase in southernmost areas and moderate increase in the northern areas.
- **Lemons**: Yield increased across New Zealand under warming in mid- and end-century. Southern regions showed higher absolute yield increases than northern regions.
- **Avocado**: Yield increased with climate change intensity. Relatively, as a percentage of current values (baseline), yields gradually increased from north to south and from mid- to end-century under a warming climate. Nevertheless, Northland showed highest absolute yield increases due to its high current values, while Southland showed the lowest.
- **Maize**: Future warming conditions are expected to result in yield gains primarily in the southern regions, with an increasing trend from Canterbury to Southland. However, no yield benefits are anticipated for the northern areas for either the mid- or late-century periods.
- **Wheat**: Yield increase is expected under high warming conditions for Canterbury and Hawke's Bay, while a decline is projected for Northland and Waikato, due to heat stress.
- **Oilseed rape**: Yield declines were estimated in northern regions under high warming scenarios, primarily due to heat stress affecting seed formation. Conversely, moderate to high yield increases were predicted in southern regions, mainly due to enhanced light interception and improved radiation use efficiency.
- **Hemp**: Yield increases were predicted for the cooler southern areas of New Zealand under warming conditions. In contrast, yield declines were expected on the east coast of both islands and in central South Island, particularly under the warmest climate scenario (RCP8.5), due to heat stress.

The implications of these findings include careful consideration of food security and economic strategies for the country.

For instance, future scenarios with truncated global international trade would make New Zealand more reliant on locally grown crops, either for food (e.g., wheat) or for high-value export markets (e.g. winegrapes). The change in land suitability to grow these crops will differ across New Zealand due to the regional variability of climate change effects. This implies localised adaptation requirements for local economies and infrastructure, such as for processing and transportation of food, feed, fibre or fuel from crops.

At the same time, we must remember that climate change is global. There will also be regional impacts of climate change affecting other countries that produce the same crops that New Zealanders consume or export. Even if we adapt our local conditions to grow new crops, climate change may also shift growing conditions and production costs in other countries — making them more or less competitive. These changes, along with global supply and demand trends for the same crops, will also influence competitiveness. Therefore, it is important to adapt locally with a simultaneous overview of global agricultural trends.

It is important to note that we have identified technical limitations and uncertainties in the methodology that require future model improvement (e.g. representation of inter-annual variability for some crops), and areas that are not yet covered by the approach. For instance, extreme events such as storms and floods, and losses caused by insects and pathogens are not considered in this analysis and are likely to more negatively affect yields as global warming intensifies. In this context, results must be considered conservative and interpreted with caution because not all types of climate change impacts are accounted for.

Overall, the model responded to the main environmental drivers of crop yield under a changing climate. This indicates that outputs are appropriate to support the assessment of climate change effects on primary production and inform further analysis of carryover impacts on regional economies.

For further information please contact:

Hamish Brown
Plant & Food Research Lincoln
Private Bag 4704
Christchurch Mail Centre
Christchurch 8140
NEW ZEALAND

Tel: +64 3 977 7340
DDI: +64 3 325 9394

Email: Hamish.brown@plantandfood.co.nz

1 Background

In the Ministry for Business, Innovation, and Employment (MBIE) project, “Impacts of climate change on regional economies”, The New Zealand Institute for Plant and Food Research Limited (PFR) developed new methods to simulate crop yield responses to climate change. The goal is to build an understanding of how climate change will affect primary production in different parts of the country − a key component to inform likely impacts on regional economies.

In this first implementation, eight crop species considered economically relevant for New Zealand, now and in the future, were studied. Crops were selected in consultation with experts from the industry and science sectors. This selection aimed to identify a widely diverse range of land-use options considering differences in plant physiology, market opportunities and the industry sector involved.

A new generic crop model was then developed, specifically for this project, to represent the physiology of these crops. The project sought to ensure consistent and transparent parameterisation across very contrasting crop options, including, for instance, arable and horticultural species.

Yield estimates considered spatial and temporal variability and uncertainty in climate change projections. Specifically, the main inputs for the model were daily weather and soil information across New Zealand arable lands. These represented both historical and future climate projections at 5 km resolution, from different climate models, and considered a range of warming intensity scenarios.

In the following sections, we describe the preparation of input data, modelling methods and simulation results for this project.

2 Methods

2.1 Crop selection

Eight agricultural crops species were selected for this modelling study. The key criteria for selection included (i) economic relevance assumed for future decades and (ii) diversity in both physiological and market aspects. The rationale was to explore a wide portfolio of crops to confer resilience through diversity, minimising risks from the inherent uncertainty in future climates and socio-economic global changes. Specifically, we aimed to balance biological/sectoral (i.e. annual/arable or horticultural/perennial species) and market aspects (i.e. established/emerging industries) during crop selection. The identification of candidate crops was carried out through consultation with industry, specifically scheduled remote workshops with representatives from the horticultural sector (HortNZ; Horticulture New Zealand; www.hortnz.co.nz) and arable sector (FAR; Foundation for Arable Research; www.far.org.nz). The initial list of options was then narrowed down to eight crops, based on discussions with the project's steering group. The selected crop species are shown in Table 1.

Table 1. Selected arable and horticultural crop species in this project.

Candidate crop	Characteristics and criteria considered	Categories
Maize (*Zea mays*)	Food security relevance globally. Food, feed, forage and fuel use. Forage (silage) and grain usage in New Zealand. Land suitability sensitive to climate change.	Annual | Arable | Established
Wheat (*Triticum aestivum*)	Food security relevance globally. Food, feed, forage use. Production potential and demand are high in New Zealand. Land suitability sensitive to climate change.	Annual | Arable | Established
Oilseed rape (*Brassica napus*)	Contributes to diversity in crop rotations. Adaptability potential through multiple uses of the crop (oil, feed and fuel)	Annual | Arable | Potential
Industrial hemp (*Cannabis sativa*)	High yield crop with multiple uses (seed, fibre, oil, fuel, feedstock). High nutritional quality and environment benefits. Contributes to diversity in crop rotations.	Annual | Arable | Potential
Grapevine (*Vitis vinifera*)	Well established industry in New Zealand with high returns in export market. Land suitability and wine quality sensitive to climate change for important New Zealand varieties.	Perennial | Horticultural | Established
Avocado (*Persea americana*)	High value crop with emerging sector in New Zealand's North Island and increasing demand in affluent markets.	Perennial | Horticultural | Established
Macadamia (*Macadamia integrifolia*)	High value crop with emerging demand projected globally. Potential expansion of establishment across New Zealand with climate change.	Perennial | Horticultural | Potential
Lemons (*Citrus limon*)	High nutritive value and market demand. Potential crop alternative for land use diversification in northern areas with socio-economic benefits.	Perennial | Horticultural | Potential

2.2 Climate and soil inputs to the model

Crop yield simulations used georeferenced information on climates and soils across New Zealand as main inputs. Specifically, climate inputs considered daily, bias-corrected, weather variables downscaled at 3-arc minute resolution (~5 km grid-cells) by the National Institute of Water and Atmospheric Research (NIWA) for New Zealand (Sood, 2014; Tait et al. 2016). These datasets encompass both a simulated baseline (1975 to 2005) and future climate change projections (2006 to

2100) at similar spatial and temporal resolution, as within the historical climate records in NIWA's Virtual Climate Station Network (VCSN) grid system.

For both climate datasets, the daily environmental variables used as input were air temperature (°C, maximum and minimum), total solar radiation (MJ/m2) and rainfall (mm). Climate change downscaled projections by NIWA were based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset and considered three Representative Concentration Pathways (RCPs; 4.5, 6.0 and 8.5). These represent a range of plausible emission scenarios with correspondent CO2 atmospheric concentrations, from low to high emissions respectively, depending on future reliance on fossil fuels and time course of assumed technological advances for the use of sustainable energy sources.

Uncertainty in climate change projections was addressed by considering six General Circulation Models (GCMs) for each RCP. Selected GCMs and respective country of origin were HadGEM2-ES (UK), CESM1-CAM5 (USA), NorESM1-M (Norway), GFDL-CM3 (USA), GISS-E2-R (USA), BCC-CSM1.1 (China). These were evaluated and recommended by NIWA for impact studies in New Zealand based on their performance in relation to historical records (Mullan et al. 2018; Tait et al. 2016).

Georeferenced soil datasets from the Manaaki Whenua–Landcare S-map database (Lilburne et al. 2004) were used in combination with local climates. Specifically, three predominant S-map "soil siblings" were selected within each climate 5 km VCSN grid cell, as explained in more detail in Section 2.3.

2.3 The agricultural model

The major challenge with this project was the need to simulate yield of some crops that had no previously available yield model as reference, and limited yield observations in New Zealand for model development and testing.

To deal with that, we decided to develop a new generic model that could represent yield formation processes consistently for all the crops in this study. This allowed us to extend basic modelling principles, and model testing techniques, from crops that we are familiar with, to crops with less information available. The principles governing growth and development of all crops are similar in essence but differ in their details, for example, specific optimum temperatures or flowering times. The elected approach allows extrapolation from a well-established modelling structure that represents physiological processes common across species and allows us to set crop specific parameters that then represent their differences.

The new multi-crop model, named the Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY), was built within Agricultural Production Systems Simulator framework (APSIM; Holzworth et al. 2014). APSIM simulates biologically relevant processes in plants (e.g. growth and development) and soils (e.g. carbon, water and nitrogen balances) at daily time steps. These processes are driven by weather (e.g. temperature) and soil (e.g. water availability) information, while considering management components (e.g. sowing dates and irrigation amounts). This is important for this project because crop yield, a key variable that influences economics of land use, is highly responsive to these factors that vary considerably across locations and time periods. In addition, the degree of sensitivity to climatic factors depends on the crop's development stage (e.g. germination, flowering and maturity), which itself varies from year to year, also in response to environmental conditions (e.g. temperature). Therefore, it is necessary for the new model to capture these multiple effects simultaneously, across all the contrasting crop species considered in this study. We opted to construct the modelling solution, common to all crops, with the Plant Modelling Framework of the APSIM Next Generation model (APSIM-NextGen PMF; Brown et al. 2014; Holzworth et al. 2018).

Half of the selected species (maize, wheat, oilseed rape and grapevine) already had crop-specific APSIM model implementations available. These were, however, at various degrees of development, with very different structures and parameterisation, depending on the objectives of the technical teams involved. This makes it difficult to interpret yield responses across crop species as was required in this project. Nevertheless, as much as possible, the parameterisation of preexisting APSIM models was used as the basis for the APSIM-DEROPAPY development. In most cases, it was not a direct transfer of information because existing versions are more complex due to their research focus, in contrast with the heuristic nature required in this project. For the other four crops (hemp, macadamia, avocado and lemons), there were no reference models available in APSIM. Therefore, these were developed and parameterised from scratch, often based on available literature, overseas models when available and expert opinion consultations.

In summary, a key feature of the new model (APSIM-DEROPAPY) is the ability to simulate very contrasting crop species (e.g. Section2.1) with a simple, traceable and consistent representation of physiological processes. This aims to facilitate the tracking of responses to specific parameters and the evaluation of the consequences of assumptions. These features are particularly critical when information for model development is scarce, as it facilitates evaluation and improvement of the model. As a trade-off for its simplicity and consistent structure, the new APSIM model differs from previous, more complex, research-focused versions. Although still mechanistic and process-based to dynamically capture climate, soil and management effects on yield, its simpler structure implies that not all process interactions are accurately represented. In practice, this means that the model is fit to “relatively” compare yields among crops but provides a limited degree of confidence on “absolute” yield estimates. Additional limitations include the fact that the model responds to water but not yet to fertiliser supply. The assumption being that nutrient is supplied at optimal levels. Finally, the structural simplifications detailed above imply that model testing cannot be performed by comparing simulated and measured data, as typically done in research focused developments.

The following sections detail the basic mechanisms considered in the new APSIM-DEROPAPY model.

2.3.1 Crop development stages

The timing of plant developmental events in the model is mostly controlled by temperature. Each crop accumulates thermal time (^{o}Cd) based on species-specific cardinal temperatures (Figure 1). The time for progression between development phases (e.g. from vegetative to reproductive) is defined by thermal-time accumulation targets. Different crop species, while grown under the exact same climate conditions, might have contrasting development rates depending on their sensitivity to temperature.

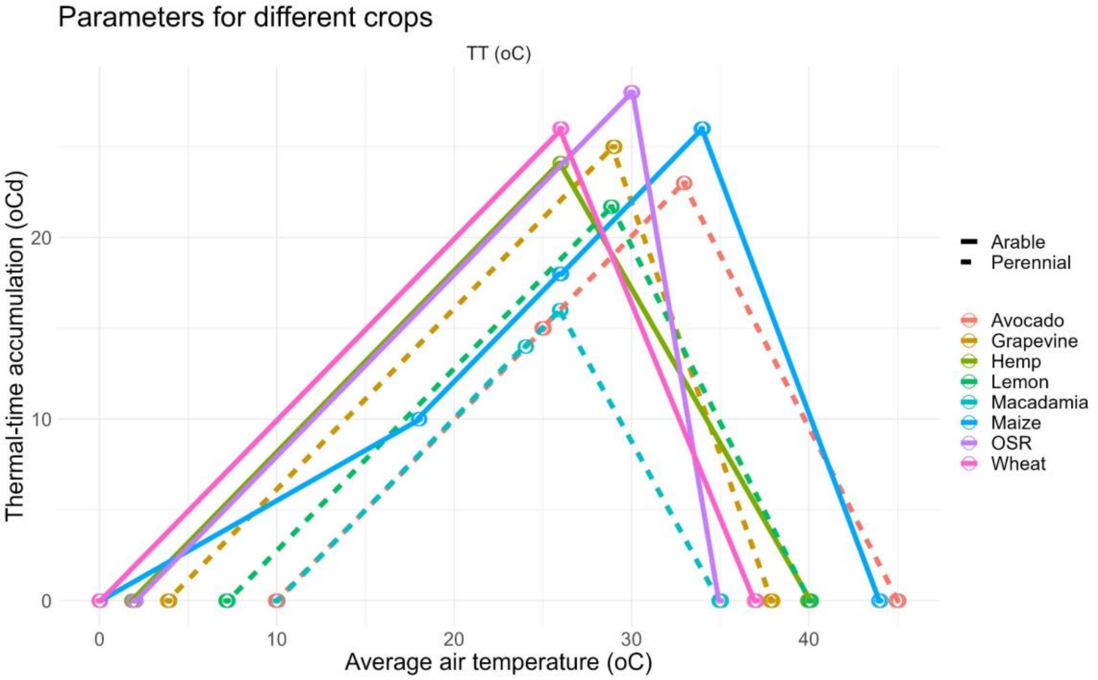

Figure 1. Thermal time accumulation at specific daily mean temperatures for the eight selected crops simulated in the Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY) model within the Agricultural Production Systems sIMulator (APSIM). OSR is oilseed rape.

The development stages, consistently considered across all crops, are a simplified combination of phenology and canopy development key events (Figure 2). The schematic representation shows the main drivers that influence the progression at a given phase of development.

Phase Number	Phase Name	Initial Stage	Final Stage
1	Dormant	Dormancy	Waiting
2	Waiting	Waiting	StartGrowth
3	Growing	StartGrowth	FullCanopy
4	DefoliateOrDevelop	FullCanopy	ReadyToGraze
5	Graze	ReadyToGraze	Rewind phase has no end
6	FullCover	FullCanopy	StartSenescence
7	Senescent	StartSenescence	Maturity
8	Mature	Maturity	ReStart
9	EndOrHarvest	ReStart	ReStart
10	HarvestAndPrune	ReStart	Dormancy
11	EndCrop	ReStart	Dormancy

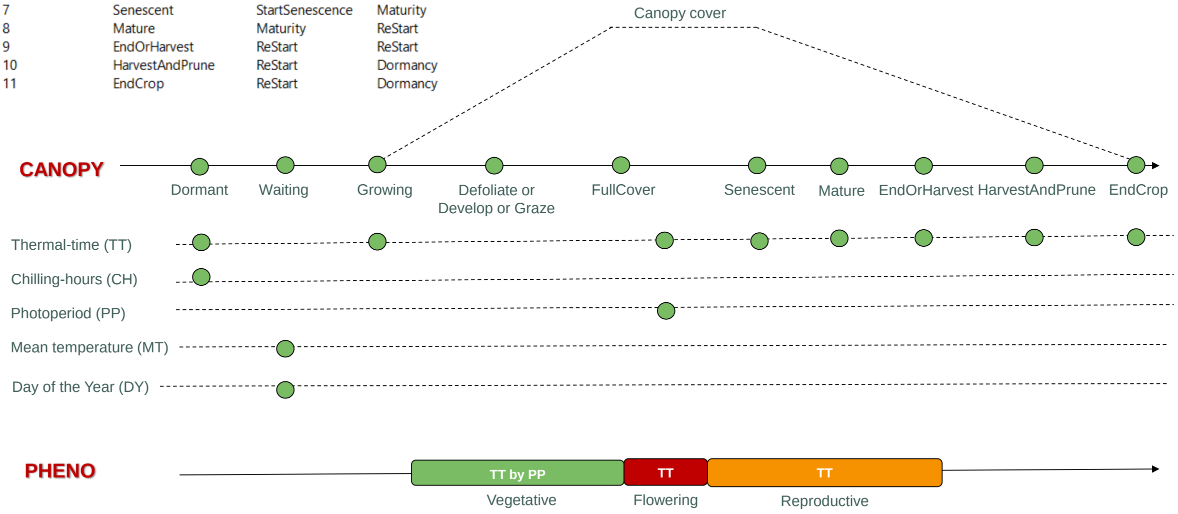

Figure 2. Schematic representation of crop phenological and canopy development stages in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY) in relation to their main environmental drivers (e.g. TT, thermal-time; PP, photoperiod).

As an example, once perennial crops are harvested there is a reset of their productive cycle, and a new cycle resumes at the “Dormant phase”. Dormancy ends when bud break is triggered by the accumulation of a certain number of chilling hours (i.e. a cold temperature threshold is crossed). In contrast, annual crops start their cycle after harvest every year at the “Waiting phase”. The waiting ends when they are sown again. Sowing is automatically set, either based on an assumed calendar date (i.e. day of the year) or more dynamically when parameterised temperature thresholds are crossed.

For both annuals and perennials, canopy expansion resumes after the start of the cycle (i.e. sowing or end-of-dormancy, respectively) and progresses until a maximum canopy cover is reached. The duration of maximum canopy cover is species-specific and defines the onset of senescence. At this stage, green canopy is reduced at species-specific rates until complete senescence, or the start of a new cycle. In parallel to canopy development, crop phenology transitions (e.g. from vegetative to reproductive) are parameterised in relation to thermal-time, chilling-hours or day-length thresholds.

This implies that there are different degrees of overlap between canopy and phenological development, depending on the species. For example, some annuals (e.g. maize and wheat) reach maximum leaf area index (LAI) near the flowering stage, while some evergreens (e.g. lemon and avocado) have a more detached progression of canopy and reproductive development dynamics. Crop yield (i.e. produce dry matter as grain or fruit productivity) is formed as biomass accumulates from the onset of flowering until crop maturation or harvest. The parameters used to control phenology and canopy progression are shown in Table 2.

Table 2. Phenology-related parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

Parameter	Unit	Description
Pp_FullCover_02	h	Photoperiod x-values for full cover target thermal-time lengths
Tt_FullCover_02	ºCd	Thermal-time duration of full-cover phase at PP x-values (FullCanopy to StartSenescence)
Tt_Senescent_03	ºCd	Thermal-time accumulation from StartSenescence to Maturity
D_StartGrowth_00	DAWS	Earliest day after winter solstice when sowing/end-dorm is resumed every year
T_StartGrowth_00	ºCd	Temperature 14-day running av temp from StartGrowthDOY_00 when growth starts
Tt_Growing_01	ºCd	Thermal-time accumulation from StartGrowth to FullCanopy
DefoliateOrDevelop	string	Phase to rewind if defoliated at FullCanopy (FullCover or Graze)
Tt_Mature_04	ºCd	Thermal-time accumulation from Maturity to Dormancy
D_EndGrowth	DAWS	The last day after winter solstice that the crop may remain active before its phenology is reset for next season
EndOrHarvest	string	If plant is harvested and pruned or dies completely at end of growth phase
AC_Dormant_05	ºCd	Accumulated chill units (x-value)
Tt_Dormant_05	ºCd	Thermal-time duration of dormant phase at accumulated chill unit (y-value)
VegetativeStartStage	Value	Phenological stage to start accumulating vegetative TT
Pp_Vegetative	h	Photoperiod x-values for pre flowering target thermal-time lengths
Tt_Vegetative	ºCd	Thermal-time duration of pre flowering phase at PP x-values
Tt_Flowering	ºCd	Thermal time for flowering window
Tt_Reproductive	ºCd	Thermal-time duration of produce growth post flowering
Chill_Temp_X	ºC	Temperatures when chilling-time accumulation occurs
Chill_Acc_Y	ºCd	Chilling rate accumulation at a given cardinal temperature
TT_Temp_X	oC	Average temperature for thermal time calculation
TT_Acc_Y	ºCd	Thermal time accumulation at average temperature

The fixed-value phenology parameters for each crop are shown in Figure 3.

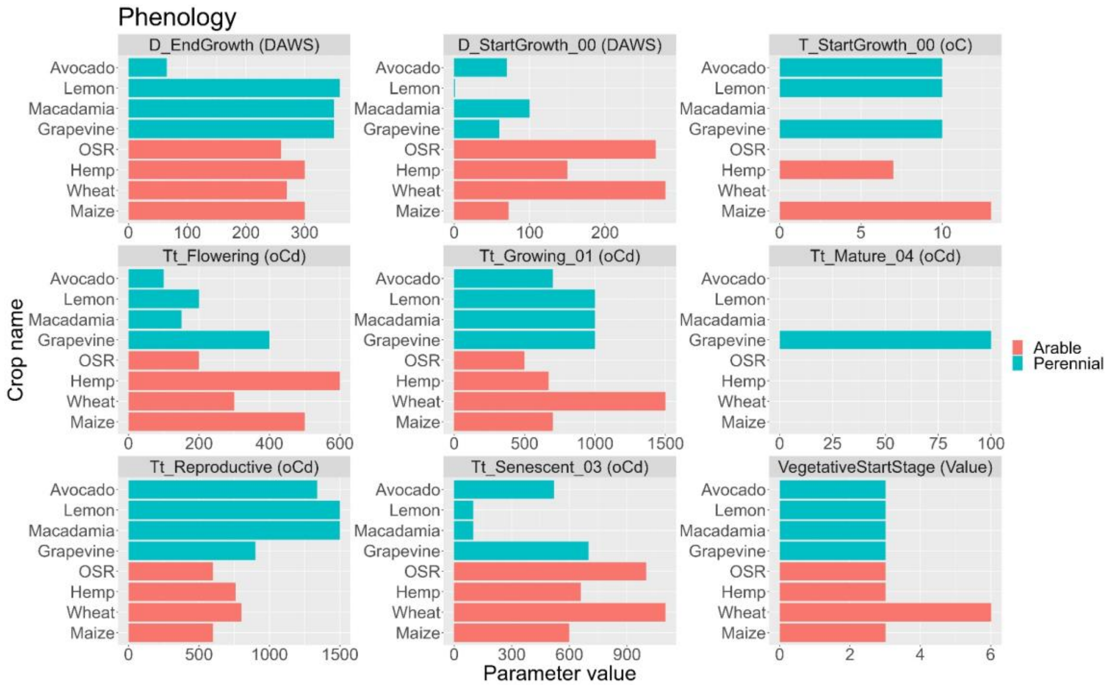

Figure 3. Phenology parameter values for the selected crops in Agricultural Production Systems sIMulator (APSIM)-Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY). OSR: Oilseed rape.

There are additional phenology parameters that respond to other dynamic drivers (e.g. temperature) as shown in Figure 4.

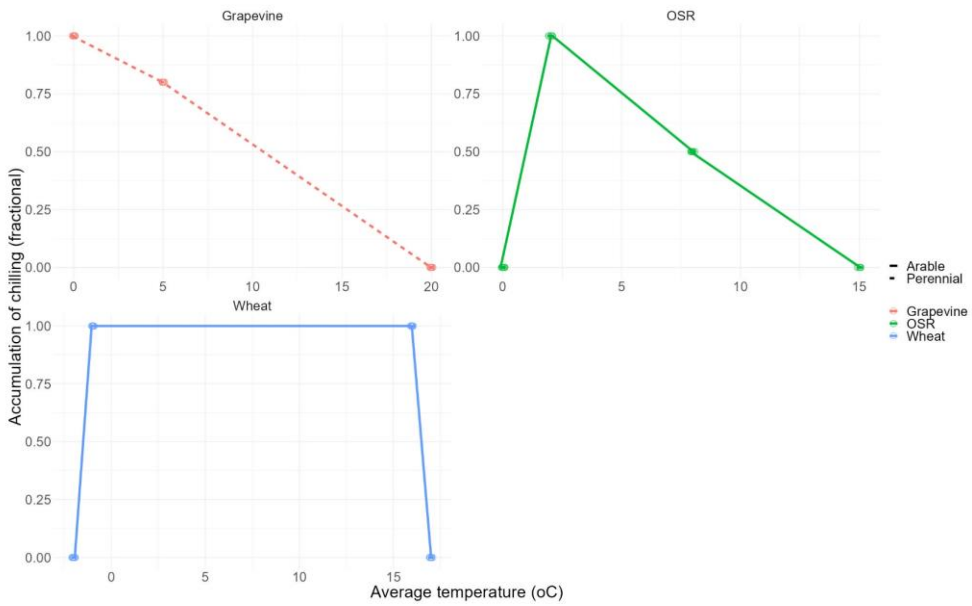

Figure 4. Dynamically driven phenology parameters in Agricultural Production Systems sIMulator (APSIM)-Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY). Only crops with chilling requirements were included.

2.3.2 Canopy expansion

Canopy expansion is computed daily and integrated into the Leaf Area Index (LAI, m2 leaf/m2 soil) state variable (Table 3). The LAI controls light interception based on a species-specific extinction coefficient for diffuse light. The potential rate of canopy expansion is calculated based on a species-specific maximum LAI divided by the canopy expansion duration. This potential rate is then reduced to actual canopy expansion rates by drought stress and frost damage. Similarly, a potential extinction coefficient for diffuse light is also multiplied by fractional drought stress coefficients and then used to estimate the actual percentage of daily solar radiation intercepted by each unit of available LAI. The senescence of canopy (i.e., LAI reduction) starts at the end of the maximum LAI phase and progresses at different rates, depending on the crop-specific duration of the Senescent phase.

Table 3. Canopy related parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

Parameter	Unit	Description
MaxCanopyBaseHeight	mm	Height of the base of the canopy of mature plant
MaxCanopyPrunedHeight	mm	Height of the top of the canopy of a mature plant after pruning or grazing
MaxCanopyHeight	mm	Maximum canopy height
MaxCanopyPrunedWidth	mm	Width of the canopy of mature plants after pruning
MaxCanopyWidth	mm	Width of the canopy of mature plants before pruning
LAIbase	m^2/m^2	The LAI during the winter period for evergreen crops
LAIAnnualGrowth	m^2/m^2	Maximum achievable leaf area index less the LAI base (optimal management)
ExtCoeff	0-1	Extinction coefficient for diffuse light across canopy
RelSlowLAI	3.1 to 3.8	Development phase code during Growing Phase when LAI reaches 10% of its maximum

The values of fixed canopy expansion parameters for each crop are shown in Figure 5.

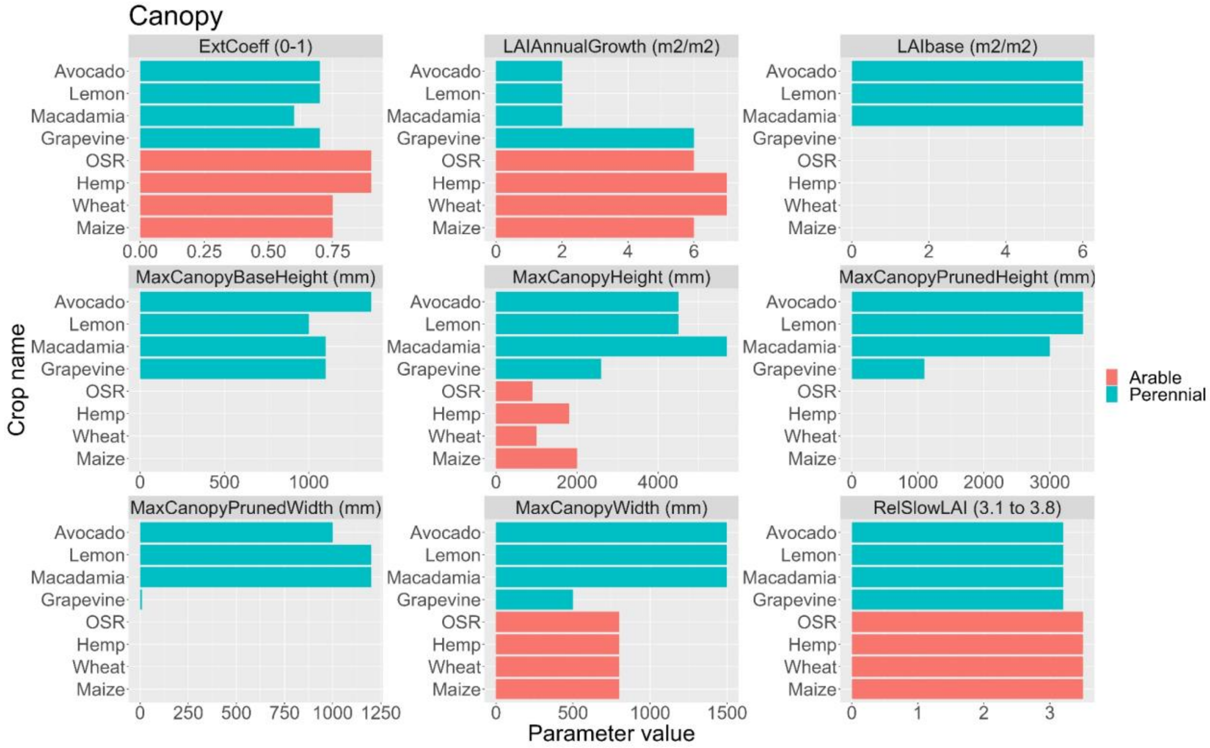

Figure 5. Canopy parameter fixed values for the selected crops in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

2.3.3 Biomass growth

Biomass accumulation is the product of estimated daily intercepted solar radiation (Session 2.3.2) and the parameter Radiation Use Efficiency for total plant biomass (RUE_{total}, g DM/MJ). The actual RUE used by the model is the product of RUE_{total} and crop-specific fractional multipliers for stress reduction (sub-optimal temperatures and drought). For species with photosynthetic pathway C_3 (i.e. cool/temperate weather crops, like wheat), RUE_{total} is however enhanced by atmospheric CO_2 concentrations greater than 350 ppm. In all crops, both C_3 (i.e. cool weather) and C_4 (i.e. warm weather crops, like maize) photosynthetic pathway, plant transpiration rates which control demand for water uptake are also influenced by CO_2. Specifically, efficiency of water use is increased under CO_2 concentrations above 350 ppm.

Daily crop biomass accumulation is allocated to four conceptual organs based on fractional partitioning coefficients (0 to 1). These are the Leaf (above-ground), Root (below-ground), Trunk (additional above-ground for perennials) and Product (harvestable produce). At harvest, specified fractions of plant biomass are removed from each organ, as defined in the crop-specific parameterisation.

There are key simplifications in the biomass accumulation module to be aware of. For instance, biomass is reset every year, and therefore there are no carryover effects across multiple years. Also, the models do not account for respiration rates, extreme events such as floods and storms and the impact of biotic stresses (e.g. insects and pathogens), which are also affected by climate change and will influence net accumulation of biomass.

Biomass related parameters for all crops are shown in Table 4.

Table 4. Biomass related parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

Parameter	Unit	Description
RUE_{total}	g DM/MJ global radiation	Radiation use efficiency for total plant biomass (global solar radiation)
PhotosynthesisType	C_3 or C_4	Select if a C_3 or C_4 crop to set sensitivity to atmospheric [CO_2]
RUETempThresholds	ºC	Radiation Use Efficiency temperatures for lower_minimum | lower_optima | upper_optima | upper_minimum
FlowerNumberMax	flowers/m^2	Maximum (potential) number of flowers per square meter
FruitWeightPotential	g DM/fruit	Dry weight potential per fruit
LeafPartitionFrac	0-1	Proportion of total biomass partitioned to Leaf (Note leaf is all above ground biomass that is not removed as product or remaining in permanent trunk)
ProductPartitionFrac	0-1	Proportion of total biomass partitioned to Product
RootPartitionFrac	0-1	Proportion of total biomass partitioned to Root

Transpiration also influences biomass growth by affecting the amount of water demanded in relation to the supply available in the soil for plant extraction daily. Transpiration related parameters are shown in Table 5.

Table 5. Transpiration related parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

Parameter	Unit	Description
Gsmax350	m/s	Maximum stomatal conductance at 350 ppm CO_2
R50	MJ/m^2	Net radiation levels at which g_s is half $g_s$max

Finally, plant growth and transpiration are also influenced by plant-structural parameters. These include, for example, the maximum depth of roots from where water can be extracted (MaxRootDepth) and the dry matter content of plant produce (ProduceDryMatterFrac) at harvest or maturity (Table 6).

Table 6. Plant structure related parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

Parameter	Unit	Description
AgeToMaxDimension	Y	Years until plant reaches mature size
AgeAtStartSimulation	Y	How old is the plant at the start of the simulation (needs to be 0 for annuals)
SeasonalDimensionPattern	0-1	Relative values for seasonal height and width at StartGrowth | FullCanopy | StartSenescence | Maturity
TrunkWtAtMaxDimension	g/m^2	The weight of perennial biomass when crop has reached max size
MaxRootDepth	mm	Potential depth that roots achieve when plant is mature
RootsInNeighbourZone	bool	Do roots grow into neighbouring zone if multi simulation run?
ProduceDryMatterFrac	0-1	Fraction of dry matter in produce

The value of plant structure parameters is given in Figure 6.

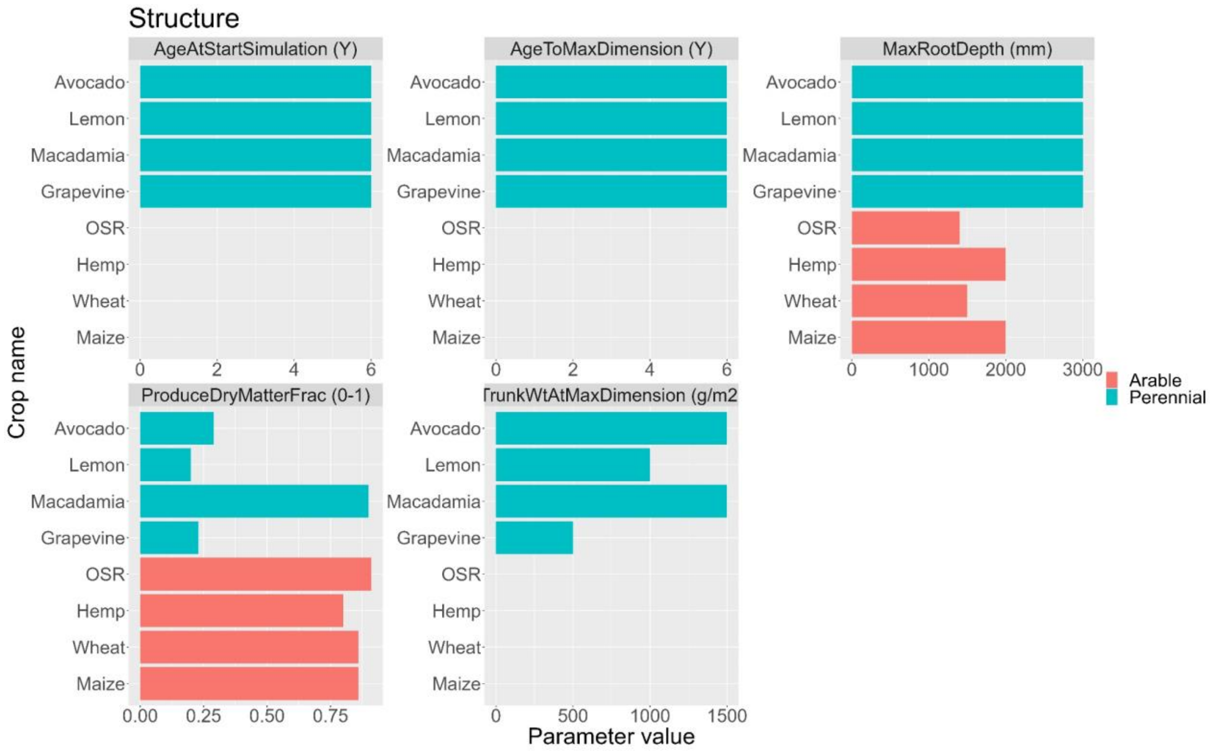

Figure 6. Plant structure parameters values in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

The additional fixed-value biomass accumulation parameters for all crops are shown in Figure 7.

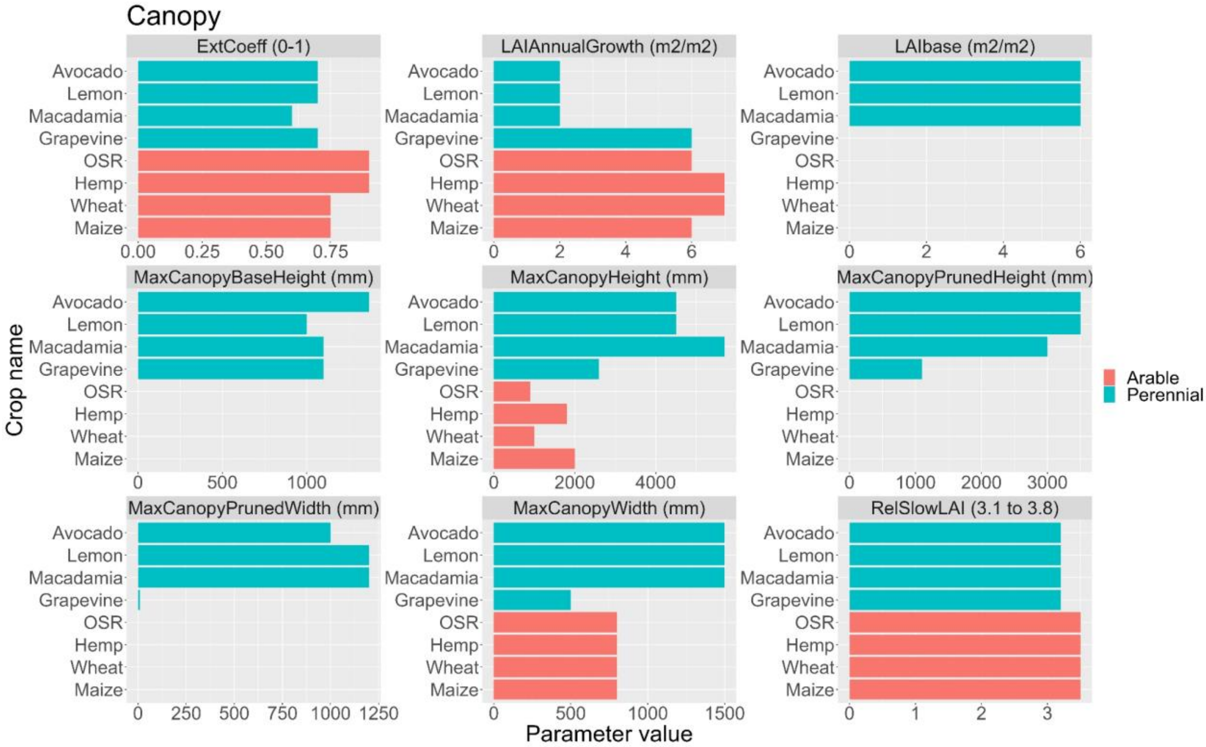

Figure 7. Values of static biomass parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

Values of transpiration related parameters for all crops are shown in Figure 8.

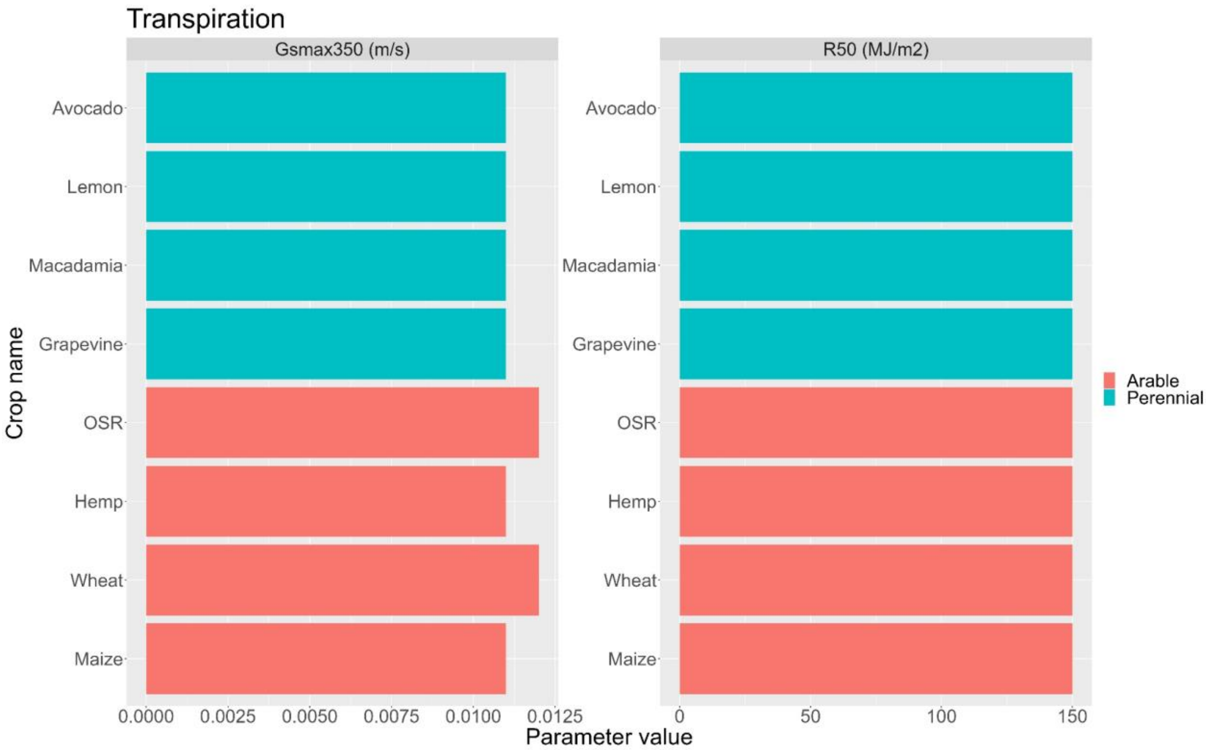

Figure 8. Transpiration-related parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

2.3.4 Stress factors

Potential rates of crop growth and/or development are reduced, or accelerated, by a wide range of stress factors. These are in large driven by environmental variables, providing dynamic yield responses to climate change across space and time by the model.

Table 7. Stress related parameters in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

Parameter	Unit	Description
Frost_Temp_X	ºC	Minimum temperatures for frost damage
Frost_Frac_Y	0-1	Frost damage at x-axes temperature
WaterStressLAI_Fw_X	0-1	Fractional degree of water stress
WaterStressLAI_Frac_Y	0-1	Fractional multiplier of LAI expansion rates
WaterStressExtCoeff_Fw_X	0-1	Fractional degree of water stress
WaterStressExtCoeff_Frac_Y	0-1	Fractional multiplier of extinction coefficient
WaterStressRUE_Fw_X	0-1	Fractional degree of water stress
WaterStressRUE_Fract_Y	0-1	Fractional multiplier of the RUE coefficient
WaterStressLAISenes_X	0-1	Fractional degree of water stress
WaterStressLAISenes_Y	0-1	The proportion of LAI senesced each day due to water stress
FlowerMaxTempStress_Temp_X	oC	Maximum temperature at flowering
FlowerMaxTempStress_Factor_Y	0-1	Multiplier of potential flower number at threshold MAXIMUM temperature
FlowerMinTempStress_Temp_X	oC	Minimum temperature at flowering
FlowerMinTempStress_Factor_Y	0-1	Multiplier of potential flower number at threshold MINIMUM temperature
FlowerWaterStress_X	0-1	Fractional degree of water stress
FlowerWaterStress_Y	0-1	Multiplier of potential flower number under water stress
RainfallExcessDamage_mm_X	mm/year	Annual rainfall amount
RainfallExcessDamage_Fract_Y	0-1	Fractional multiplier of produce (excess water damage)

The dynamic stress parameters, which respond to other driving factors, are shown in Figure 9 for all crops.

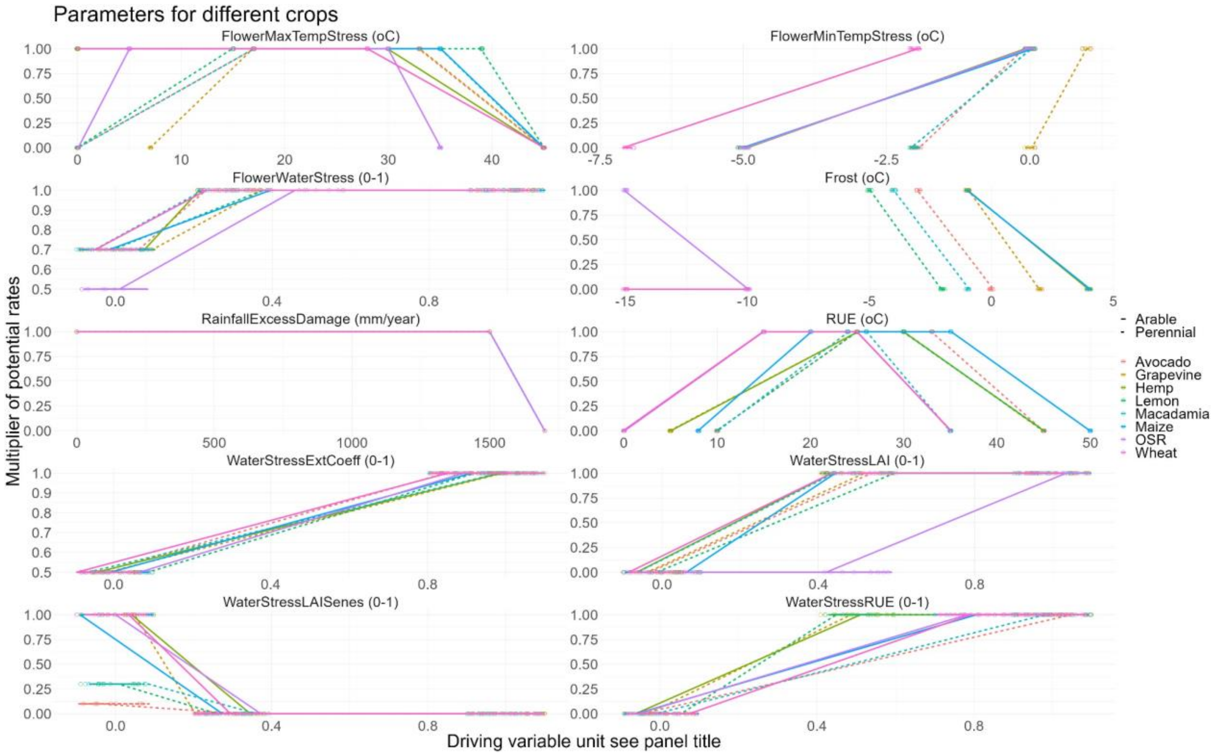

Figure 9. Stress related parameters for different crops in Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY).

The current documentation for the model, including its source code, can be openly accessed at the GitHub repository: github.com/APSIMInitiative/ApsimX/tree/master/Prototypes/DEROPAPY.

2.4 The spatiotemporal modelling framework

The simulations performed by APSIM-DEROPAPY, the newly developed APSIM-NextGen model (Section 2.3), were run in parallel with a High-Performance Computer (HPC) framework to enable multiple locations and time periods to be considered. Model runs for 30-year periods, at daily timesteps considering various RCP and GCM combinations, were spatialised across New Zealand using the ATLAS (Assessment Tool for Landscape Agricultural Systems) framework (Teixeira et al. 2020) to perform multi-year wide scale simulations of climate change impacts.

For this project, simulations were done considering lands suitable for arable and horticultural crops across New Zealand. These areas were identified by selecting categories 1 to 4 in the Land Use Categories (LUC) classification for New Zealand (Newsome et al. 2008). Within each 5 km climate grid cell, the three most predominant soils (i.e. soils with largest areas intersecting the grid) were considered based on the S-map database (Lilburne et al. 2004). The flow of information across the data pipeline is shown in Figure 10 and encompasses the following steps:

1. Input Database stage, which holds the base input data harmonised to the common VCSN spatial resolution.
2. Modelling stage, which encompasses the formatting of the data as input for APSIM to represent all selected crops within a consistent code-structure and parameterisation for simulations running in a High-Performance Computing (HPC) environment.
3. Output Database and Analysis stage, during which final outputs are stored, analysed, visualised and tailored for the next stage of the analysis, as inputs for land-use and economic models.

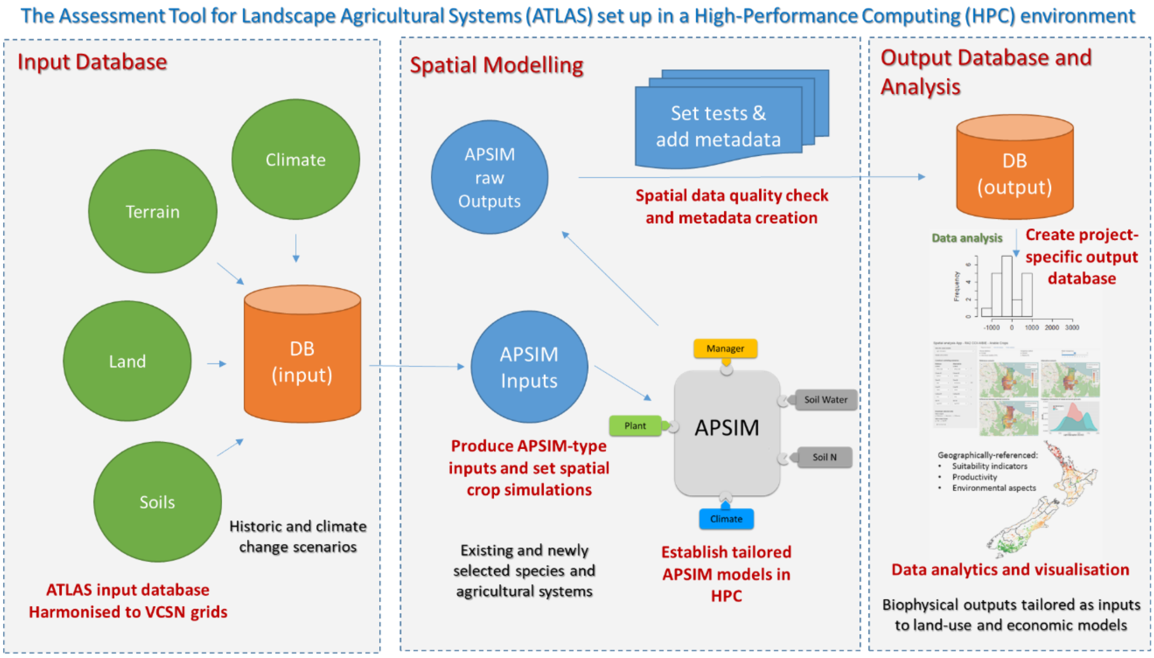

Figure 10. Schematic representation of Agricultural Production Systems sIMulator (APSIM) models within the spatial framework, ATLAS (Assessment Tool for Landscape Agricultural Systems), which runs multi-location and multi-year simulations in a High-Performance Computer (HPC) environment.

This system enabled yield from selected crops to be estimated for each location by considering a wide range of genotypes, climates, soils, and management combinations, representing both spatial and temporal variability in agricultural land uses across New Zealand. Finally, climate change effects on yield were estimated by calculating the difference between the baseline period (1975–2005) and future climate change scenarios for mid-century (2035–2065) or end-of-century (2070–2100). These allowed calculated 30-year medians and inter-annual yield variability.

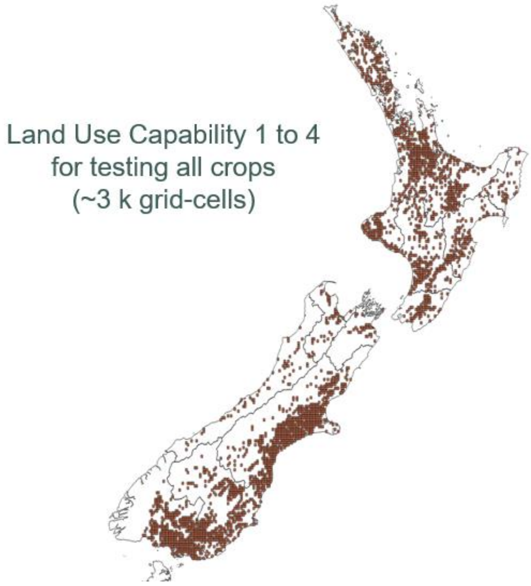

Figure 11. Arable and horticultural lands selected for simulations with Agricultural Production Systems sIMulator (APSIM)- Dynamic Environmental Response Of Phenology And Potential Yield (DEROPAPY) within the ATLAS (Assessment Tool for Landscape Agricultural Systems) framework.

2.4.1 Evaluation of model results

The model's fitness-for-purpose was indirectly evaluated using "sensibility" and "sensitivity" tests, considering simulated results of crop yield. For all crops, simulations of productivity were assessed across contrasting environmental conditions by:

1. Contrasting results across four or more different climatic locations (i.e. VCSN grid-cells)
2. Running crop models across 30-years of baseline daily weather conditions
3. Considering two different water supply managements (irrigated or rainfed)
4. Considering two different hypothetical soils with drastically contrasting plant available water (PAW) amounts at a 2 m depth. These were Sandy soils with 68 mm PAW and Silty soils with 473 mm PAW.

Results are shown in maps as median values over 30-year simulations per 5 km grid-cell or in box-violin plot distributions by crop.

or each crop, maps are divided in two panels. The left-hand map shows how much is currently produced ("baseline" values in kilograms per hectare per year). The right-hand map shows how crop yields are expected to change in the future — as a percentage of current levels (% of baseline) — based on different 30-year periods (mid- or end-of-the-century) and climate change scenarios (i.e. RCP, polled for all GCMs). These maps help highlight areas that currently produce less but might see big improvements, as well as regions that could lose productivity.

The box-violin plots expand the analysis by giving a more detailed view of how much crop yields are expected to increase or decrease in actual numbers (kg/ha per year). Such graphs offer a dual representation of yield (or yield change) distributions (Figure 12). The violin shape gives a kernel density estimation (i.e. curvilinear smooth distribution), while the boxplot provides key descriptive summary statistics. Specifically, the central box represents the interquartile range, spanning from the first quartile (Q1, 25th percentile) to the third quartile (Q3, 75th percentile), with the median indicated by a horizontal line. The whiskers typically extend to 1.5 times the interquartile range (IQR), identifying potential outliers beyond these bounds.

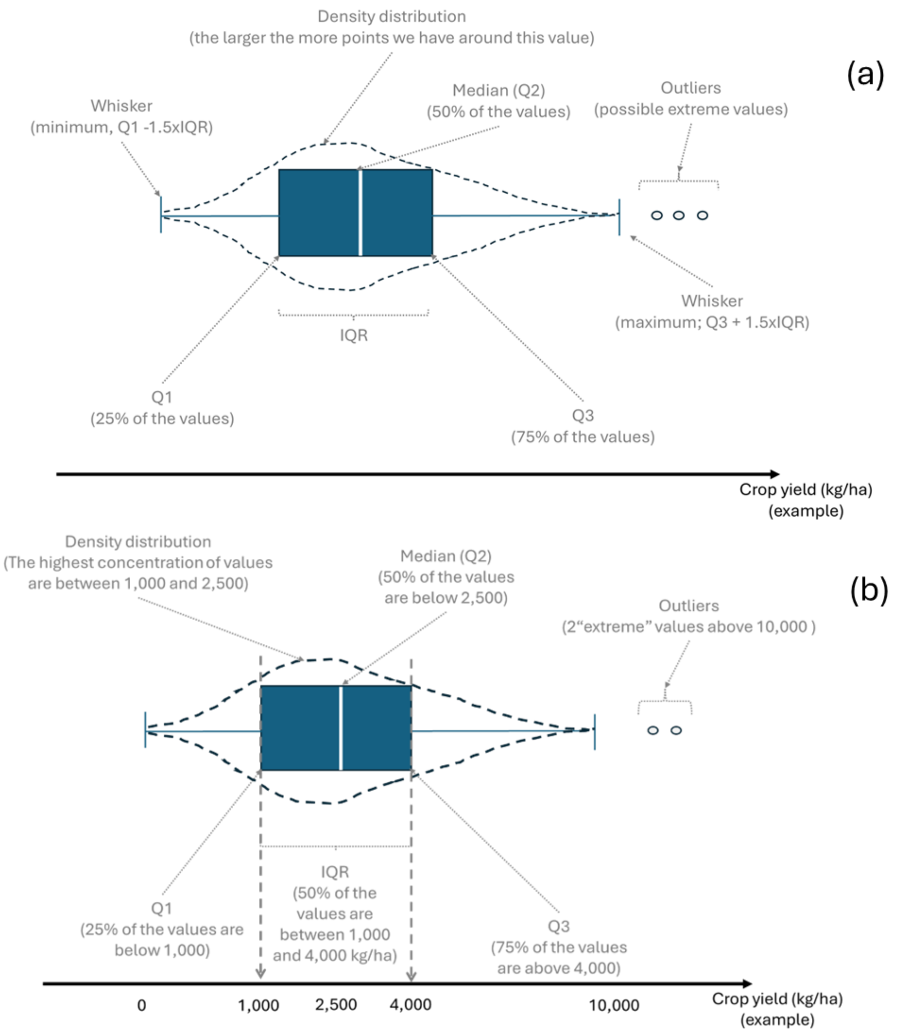

Figure 12. Schematic view of an interpretation of the box-violin plots showing quartiles (Q1, Q2 and Q3) and interquartile range (IQR) (a) and a hypothetical example of its use with crop yields for 30-year periods as in model simulations (b).

2.5 Crop species context, model testing and selected results

2.5.1 Maize (*Zea mays*)

Crop characteristics

Maize is a warm weather (i.e. C_4) crop originated in Central America. Globally, it is widely cultivated for grain, which is used for both human consumption and animal feed. Maize can also be grown for silage, an important feed supplement for wintering livestock in New Zealand (Wilson et al. 1994). Average silage yields are around 20 t/ha and high yields range from 25 to 30 t/ha in New Zealand under historical climatic conditions (Tsimba et al. 2013). The crop can be further utilised in the production of biofuels, oil and industrial starch. In New Zealand, maize is predominantly cultivated for silage in both islands to support the dairy industry. In the North Island, particularly due to its warmer climate and extended growing season, maize is also produced as grain for the internal market.

Climate change effects

Climate change effects on maize include warmer temperatures accelerating maize development, and therefore shortening the growing period, which leads to reduced yields due to less time for biomass accumulation through photosynthesis (Teixeira et al. 2018). Droughts and heat waves, particularly around the flowering stage, can also significantly reduce yields. However, areas that are currently unsuitable for maize cultivation due to low temperatures may become viable as temperatures rise. The effect of rising CO_2 is assumed negligible for maize, given the C_4 nature of the crop's photosynthetic pathway, but there is a reduction in water use as transpiration efficiency is enhanced (Bassu et al. 2014). For this study we simulated maize grain yields for a medium cycle duration hybrid. Tactical farmer adaptation by advancing sowing date with warming is considered, but shifts in hybrid cycle length are not yet explored at this stage. In summary, the main climate change effects considered for a maize grain assumed for this study are:

1. Cycle length shortening due to warming
2. Atmospheric CO_2 effect on crop transpiration
3. Heat stress on reproductive stages reducing grain yield
4. Drought stress on yield formation.

Model evaluation

For the test locations, maize grain yields ranged between ~2.5 and 13 t/ha, being consistently lower and more variable for rainfed and sandy soils than under irrigated and silty soil conditions (Figure 13). The upper limits simulated match well with recent survey statistics by FAR (FAR | Arable Industry Marketing Initiative, 2022) . Drought stress was the most prominent yield reducing factor for maize simulations. Assuming a harvest index of 50%, silage dry matter yields would range between 5 and 26 t/ha, which is close to measurements taken under resource supply extremes in Canterbury, New Zealand (Teixeira et al. 2014). The 30-year variability for silty soils was unrealistically narrow in warmer climates, indicating that the model might be underestimating yield changes under high temperature and high water supply conditions. Model inspection showed this lack of response was due to the oversimplified representation of biomass allocation to grains, which will be revisited in following model revisions. Nevertheless, current results give confidence that the maize yield simulations are sensible both considering median absolute values and the direction of responses to stress factors.

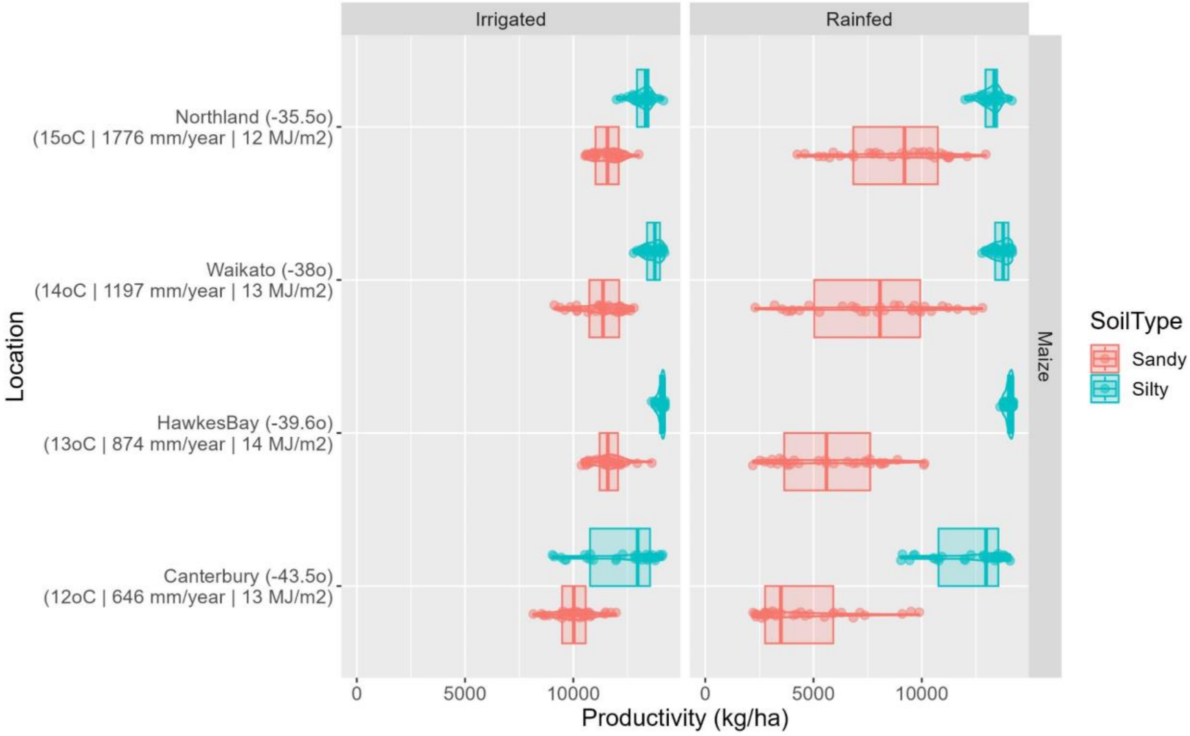

Figure 13. Sensitivity testing of maize grain yield simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975–2005). Values in parenthesis are latitude, mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

Simulations for maize show a clear pattern of yield increase projected for higher altitudes and most southern New Zealand regions (Figure 14). These environments are currently too cold to grow maize reliably but will become suitable in the future. The main driver of such yield increases was the lengthening of the available growth period under warmer temperatures, enabling sufficient time for grain formation and growth. Northern regions will not benefit from warming at the same rate and, in general, show stagnated yields (Figure 15). Our simulations indicate minimal yield losses for the crop in the warmest northern regions of New Zealand. This contrasts with more detailed modelling which showed that without some level of adaptation, such as the use of longer-cycle hybrids, there is a risk of yield reductions in northern regions due to the shortening of growth cycles in these areas (Rutledge et al. 2017; Teixeira et al. 2018). Given the fact that we considered only a single mid-cycle hybrid, our results can be considered conservative regarding yield damage risks.

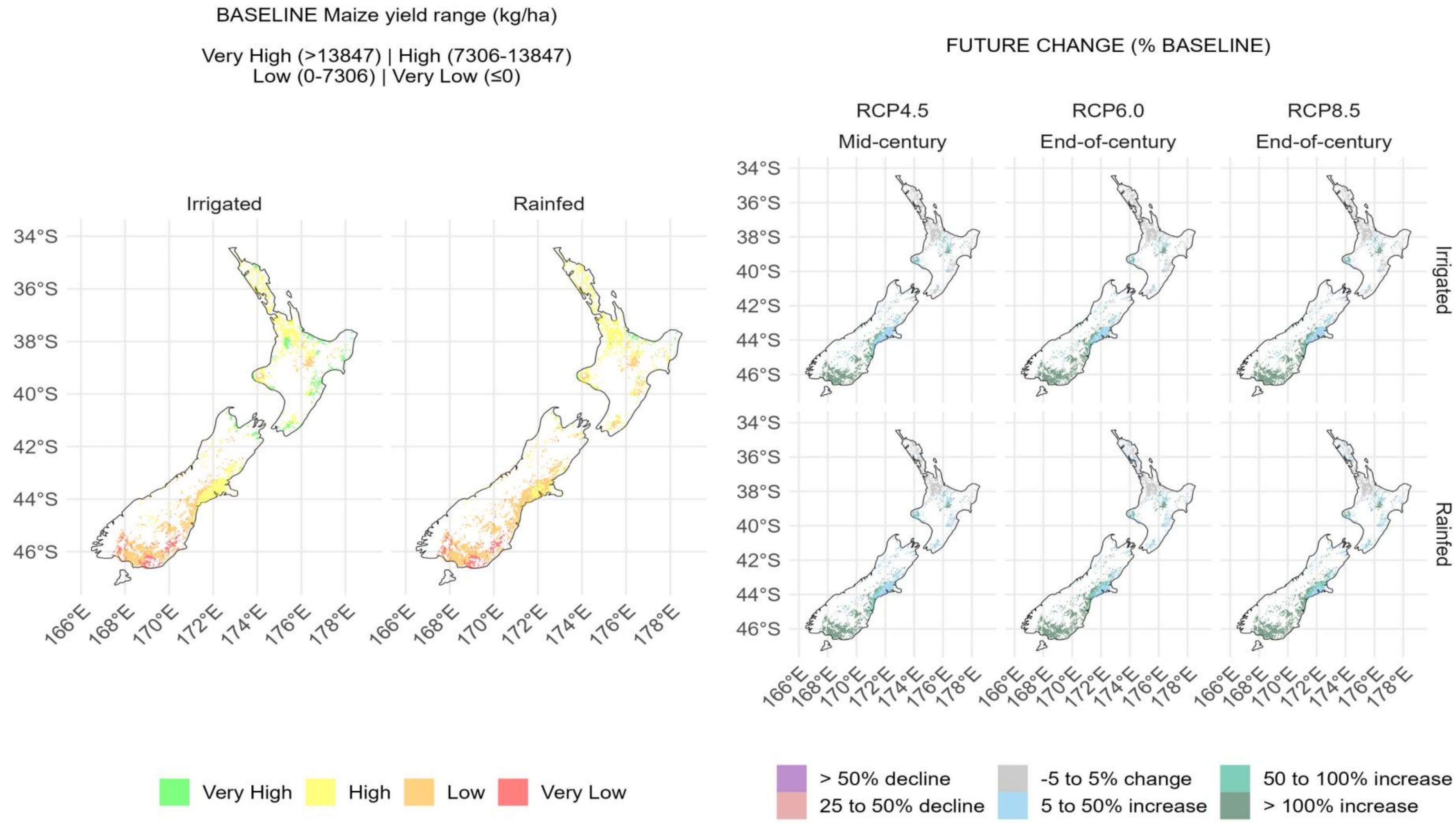

Figure 14. Median 30-year yield of maize grain (kg/ha) across New Zealand for the baseline and percent changes for selected climate change scenarios.

Absolute yield differences, estimated for each New Zealand region (5, Annex), can be seen for selected regions in Figure 15. For example, these ranged from null to slightly negative in Auckland and Nelson, to more than 10 t/ha yield increase in some grid-cells across Southland for RCP 8.5.

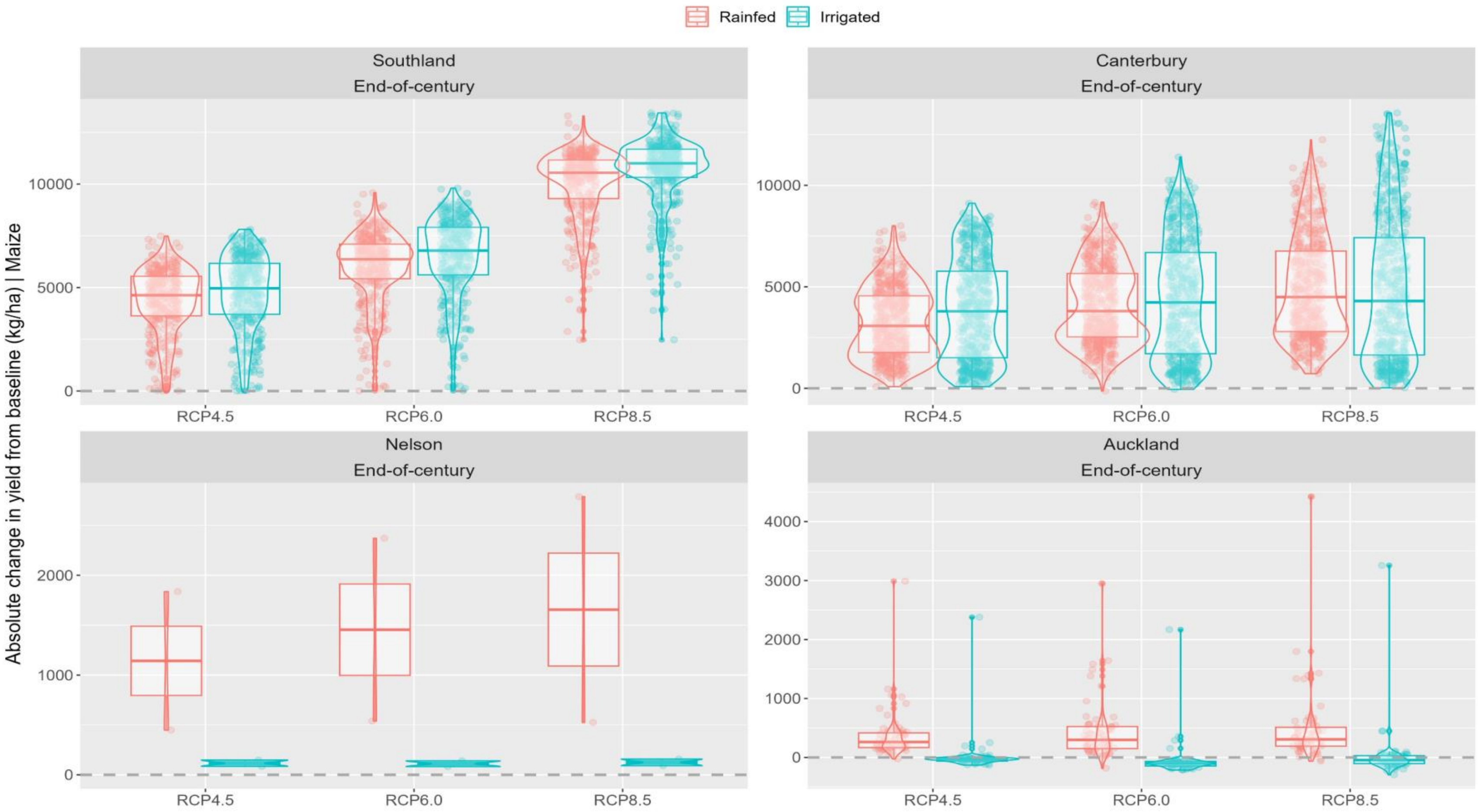

Figure 15. Yield differences for maize under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

2.5.2 Wheat (*Triticum aestivum*)

Crop characteristics

Wheat is a C_3 (i.e. cool weather) cereal crop that traces its origins to the Near East's Fertile Crescent. It is a staple food, primarily cultivated for its grain for human consumption or grain and fodder for animal feed. In New Zealand, wheat is predominantly grown in the South Island, with the Canterbury Plains as a key region, to support the production of grain for the domestic flour and baking industry, or for livestock feeding as forage-wheat (NZGSTA 2020).

Climate change effects

Climate change impacts include rising temperatures that reduce wheat yields, particularly in warmer regions, due to the shortening of production cycles, heat stress near flowering and increased water demand when supply (rainfall or irrigation) is insufficient (Jamieson and Cloughley, 1998). Higher levels of atmospheric CO_2 can enhance photosynthesis rates and transpiration efficiency, potentially increasing yields as in other C_3 crops (Wheeler et al. 1996). But this benefit must be considered in relation to other stresses such as more frequent droughts and extreme weather events. The main climate change impacts considered in this study for wheat are:

1. Cycle length shortening with warming
2. Atmospheric CO_2 effect on crop photosynthesis
3. Atmospheric CO_2 effect on crop transpiration
4. Heat stress on flowering time
5. Drought reduction on canopy expansion and photosynthesis
6. Change to development rates and overlap with stresses (e.g. heat or frost)

Model evaluation

Wheat meadian grain yields ranged from 5 to 13 t/ha across four contrasting climates (e.g. 9 to 13°C of mean temperature and 560 to 1600 mm/year rainfall) and the two hypothetical soil types (Figure 16). This yield range realistically encompasses current average productivity in New Zealand, but does not represent highest observed field yields in the country. Similar to maize, overall patterns of yield response to soil and climate were sensible. For instance, low rainfall locations (Canterbury and Central Otago) showed higher variability and lower yields than high rainfall areas (Gisborne and Southland), particularly for sandy soils. The lowest yields in Central Otago, where variability was the largest, were due to low temperature and frequent drought events particularly for rainfed crops on sandy soils. The interannual variability simulated for wheat on silty soils was very low in three of the four test locations. This was in part due to the absence of drought stress events for autumn sown crops, which are subjected to more abundant rainfall, particularly considering soils with extremely high capacity to hold water. Methods to evaluate accuracy of variability estimates at high yield levels, in wheat and other crops, could be investigated in future model development iterations.

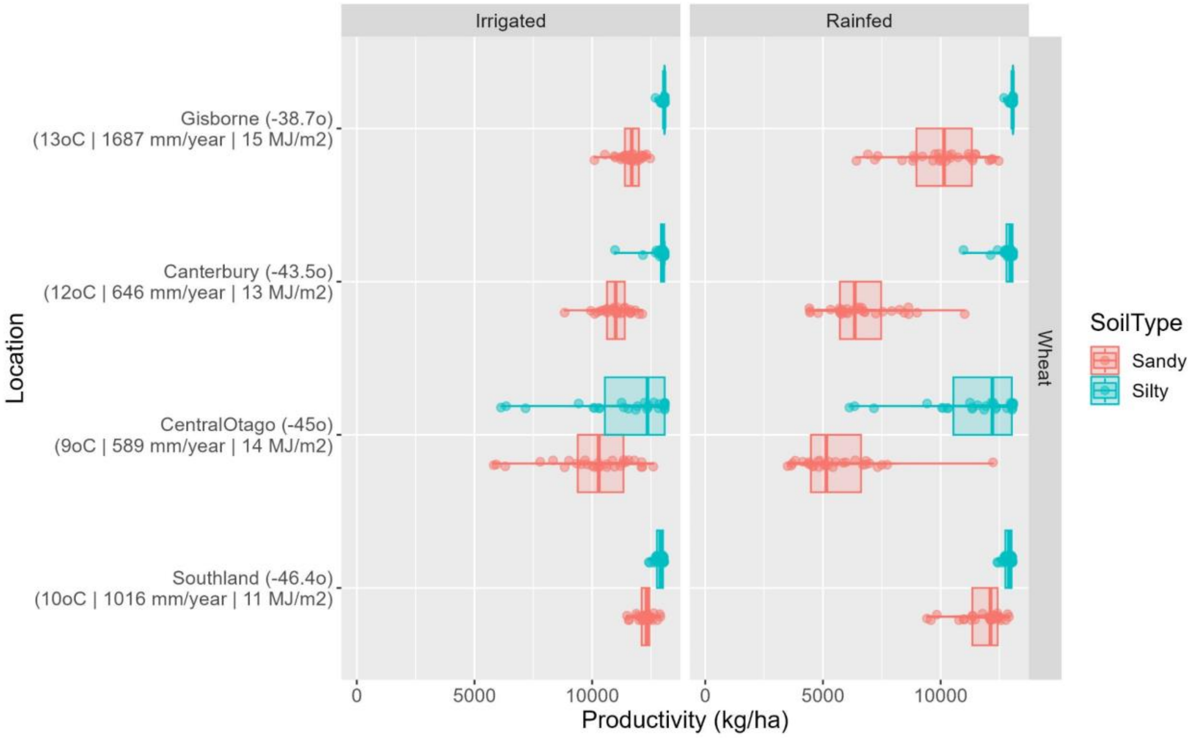

Figure 16. Sensitivity of wheat grain yield simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975–2005). Values in parenthesis are latitude, mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

For irrigated wheat, map results indicate negligible yield changes across most arable lands. For rainfed crops, a moderate increase (5 to 50%) was projected for the east coast of the North Island and in Central Otago (Figure 17) although, as expected, irrigated crops outperformed rainfed crops under current and future conditions. These increases in yield projected for rainfed crops in regions expected to become drier indicate that water use efficiency enhancements under high CO_2 must be further reviewed in the wheat model.

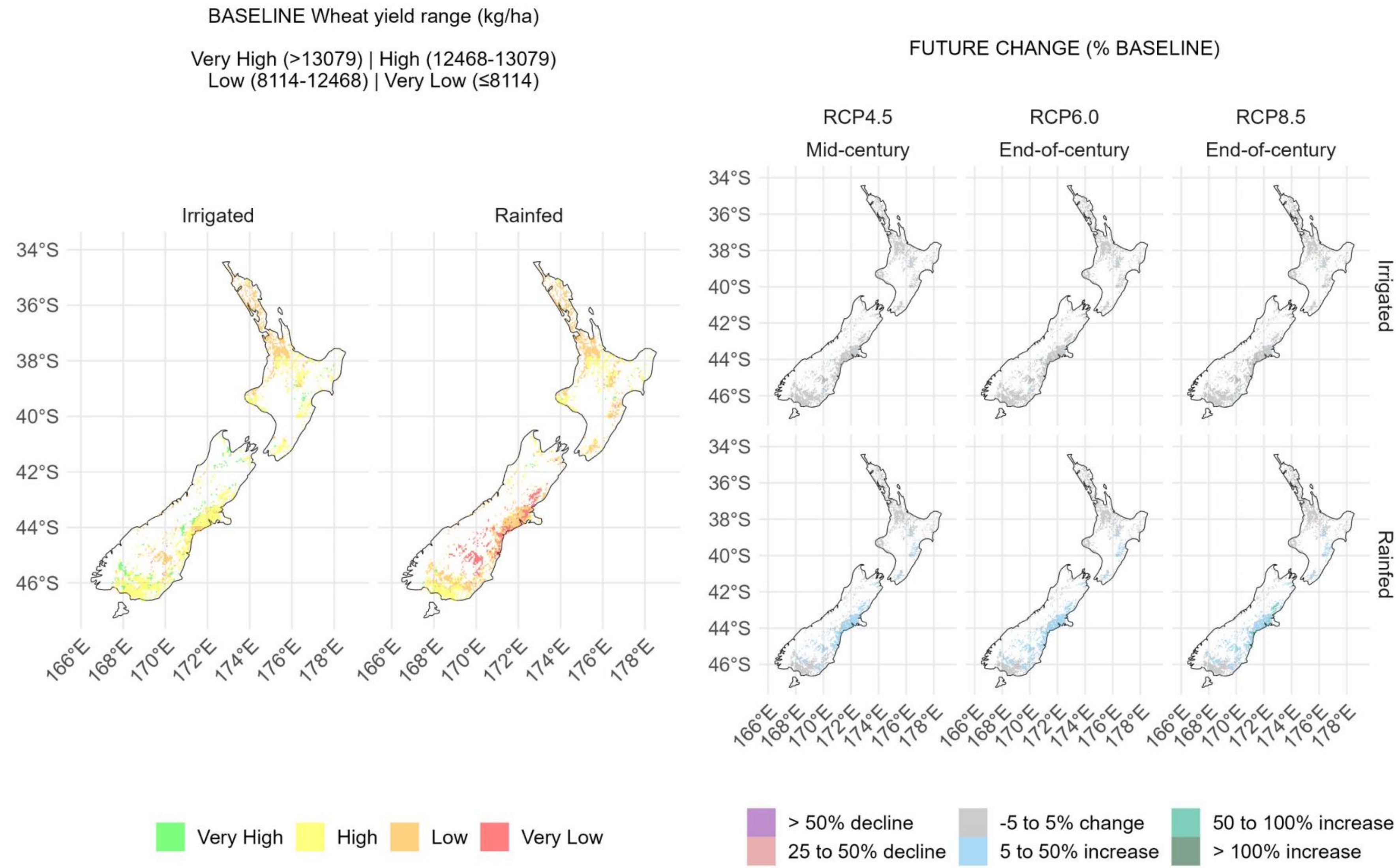

Figure 17. Estimated yield of wheat grain (kg/ha) across New Zealand for the baseline scenario and percent changes for selected climate change scenarios.

For wheat, the only two regions that showed absolute yield declines, for some grid-cells, were Otago and Canterbury for irrigated crops (Figure 18). Further analysis indicated that heat stress reduced flower numbers in these regions. These regions however, like others such as Marlborough and Hawke's Bay, mostly showed increases in rainfed yields when under more stringent climate change scenarios. In rainfed crops, this suggests negative effects on yields were counterbalanced by increased radiation and transpiration efficiencies under high CO_2, resulting in increased yield under climate change conditions. Potentially limited response of wheat to drought stress is an area for future improvement.

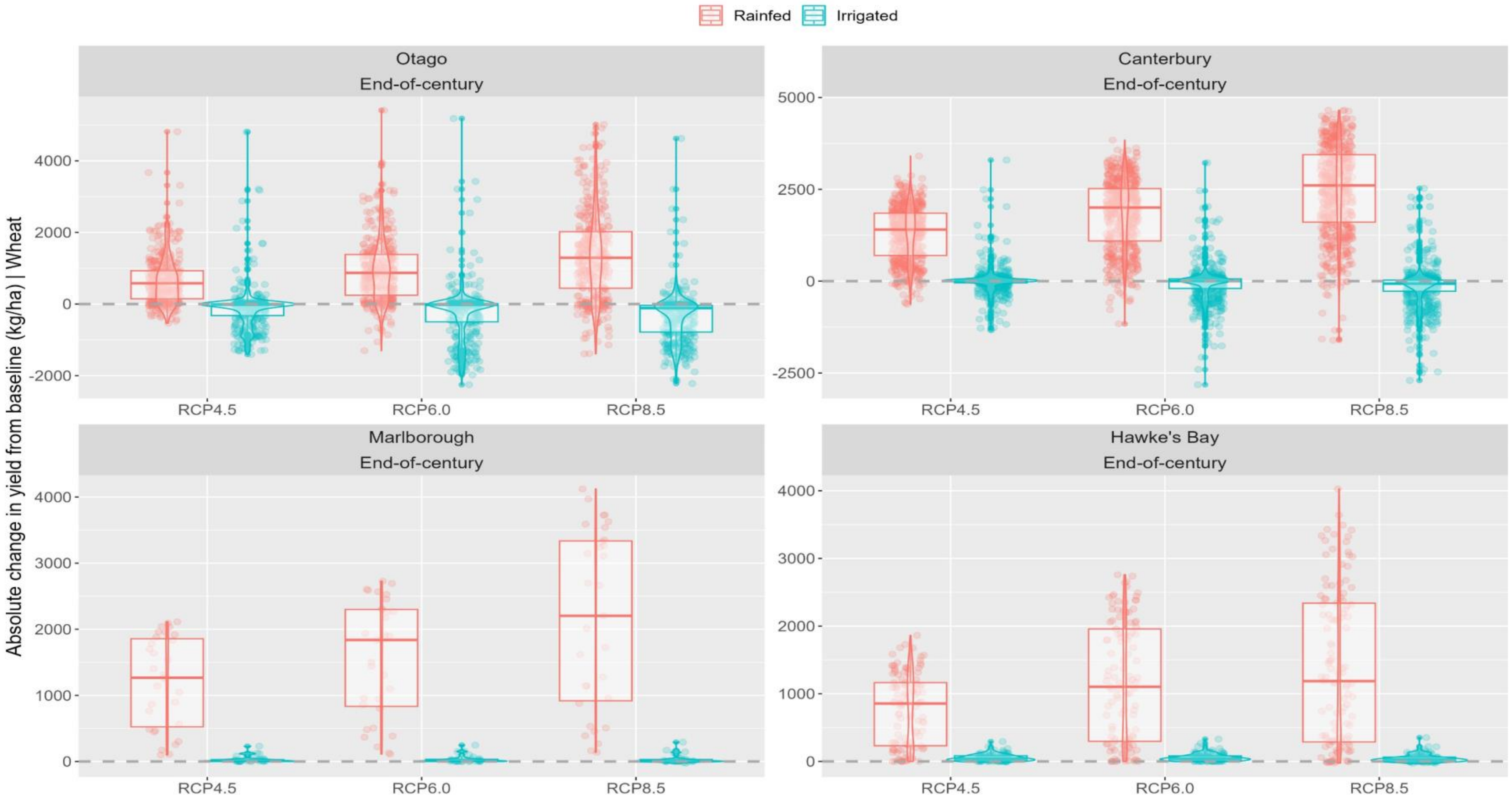

Figure 18. Yield differences for wheat under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

2.5.3 Hemp (*Cannabis sativa*)

Crop characteristics

Hemp is a cool weather (i.e. C_3) multipurpose crop that originated in Central Asia. It is cultivated for fibre production, which is used for multiple outcomes (textiles, rope, and paper) as well as for its seeds, which are processed into oil (Dudziec et al. 2024). Hemp also has other industrial applications such as bioplastics and biofuels. In New Zealand, hemp is an emerging crop, grown primarily for industrial fibres and seeds used in health and high value food products. Additionally, hemp oil is used in cosmetics and dietary supplements.

Climate change effects

Climate change impacts on hemp include reduced productivity in areas affected by more frequent and severe droughts, when irrigation is not applied. The main climate change impacts considered for hemp are:

1. Cycle length shortening with warming
2. Atmospheric CO_2 effect on crop photosynthesis
3. Atmospheric CO_2 effect on crop transpiration
4. Heat stress on flowering time
5. Drought reduction on canopy expansion and photosynthesis
6. Change to risk of frost from phenology changes with warming.

Model evaluation

Simulated median yields of hemp ranged from ~1.0 to 3.8 t/ha across the 4°C temperature range (10 to 14°C) from four tested locations. With the exception of the Southland irrigated scenario, sandy soils showed lower yields and higher variability than silty soils due to drought stress, as expected. Lowest yields were estimated for Southland (~1.2 t/ha), which indicates sensible responses to low temperature stress in the model.

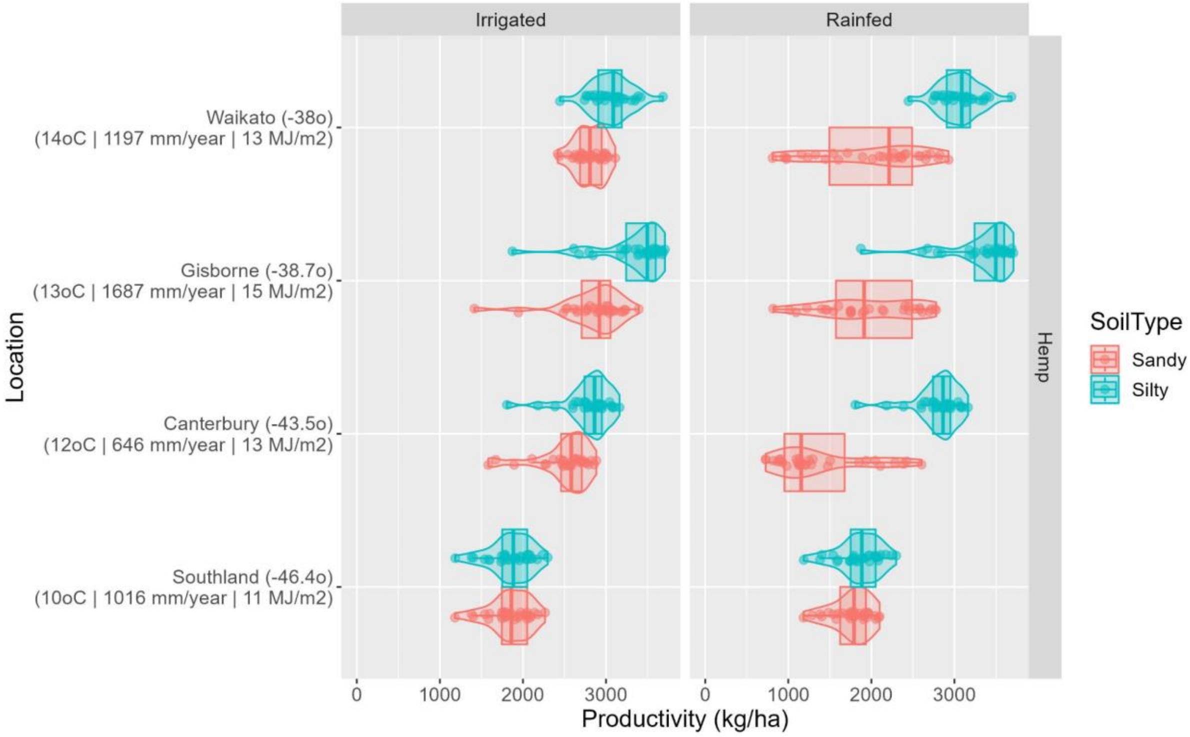

Figure 19. Sensitivity of hemp grain yield simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975–2005). Values in parenthesis are latitude, mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

Simulation results (Figure 20) indicate a moderate increase (5 to 50%) for hemp yields in warmer (northern) areas, more widespread under moderate warming (RCP 4.5 mid-century). The highest percentage of yield increases was in current low-yield southern areas of New Zealand. In contrast, the east coast of both islands, and central South Island, showed a strong pattern of yield decline (≥ 50%) with warming, particularly under the more extreme RCP 8.5 scenario. Model inspection showed that this was mainly due to the high incidence of heat stress in areas where maximum temperatures frequently surpassed optimum threholds for the crop, particularly during the flowering period.

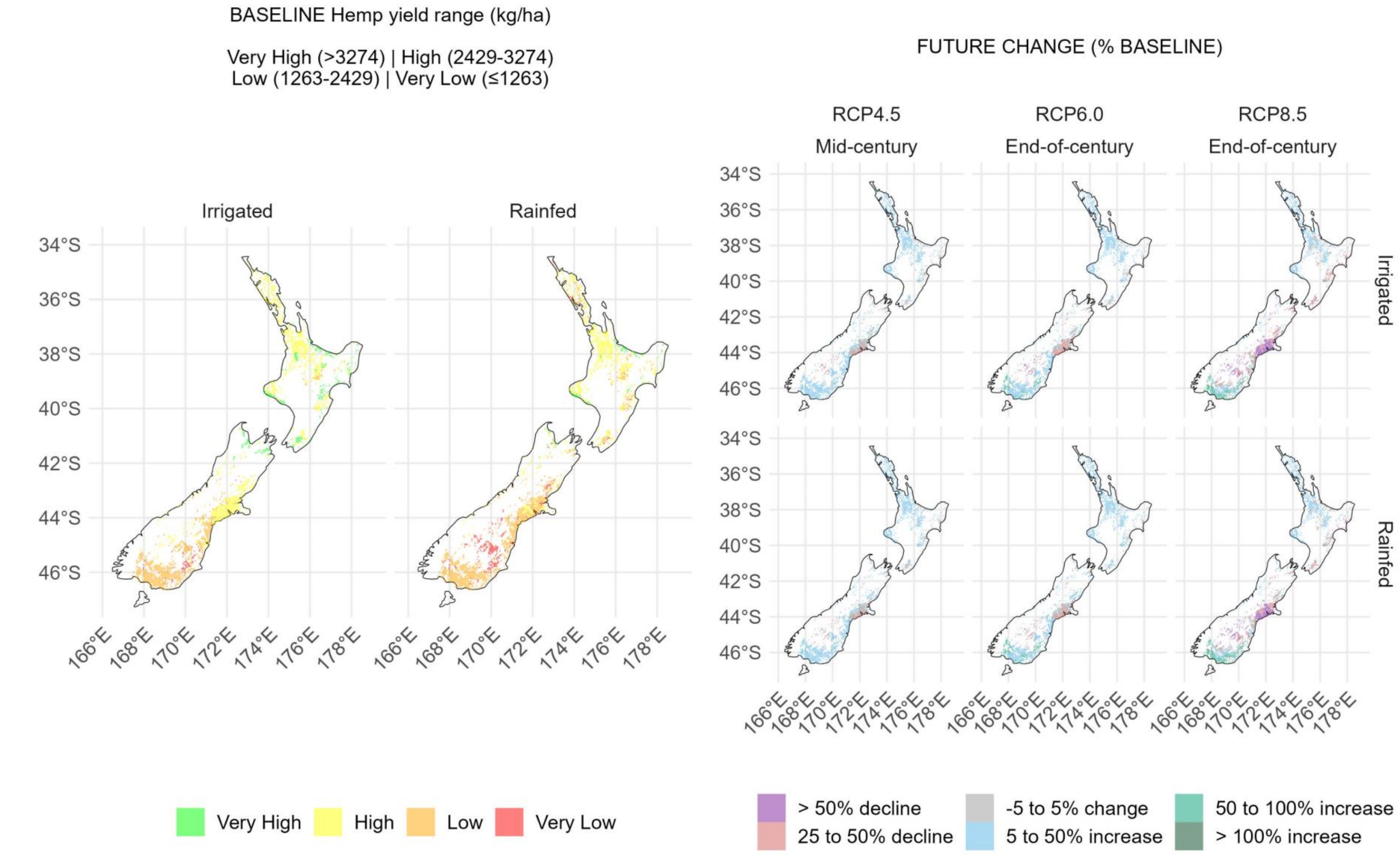

Figure 20. Estimated yield of hemp seed (kg/ha) across New Zealand for the baseline scenario and percent changes for selected climate change scenarios.

Regionally, largest absolute yield changes occurred in Southland, Otago, Gisborne and Canterbury (Figure 21). These regions showed more volatile responses, with some grid-cells showing positive and others negative yield changes. This is because average temperatures increased to near the optima for photosynthesis and canopy expansion, increasing yields in years when other stresses were negligible. Concomitantly, higher temperatures caused higher incidence of heat stress during specific years, reducing yield mainly during the flowering period.

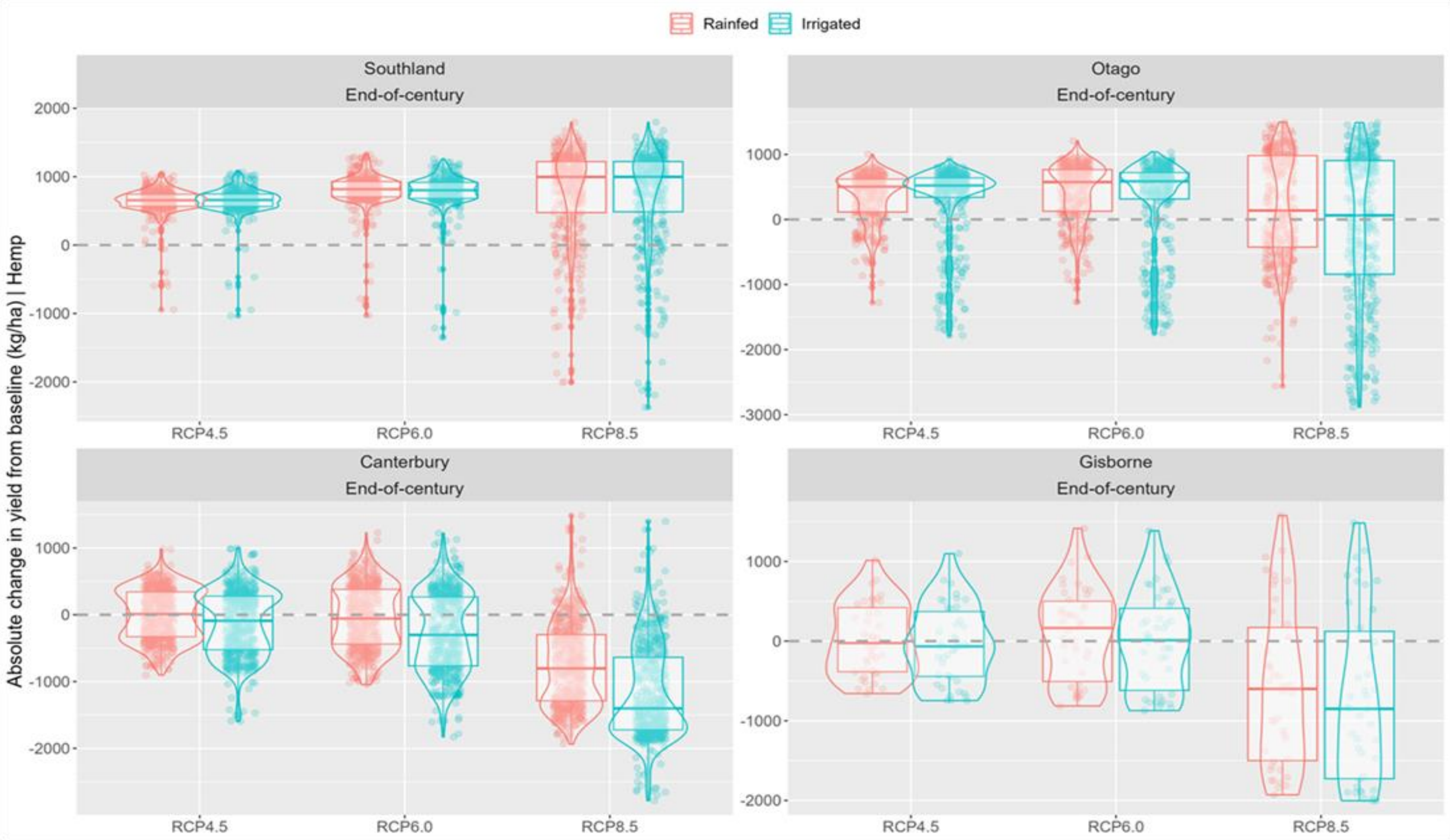

Figure 21. Yield differences for hemp under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

2.5.4 Oilseed rape (*Brassica napus*)

Crop characteristics

Oilseed rape originated in Europe and is cultivated for its oil-rich seeds. The oil extracted from the seeds is used for cooking and as a biofuel, while the remaining meal is used as animal feed. Oilseed rape is also beneficial as a rotational crop, improving soil health and reducing pest pressure in agricultural systems such as from cereals (Daly and Martin, 1988).

In New Zealand, the cultivation of oilseed rape is concentrated in the South Island, where it is grown primarily to produce cooking oil and biodiesel. The byproducts are used as livestock feed, contributing to the multipurpose use in farming operations.

Climate change effects

Climate change impacts on oilseed rape include higher than optimal temperatures and more frequent droughts that could lead to reduced yields, particularly if grown in water-scarce regions. However, warmer conditions in areas that are currently too cold to grow the crop may allow its extension. Changes in pest and disease pressure, not yet considered in this study, are also expected with climate change. This could increase the need for integrated pest management strategies for this crop.

The main climate change impacts considered for oilseed rape in this study are:

1. Cycle length shortening with warming
2. Atmospheric CO_2 effect on crop photosynthesis
3. Atmospheric CO_2 effect on crop transpiration
4. Heat stress on flowering.

Model evaluation

Oilseed rape yieds varied from 4 to 7 t/ha across the four tested locations (Figure 22). Yield estimates showed a low variability across 30 years when compared to other crops and field records. Part of this lack of variability may be explained by the fact that the crop is sown in autumn when drought stress is less intense. This also implies less exposure to spring-summer drought events and extremes of high temperatures. Nevertheless, the high yields with limited variability must be interpreted with caution as the model may not yet be sufficiently sensitive to the combinations of environment and management stresses considered. Gisborne, the warmest location, was the environment where temperature and drought stress responses were more prominent showing greater variability, but only on sandy soils. The direction of drought stress responses was nevertheless sensible, with slightly lower yields in sandy soils, particularly for rainfed conditions.

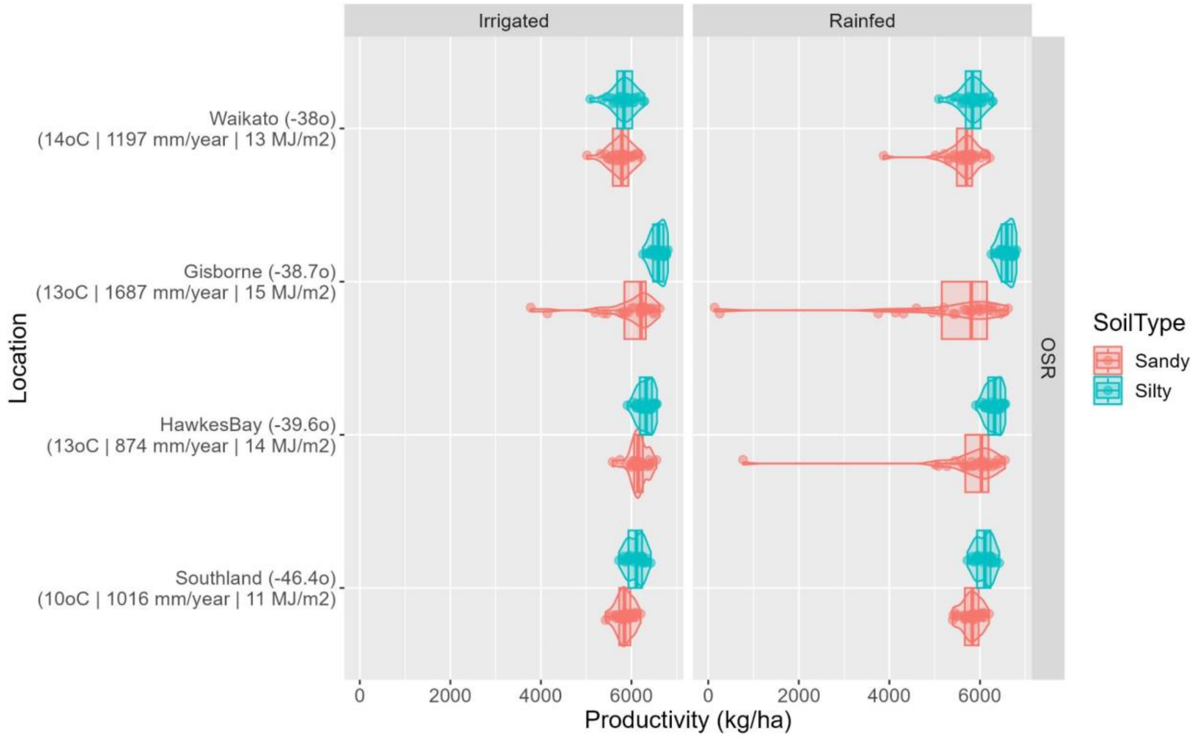

Figure 22. Sensitivity of oilseed rape grain yield simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975-2005). Values in parenthesis are latitude, mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

For oilseed rape, simulations suggest from minimum change (-5 to +5%) to moderate (5 to 25%) to high (≥50%) yield declines in the northern regions. This was mainly due to heat stress on grain formation during flowering and reduction in the growing cycle length. These are locations where yields are currently the lowest. Moderate yield increase (5 to 50%) was projected across the central and eastern parts of the South Island. The same regions showed higher rates of yield increase (50 to 100%) at more extreme climate scenarios (RCP 8.5 end-of-century). This was due to an increase in light interception and efficiency of radiation use as low-temperature limitations were minimised in the central southern areas of the country.

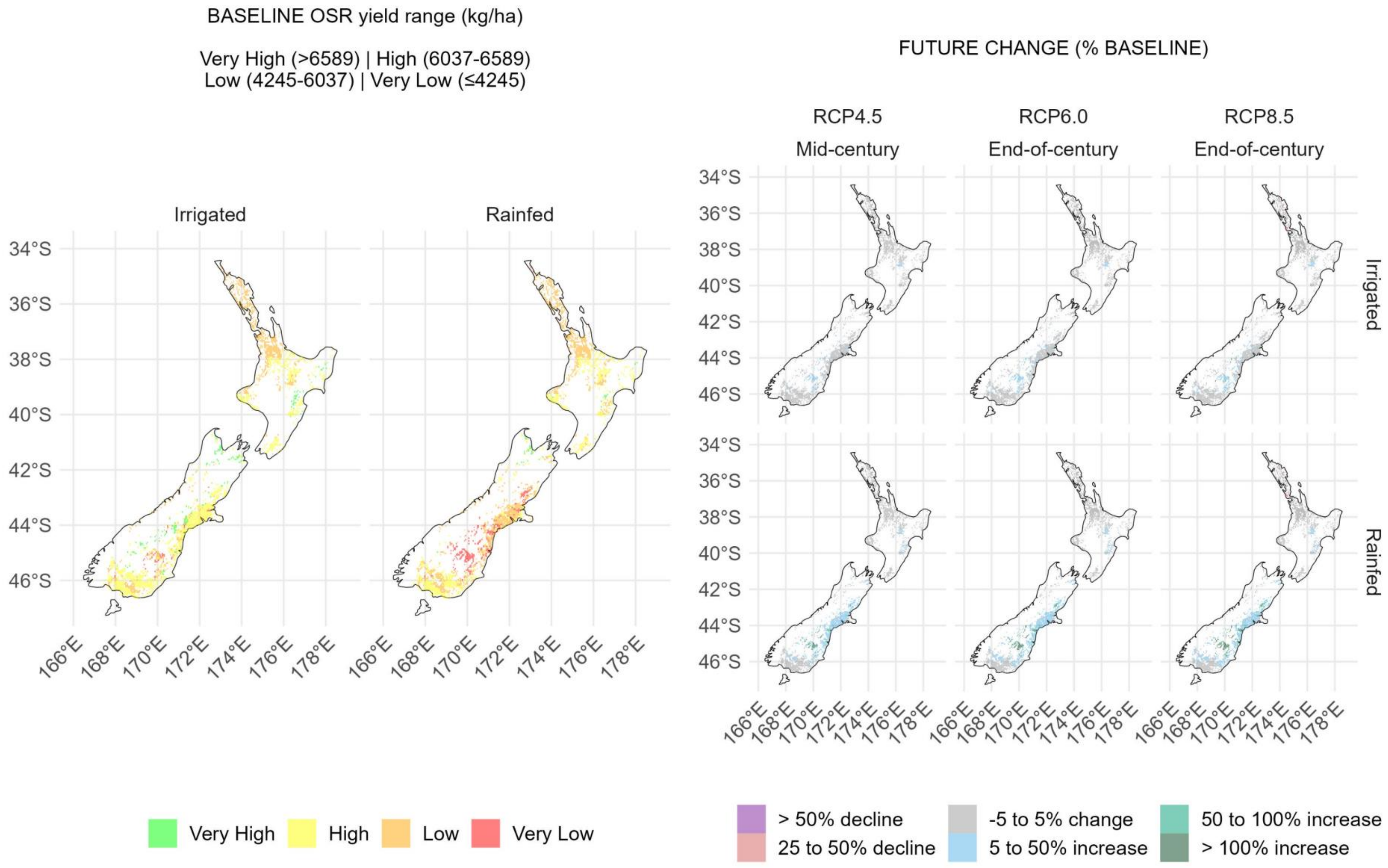

Figure 23. Estimated yield of oilseed rape (kg/ha) across New Zealand for the baseline scenario and percent changes for selected climate change scenarios.

In alignment with the spatial patterns in the Figure 23, Auckland, Waikato and Northland regions show yield decline for oilseed rape while Otago and Canterbury show largest yield increases, particularly for rainfed crops (Figure 24).

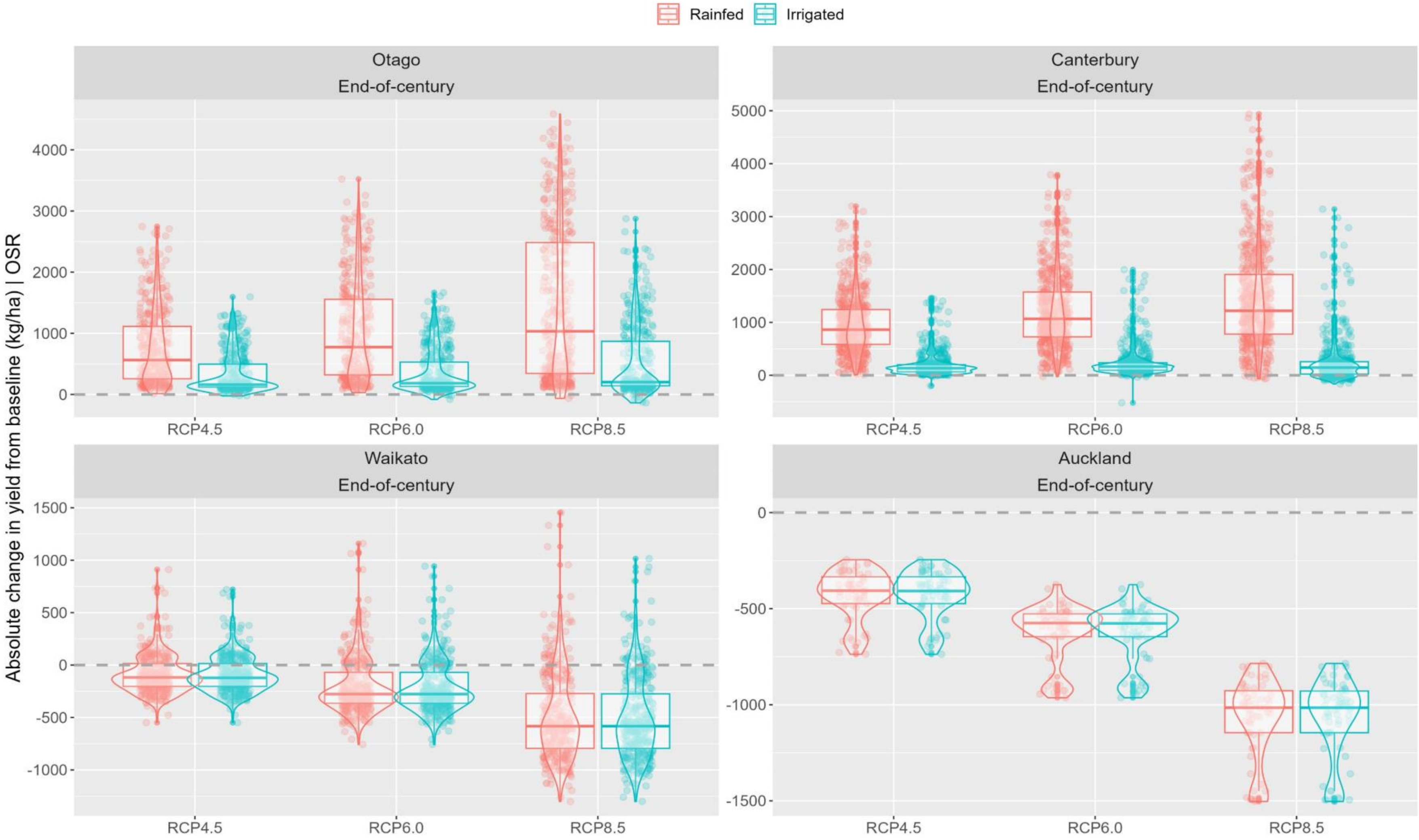

Figure 24. Yield differences for oil seed rape under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

2.5.5 Grapevine (*Vitis vinifera*)

Crop characteristics

Grapevines are woody perennial plants native to the Near East, modern-day Turkey and the Caucasus. Grapes are cultivated for a variety of purposes, including fresh consumption, dried as raisins, and to produce wine and juice. Grapeseed oil, extracted from the seeds, is utilised in culinary and cosmetic applications.

The wine industry is a significant export sector for New Zealand (Gabzdylova et al. 2009). In New Zealand, grapevines are grown primarily for wine production, with the regions of Marlborough and Central Otago being particularly renowned for their Sauvignon Blanc and Pinot Noir wines, respectively.

Climate change effects

Climate change effects include warmer temperatures changing timing of bud-break, *verasion* and harvesting (Ausseil et al. 2021). These also impact operations and can affect the quality of wine, especially in regions where grapes ripen too quickly. Some areas may become too hot for high-quality grape production, while cooler regions may become suitable for viticulture as temperatures increase.

The main climate change impacts considered for the *Sauvignon Blanc* grapevines assumed in this study are:

1. Cycle length shortening with warming
2. CO_2 effect on crop photosynthesis
3. CO_2 effect on crop transpiration
4. Heat stress during flowering time
5. Drought reduction on canopy expansion and photosynthesis
6. Change in phenology affecting risk of frost with warming.

Model evaluation

Simulations for grapevine showed yield ranges between 1.5 and 21 t/ha across four tested climates (Figure 25). Although these are within realistic ranges for *Sauvignon Blanc* crops, the 30-year interannual yield variability of simulations was wider than previously reported for New Zealand. In contrast, for the rainfed sandy soils conditions, there was a narrower variability centred around relatively low yields. Drought stress for rainfed conditions, particularly on sandy soils, was the most impactful yield-reducing factor. This coincides with the fact that irrigation is widespread in New Zealand orchards. A deeper analysis of model results indicated that the lowest yields were mostly driven by reduced fruit number in response to heat stress events during the flowering period. Under more stringent climate change scenarios, the maximum temperature threshold of 33°C assumed for heat stress was crossed during multiple years in all locations. There is considerable uncertainty about yield sensitivity to heat stress, which translates into uncertainty about such large yield variability, implying in cautious interpretation of extreme increases or declines. Again, sensible median yields and the response to soil and water supply provide confidence in the use of the model for the current project even though variability might be overestimated.

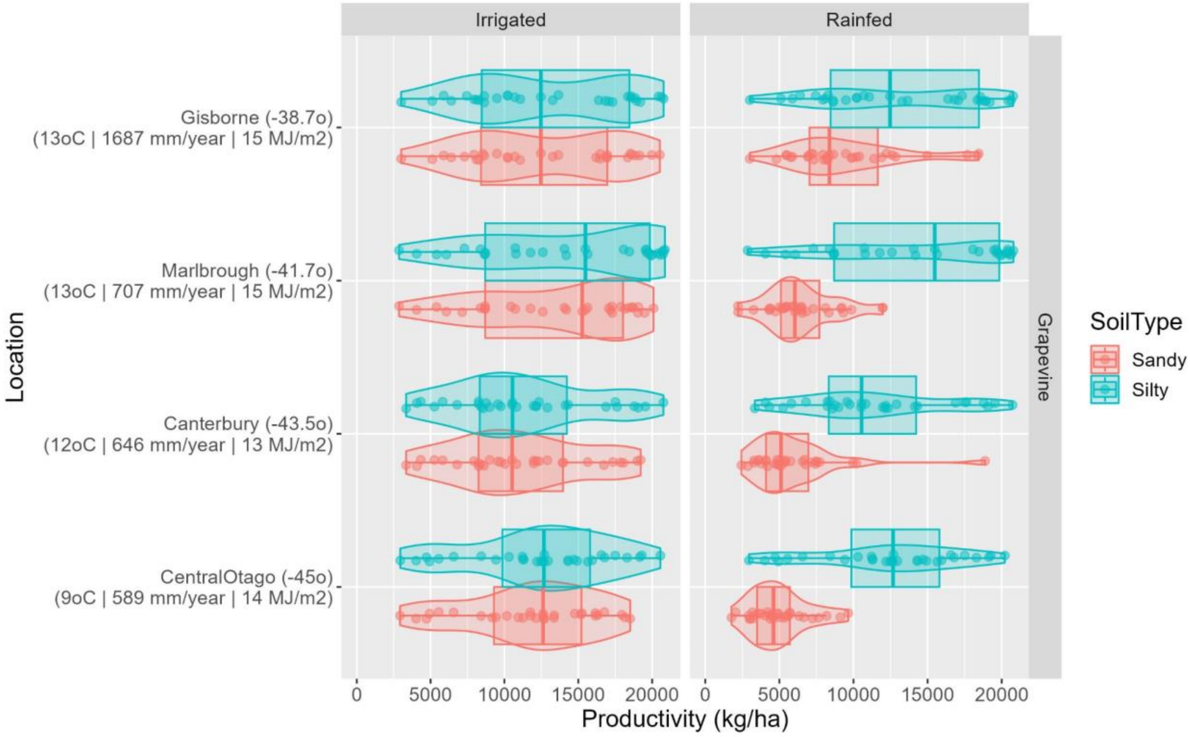

Figure 25. Sensitivity of grape simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975–2005). Values in parenthesis are latitude, mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

For most of New Zealand's North Island, there was a slight to moderate (5 to 50%) increase in yields with warming scenarios. The highest magnitude of yield increases was however found in the South Island, particularly in currently low-yielding areas. There were some hotspots of yield decline (25 to 50%) found in east coastal locations. These patterns were mostly explained by high temperatures causing heat stress during the flowering period in future climates.

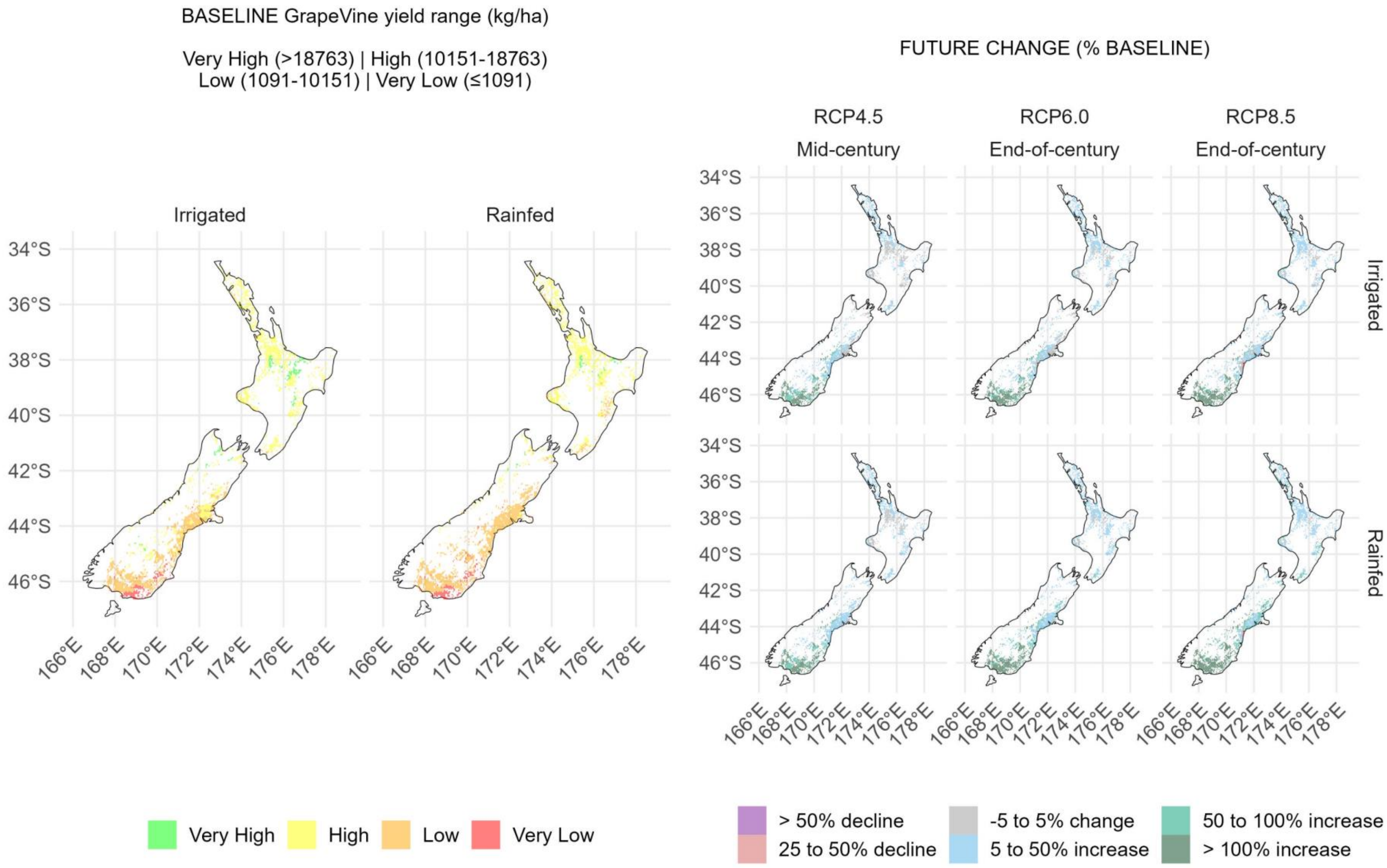

Figure 26. Estimated yield of grapevines (kg/ha) across New Zealand for the baseline scenario and percent changes for selected climate change scenarios.

Examples of regions with absolute yield increases were Southland and Central Otago (Figure 27). In contrast, Nelson showed consistent yield declines. Heat stress during flowering was again the main driver of such decline, limiting the number of fruits per hectare during crop maturation.

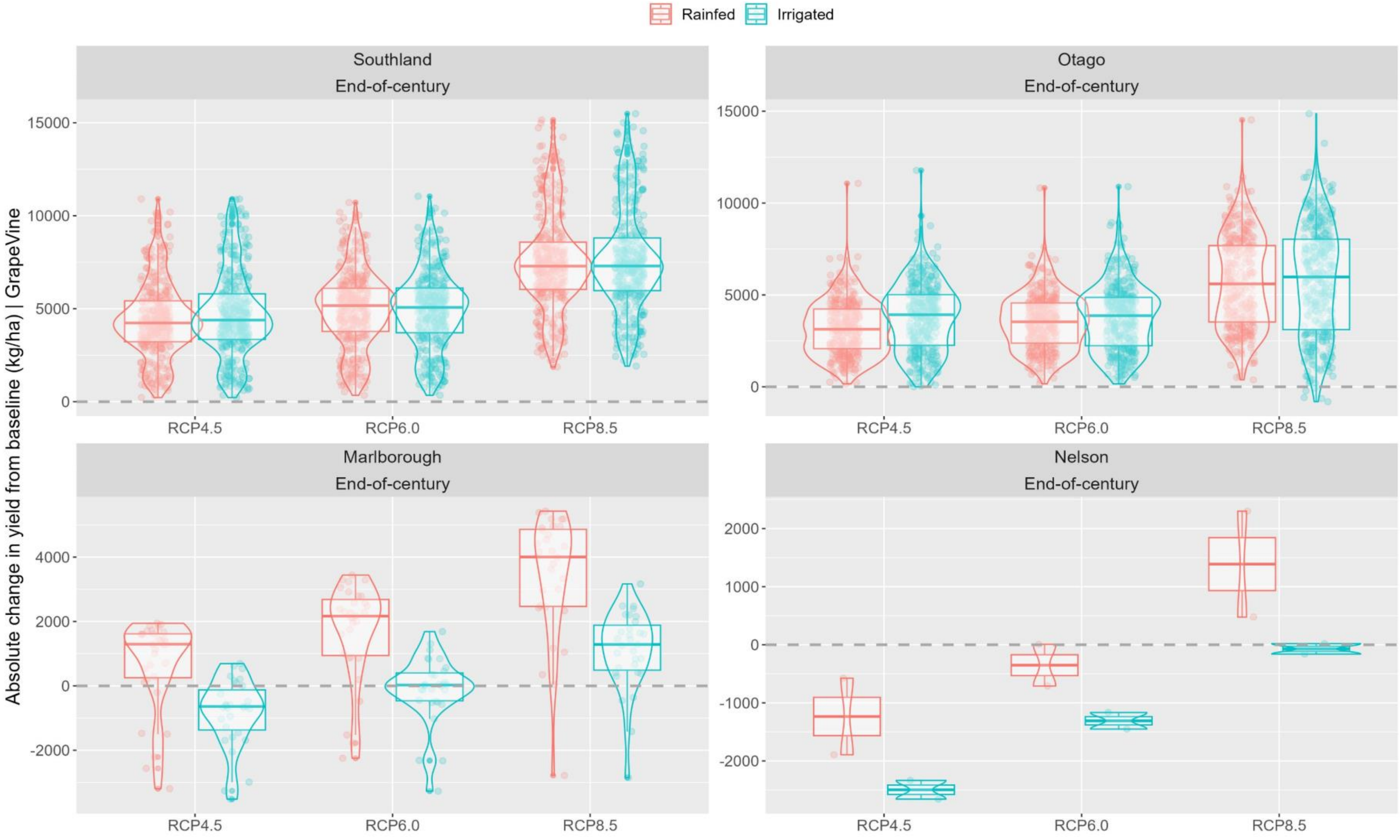

Figure 27. Yield differences for grapevine under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

2.5.6 Macadamia (*Macadamia integrifolia*)

Crop characteristics

The macadamia tree is native to Queensland, Australia. Macadamia nuts are consumed as snacks, used in confectionery, and processed into oil for culinary and cosmetic uses. The physiological and agronomical aspects for optimising macadamia productivity have been, in general, less studied than for other orchard commercial crops (Huett, 2004).

In New Zealand, Macadamia cultivation is concentrated in the North Island, where the subtropical climate better supports the species' physiological requirements to establish. The nuts are primarily used in food products, with oil also being produced for high-value health and beauty applications.

Climate change effects

Climate change main effects include the vulnerability of orchards to excess rainfall and extreme weather events such as droughts and storms. These can reduce yields, affect produce quality and damage trees (Bouarakia et al. 2023). In cold regions trees may benefit from warmer temperatures with expansion of suitable areas. The main climate change impacts considered in the model for macadamia are:

1. Acceleration of phenological development with warming
2. Atmospheric CO_2 effects on crop transpiration efficiency
3. Atmospheric CO_2 effects on photosynthesis rates
4. Heat stress during flowering time
5. Drought reduction on canopy expansion and photosynthesis
6. Change to intensity and frequency of frosts.

Model evaluation

Macadamia median yields ranged from ~4 to 7 t/ha (Figure 28). Lower yields were simulated in Gisborne due to temperature extremes. A decline in fruit numbers was driven by heat stress in summer when temperatures >35°C were experienced during flowering, both for irrigated and rainfed crops. During winter, below optimum temperatures for photosynthesis and the high frequency of frosts also reduced yields. Low rainfed yields in Auckland were mainly due to drought stress, particularly on sandy soils and the frequency of frosts.

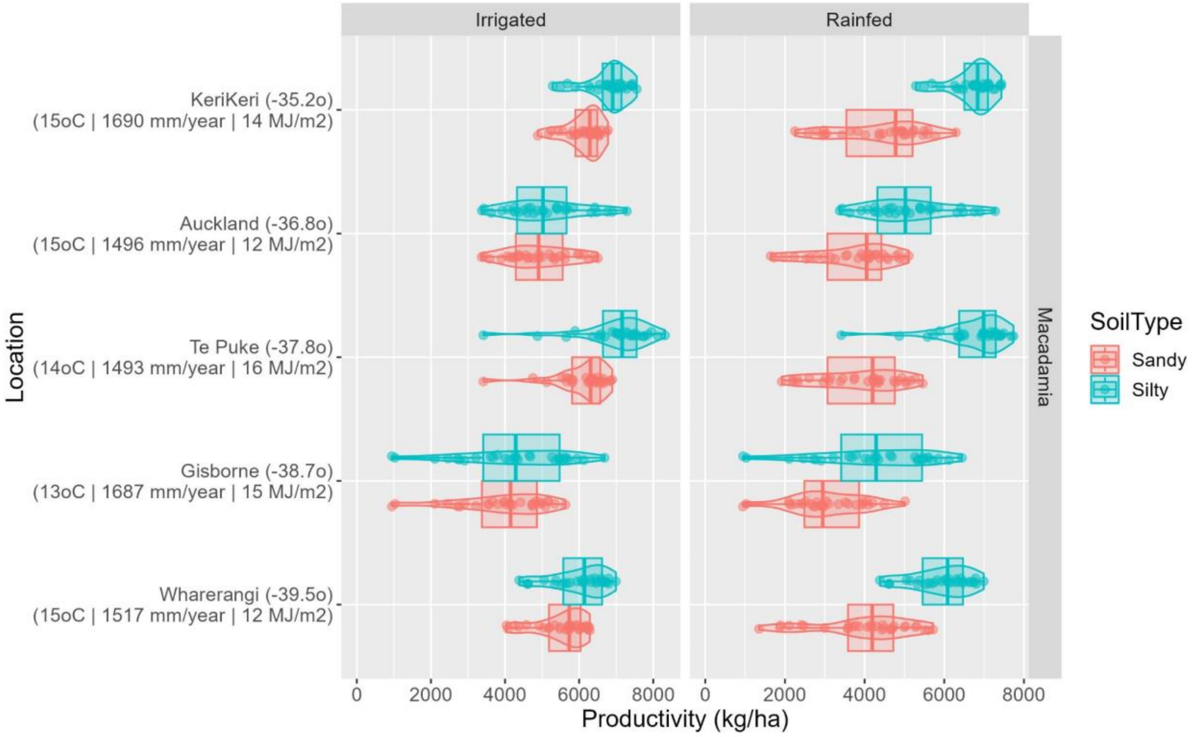

Figure 28. Sensitivity of macadamia yield simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975–2005). Values in parenthesis are mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

With warming, macadamia yields showed an overall increase across all arable lands in New Zealand. There were however large regional differences in relation to the magnitude of this increase. Specifically, highest values (over 100% in relation to the baseline climate) were simulated for southernmost areas, where current yields are the lowest. In contrast, in the warmer northern areas, current yields are the highest, the increases in yield under climate change scenarios were smaller (5 to 50%) but noticeable.

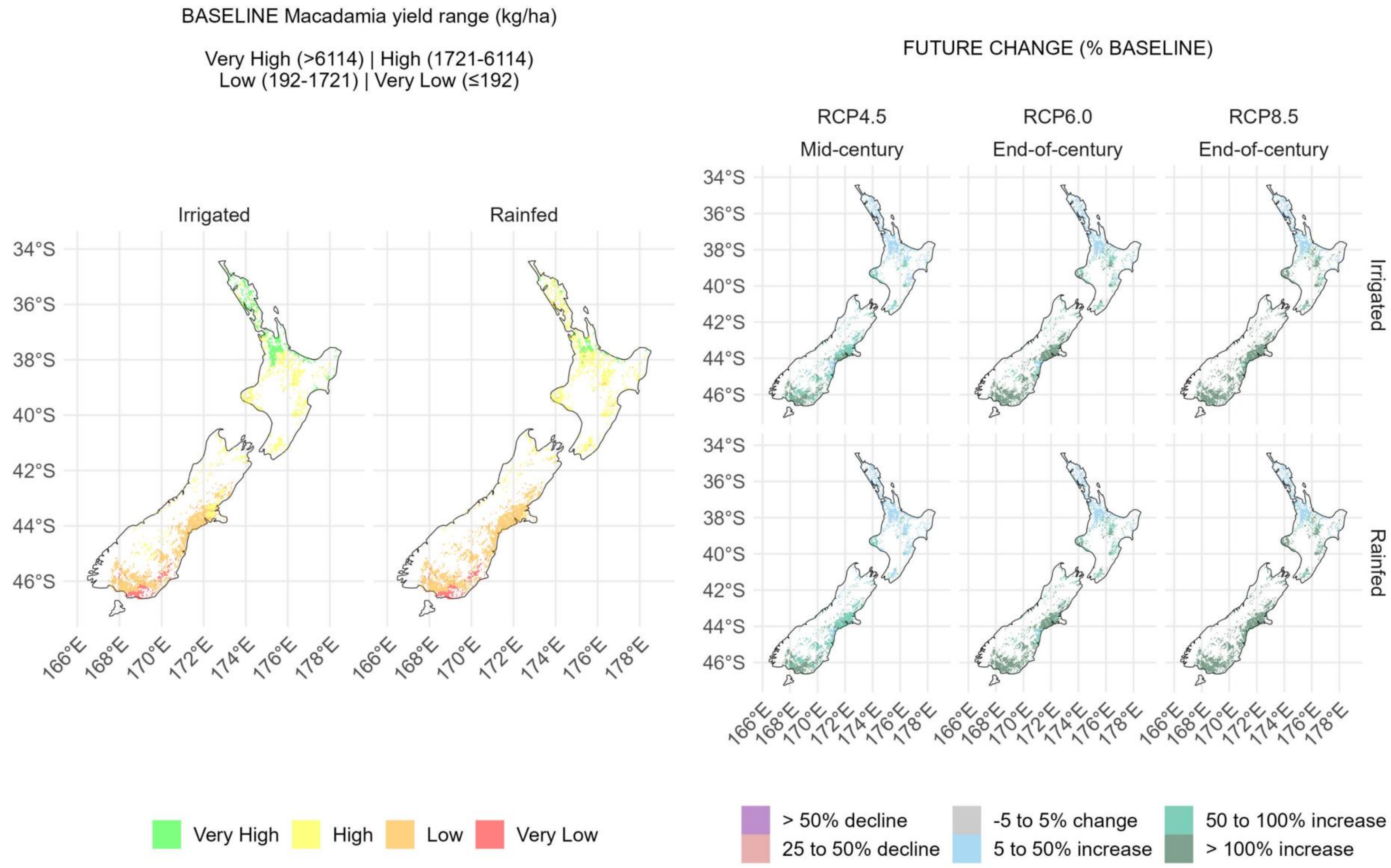

Figure 29. Estimated yield of macadamia (kg/ha) across New Zealand for the baseline scenario and percent changes for selected climate change scenarios.

In absolute terms, the positive effects of yield increase were more important in northern regions given the highest baseline references, as shown in Figure 30. The increases in median yield observed for RCP 8.5 end-of-century, in almost all regions, were in general followed by increased variability. This was because although temperatures were close to the optimum for macadamia, sporadic yield declines occurred due to heat stress which varied from year to year.

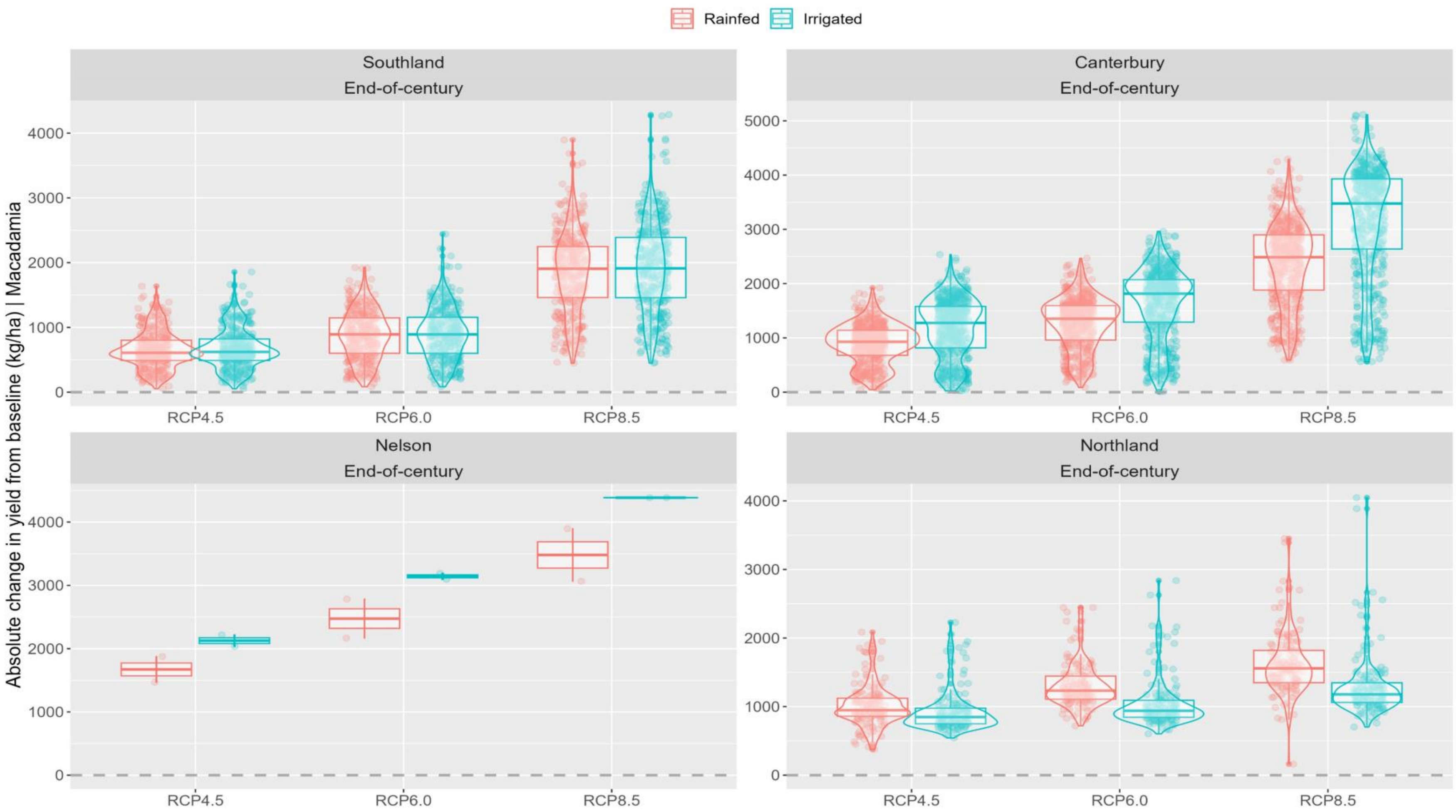

Figure 30. Yield differences for macadamia under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

2.5.7 Lemon (*Citrus limon*)

Crop characteristics

Lemons may have first grown in northern India, from where they spread across Asia and the Mediterranean (Huang et al. 2023). The fruit is valued for its tart juice, which is used in beverages, cooking, and cleaning products. Lemon oil, extracted from the peel, is used as a flavouring agent and in cosmetics.

In New Zealand, lemons are grown primarily in Gisborne and Northland, where the warmer climate supports citrus production. The fruit is used for fresh consumption, juice extraction, and as a source of essential oils for culinary and industrial applications.

Climate change effects

Climate change impacts citrus yield in various forms (Dong et al. 2024). These include directly through sensitivity to climate extremes (e.g. intense rainfall or heat stress near flowering) or indirectly through, for example, pest pressure. Together these impacts can affect both yield and quality. Rising temperatures in cooler regions may expand the suitable growing areas for lemons. In contrast, water scarcity can limit productivity in areas that will become drier.

The main climate change effects considered for lemons are:

1. Acceleration of phenological development with warming
2. Atmospheric CO_2 effects on crop transpiration efficiency
3. Atmospheric CO_2 effects on photosynthetic rates
4. Heat stress during flowering time
5. Drought reduction on canopy expansion and photosynthesis
6. Change to frost risk.

Model evaluation

Median lemon yields reached up to 28 t/ha across the four locations tested (Figure 31, Figure 32). Canterbury showed the lowest median yields, ranging from 15 t/ha for rainfed crops on sandy soils to 23 t/ha for irrigated crops on silty soils. These values are well centred around the current average productivity in New Zealand. The wide range of simulated yields was caused by a combination of stresses. For example, cold stress and droughts prevailed in Canterbury, which has the lowest average temperature and the lowest annual rainfall of ~650 mm/year. This contrasts with >1450 mm/year for other three locations. Heat stress at flowering explained most of the large yield variability. In Auckland, yield variability was also caused by high frequency of frost damage. In both cases, these are biologically sensible model behaviours which provide confidence in the first model implementation but also highlight the relevance of uncertainties in the magnitude of stresses. In particular, the extreme drop in yield in Auckland suggests that the sensitivity to stresses might be overestimated and highlights the need for model revision in future versions.

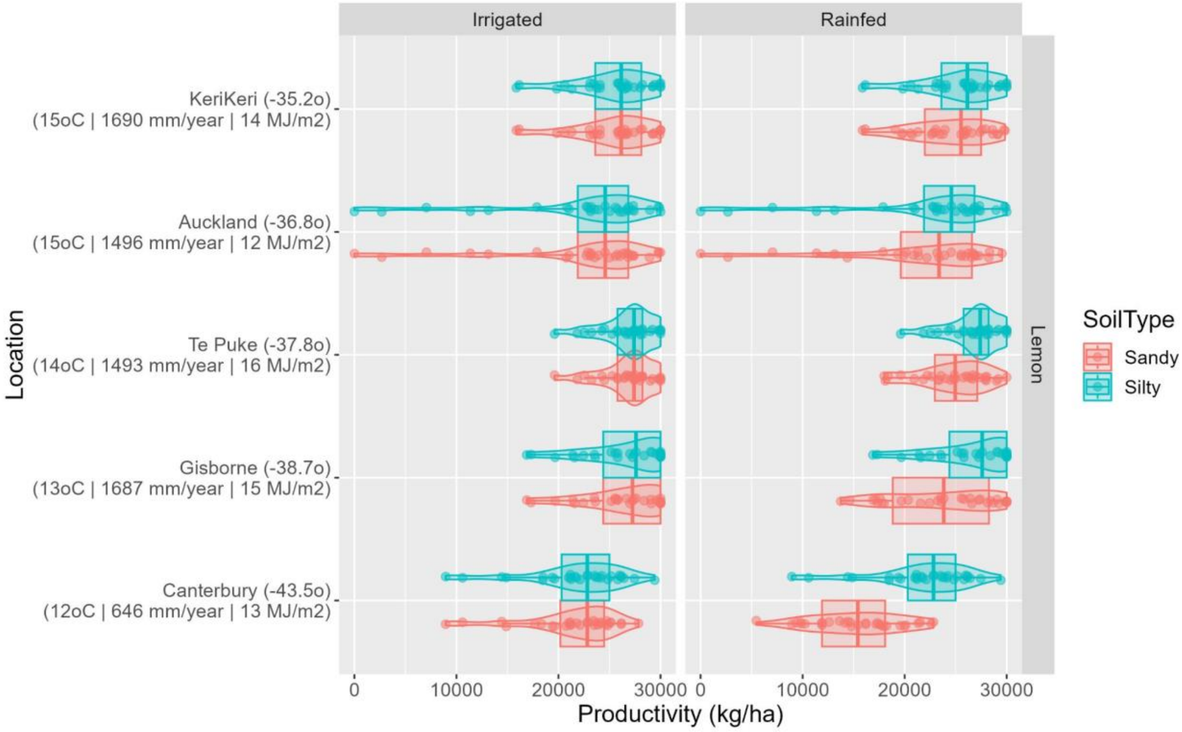

Figure 31. Sensitivity of lemon simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975–2005). Values in parenthesis are latitude, mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

Simulations for lemons showed, generally, yield increases across New Zealand with warming (Figure 32). Again, the highest relative yield increase was simulated in southern regions where currently yields are the lowest. The main driver of such yield increases was the fact that average temperatures moved closer to the optimum for photosynthesis and canopy expansion of this species. Nevertheless, there were isolated hotspots of yield reduction across the east coast of both islands, particularly in more extreme climate change scenarios.

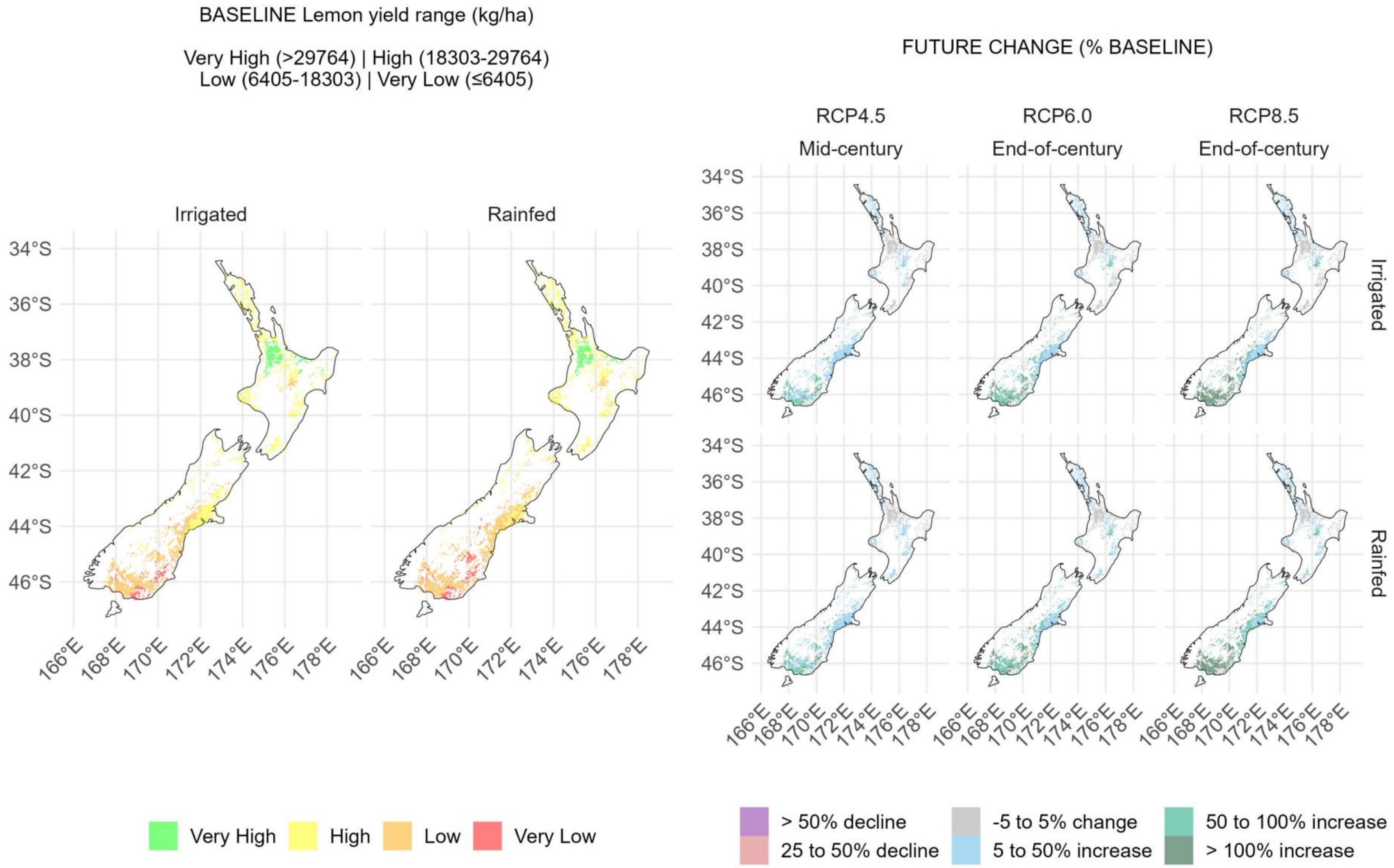

Figure 32. Estimated yield of lemon (kg/ha) across New Zealand for the baseline scenario and percent changes for selected climate change scenarios.

Most southern regions, like Central Otago and Southland, showed the most consistent absolute increases in lemon yields (Figure 33). Warmer regions, such as Auckland and Northland, also showed positive yield changes with warming, although at lower absolute values. Although average temperature moved closer to optimum for lemons under warming, increased variability was caused by the frequency of frosts or below-optimal temperatures in some years.

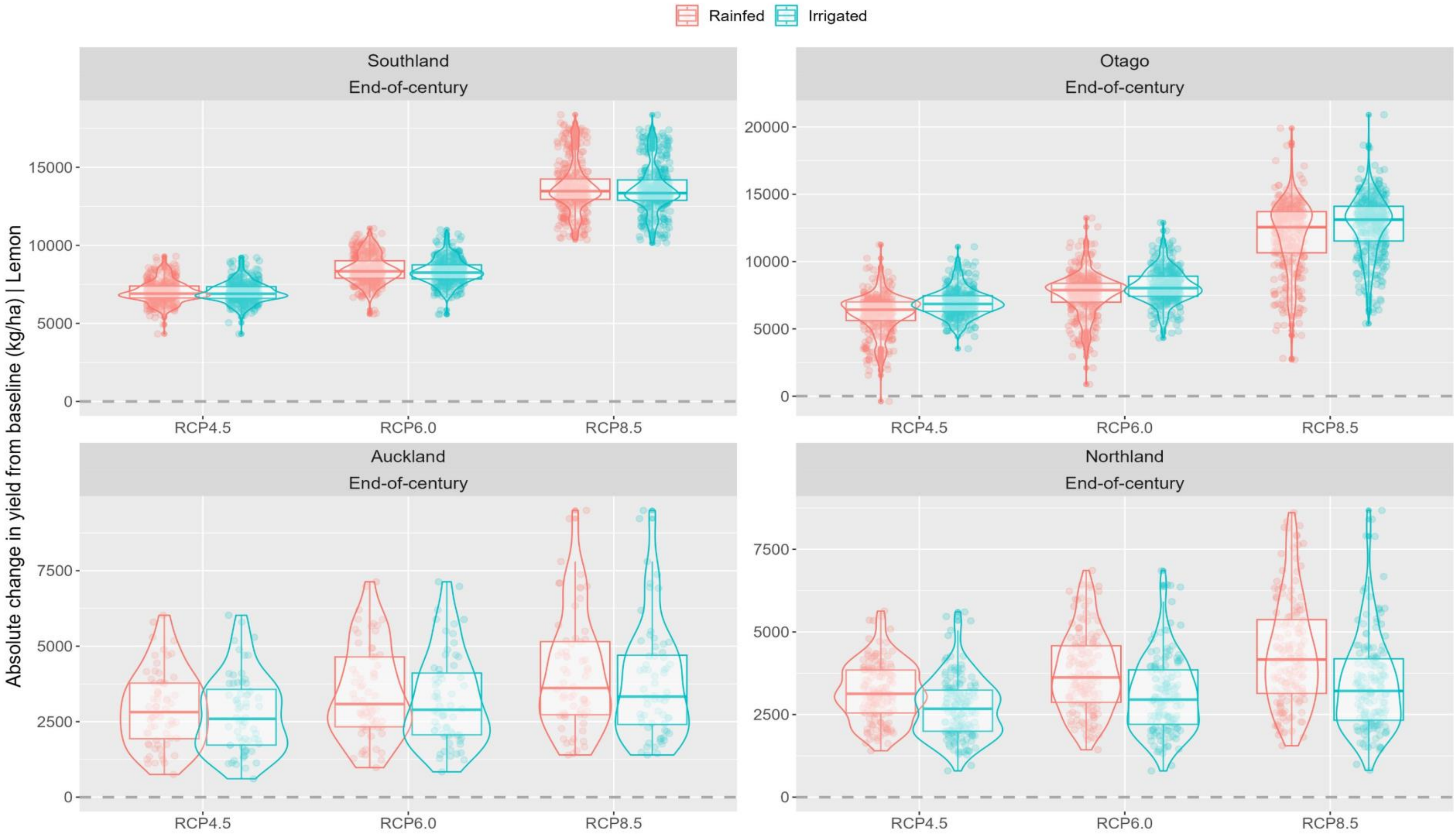

Figure 33. Yield differences for lemon under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

2.5.8 Avocado (*Persea americana*)

Crop characteristics

The avocado tree originated in Central America (Ayala Silva and Ledesma, 2014). The fruit is rich in fats and is widely consumed fresh, mashed in dishes like guacamole, or used to extract oil. Avocado is valued in both the food and cosmetic industries due to its high oil and nutrient content.

In New Zealand, avocados are predominantly grown in the Bay of Plenty and Northland regions, where the warmer climate supports their growth. The fruit is produced mainly for consumption, both domestic and export, with increasing demand for avocado oil in high-value health and cosmetic products.

Climate change effects

Climate change was projected to affect land suitability for avocados across New Zealand (Vetharaniam et al. 2024). Physiological responses include sensitivity of fruit formation to temperature extremes near flowering and susceptibility to drought. Heat stress near flowering, i.e. short episodes of high temperature, affects fruit quality and yield. However, in areas where it is currently too cold for avocado cultivation, rising temperatures may create new opportunities for orchard expansion. Water scarcity is also expected to be a limiting factor for avocado production, particularly where precipitation is limited, and irrigation is economically or ecologically unsustainable.

The main climate change impacts considered for avocado are:

1. Acceleration of phenological development with warming
2. Atmospheric CO_2 effects on crop transpiration efficiency
3. Atmospheric CO_2 effects on photosynthesis rates
4. Heat stress during flowering time
5. Drought reduction on canopy expansion and photosynthesis
6. Change to risk of frost with warming.

Model evaluation

Avocado yield simulations ranged from 3 to 30 t/ha across New Zealand arable lands (Figure 34). The lowest yields, and greater variability, were found for the Gisborne test site. These were mostly explained by above optimum temperatures, including frequent heat stress events during flowering. As for other perennial crops, particularly grapevines, the degree of sensitivity to heat stress seems to be overestimated in the current model implementation. Even though heat stress threshold temperatures are similar to grapevines, the earlier flowering of avocado caused a lower exposure to above optimal temperatures. Drought stress played an important yield-limiting role mainly in rainfed conditions under sandy soils, with some locations such as Te Puke being more negatively affected than others.

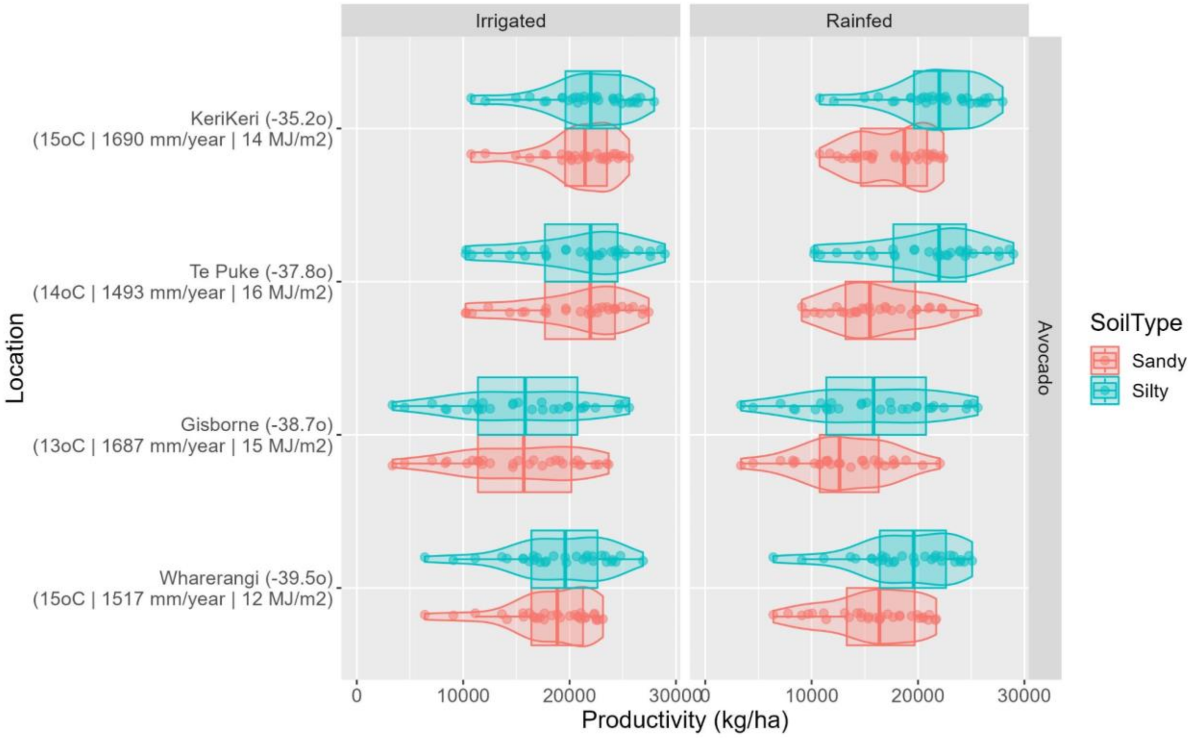

Figure 34. Sensitivity avocado yield simulations to location, watering regime and soil type for 30-year runs considering the baseline scenario (1975–2005). Values in parenthesis are latitude, mean temperature, annual precipitation and mean daily total solar radiation per location.

Model results

Avocado yield simulations, under climate change, showed a gradient of yield increase from north to the south of New Zealand (Figure 35). The relative increase in yields was greater in southern regions and high elevations, like other perennial crops.

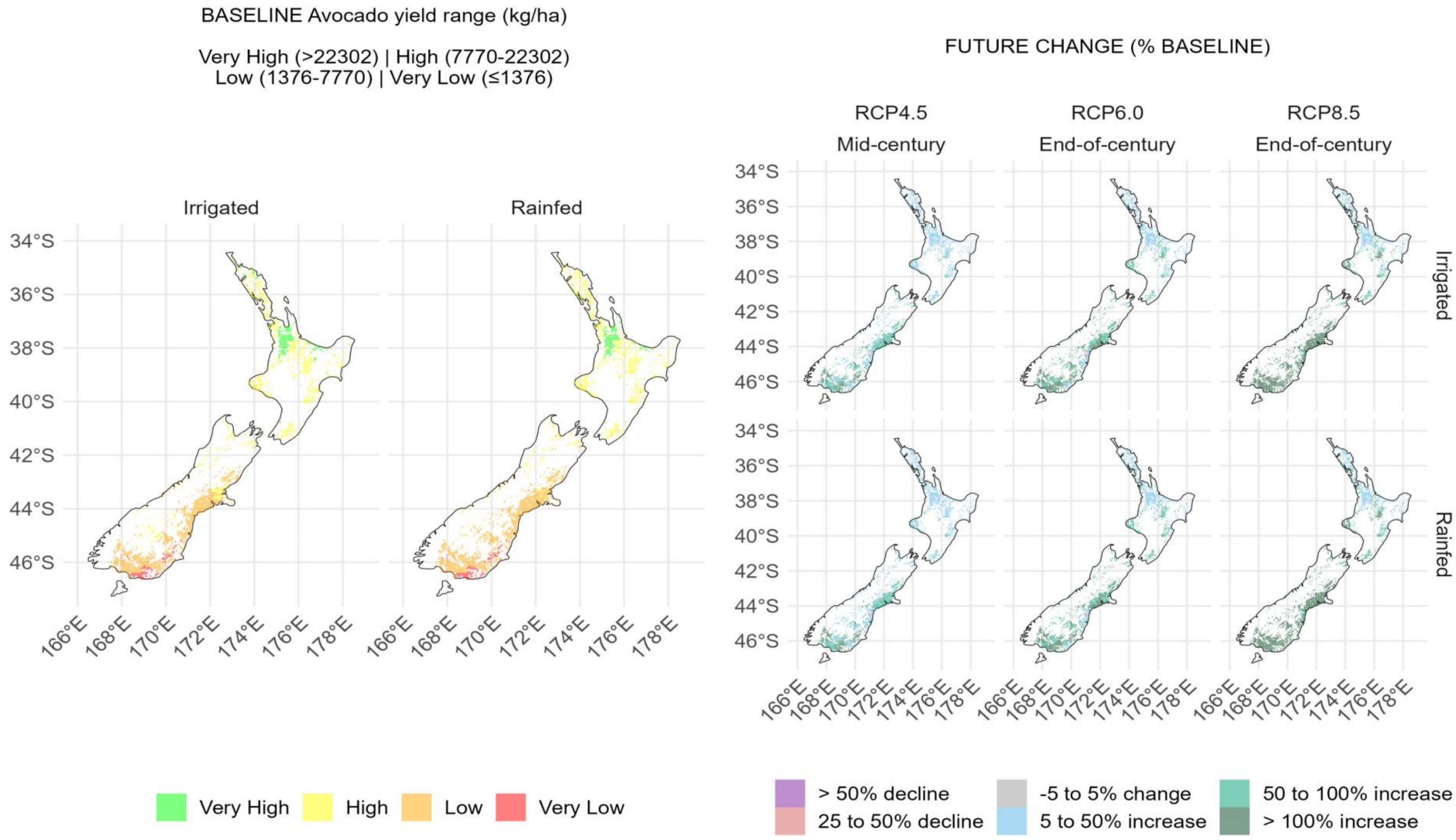

Figure 35. Estimated yield of avocado (kg/ha) across New Zealand for the baseline scenario and percent changes for selected climate change scenarios.

All regions showed absolute yield increases under RCP 8.5 end-of-the-century (Section 5, Annex), as exemplified for selected regions with contrasting climatic conditions in Figure 36.

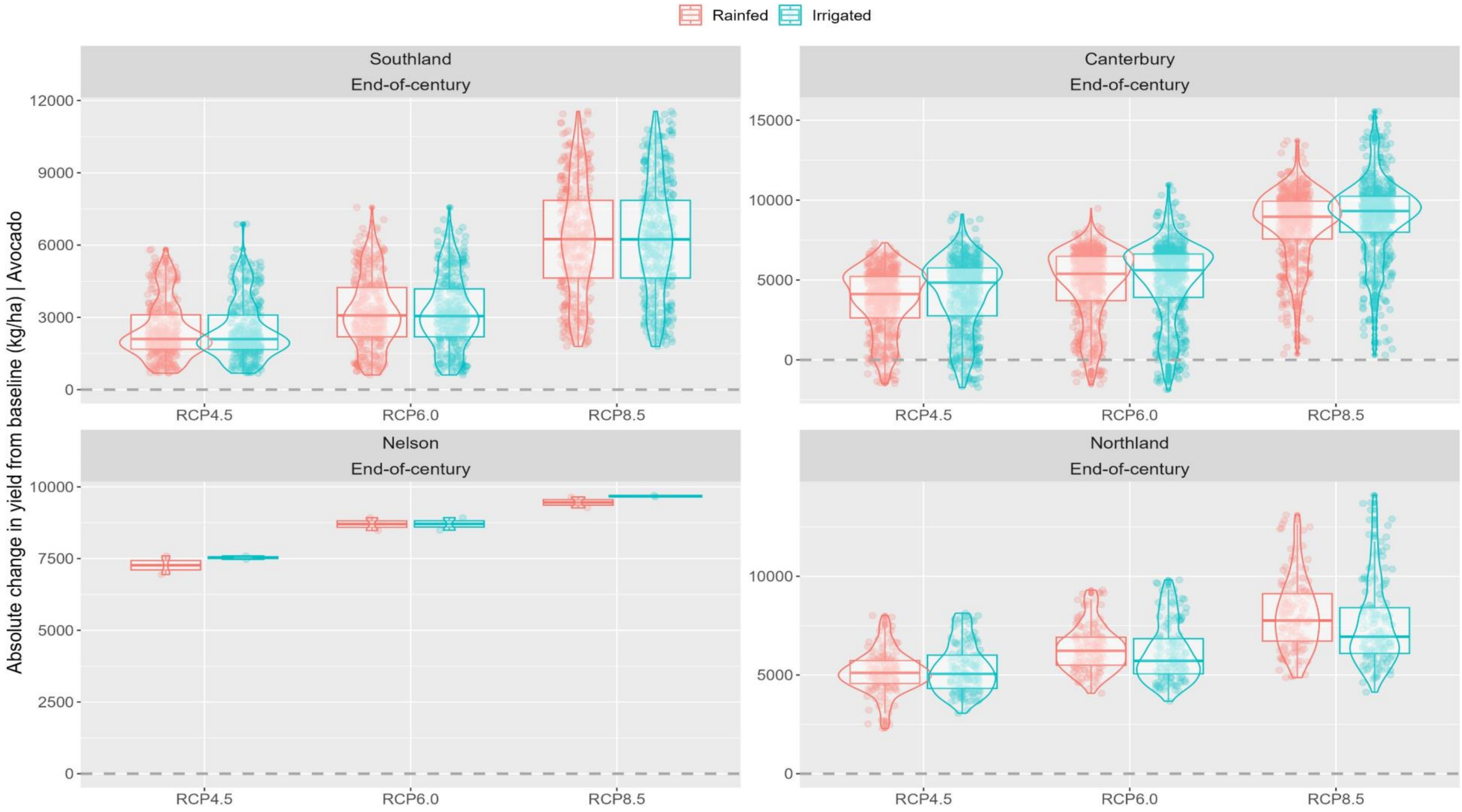

Figure 36. Yield differences for avocado under climate change scenarios (Representative Concentration Pathways, RCPs) across selected New Zealand regions, ordered by latitudinal range. The full dataset is provided in the Annex.

3 Discussion, conclusions and implications

The aim of this work was to develop a modelling methodology able to compare crop yields among contrasting land use options, in response to climate change. The novel element of this development was the design of a consistent model framework able to mechanistically represent the physiology of a wide range of contrasting crop species (i.e. agronomic, economic and market diverse land use options). In consultation with the industry sector and project steering group, eight crop species were selected for implementation in the new model. These were based on their expected relevance to the New Zealand primary sector in future decades. To balance physiological, market and industry aspects, these eight crops were equally categorised into annuals/perennials, established-/emerging-markets and arable/horticultural categories. The eight crops were maize, wheat, oilseed rape, industrial hemp, grapevine, macadamia, avocado and lemons.

The modelling methodology developed for this project was then used to assess yield changes across coming decades, up to the year 2100, and across New Zealand lands. A simpler model structure, when compared to research-focused models, was required to accommodate parameter consistency across different species. This advantage has a trade-off by limiting the model fitness for providing absolute yield changes at fine time and space resolution. Nevertheless, the model was tested for different crops and found suitable to assess relative yield changes at a regional scale when comparing different crop species, as required by this project.

The following insights emerged from the initial analysis of model results:

- **Climate change will affect crop yields differently across regions.** For most crops, climate change caused relatively higher yield gains in southern (cooler) regions. Examples of this pattern are avocados and macadamia.
- **Northern regions might disproportionally endure more intense yield stagnation or decline under climate change**. Baseline temperatures in northern locations are relatively higher and optimum thresholds, for the species of agronomic interest here considered, are more easily surpassed with warming. Examples include maize and hemp crops.
- **Climate change will affect yields differently across crop species.** For any given region, climate change effects on yield differed among crop species due to their specific sensitivity to abiotic factors. For instance, tropical species such as avocado tend to benefit from warming more broadly across New Zealand than temperate crops such as wheat.
- **The change in land suitability for annual crops suggests careful consideration of food security strategies.** Under hypothetical future scenarios with truncated global international trade, negative climate change effects on staple food crops, like maize and wheat, indicate that food security in New Zealand would benefit from further consideration**.**
- **The benefits from yield gains found for perennial crops under climate change are dependent on access to international markets.** The perennial crops evaluated are all targeting high-value horticultural products for export to affluent markets (i.e. winegrapes,

avocados, macadamia nuts and lemons). Therefore, the potential benefit of yield increases and expansion of suitable growing areas, mostly southward, are both conditioned to increasing product demand overseas. Climate change effects on other countries' land resources and their national economies add to the uncertainty in future supply and demand of these products.

The local climate change impact on yields will always be the net result of a combination of multiple factors: increased temperatures, seasonal shifts in rainfall and water availability, more frequent and intensive weather events, under the background of increasing CO_2 concentrations. Together, these factors have both direct and indirect effects on crops that are likely to influence land use and regional economic activity. For example, the frequency and intensity of pest and disease incursions is largely affected by environmental conditions. In this sense, our results are in general conservative, because they do not consider all these dimensions of climate change effects on crops. For instance, biotic stresses (pathogens, insects and weeds) and extreme weather events, such as storms and floods, were not accounted for in this analysis. These are mostly yield-reducing factors which are strongly influenced by climate change. Therefore, when interpreting our results at the local level, it is strongly recommended to also consider maps and data showing other climate-related risks (e.g., floods, storms and sea level rise), as our analysis does not account for these.

It is important to note that during this first phase of model development and application, some model limitations and areas of improvement were identified. These include uncertainty about drivers of yield variability in some crops, the limited responsiveness to yield changes at high productivity for arable crops, and the limited understanding of heat stress responses in horticultural crops. These are focus areas for evaluation and improvement through future research. Hence, we have higher confidence in relative patterns of yield change when comparing crops, regions and time periods than on the absolute yield values simulated. Adaptation via change in crop varieties was also not explored in this exercise, but the current modelling framework is a viable platform to test these and other hypotheses in the future.

Finally, as the primary goal of the work for this project, we have produced a set of crop yield results to support building an understanding of how climate change will affect primary production in different parts of the country. These data can also support broader analysis such as to inform likely impacts on regional economies by serving as inputs to land-use and economic models.

4 References

Ausseil, A.E., Law, R.M., Parker, A.K., Teixeira, E.I., Sood, A., 2021. Projected Wine Grape Cultivar Shifts Due to Climate Change in New Zealand. Front. Plant Sci. 12, 679.

Ayala Silva, T., Ledesma, N., 2014. Avocado History, Biodiversity and Production BT - Sustainable Horticultural Systems: Issues, Technology and Innovation, in: Nandwani, D. (Ed.), . Springer International Publishing, Cham, pp. 157–205. https://doi.org/10.1007/978-3-319-06904-3_8

Bassu, S., Brisson, N., Durand, J.L., Boote, K., Lizaso, J., Jones, J.W., Rosenzweig, C., Ruane, A.C., Adam, M., Baron, C., Basso, B., Biernath, C., Boogaard, H., Conijn, S., Corbeels, M., Deryng, D., De Sanctis, G., Gayler, S., Grassini, P., Hatfield, J., Hoek, S., Izaurralde, C., Jongschaap, R., Kemanian, A.R., Kersebaum, K.C., Kim, S.H., Kumar, N.S., Makowski, D., Müller, C., Nendel, C., Priesack, E., Pravia, M.V., Sau, F., Shcherbak, I., Tao, F., Teixeira, E., Timlin, D., Waha, K., 2014. How do various maize crop models vary in their responses to climate change factors? Glob. Chang. Biol. 20, 2301–2320. https://doi.org/10.1111/gcb.12520

Bouarakia, O., Anders, M., Linden, V.M.G., Grass, I., Westphal, C., Taylor, P., Foord, S.H., 2023. Reduced macadamia nut quality is linked to wetter growing seasons but mitigated at higher elevations. J. Agric. Food Res. 12, 100569. https://doi.org/https://doi.org/10.1016/j.jafr.2023.100569

Brown, H., Huth, N., Holzworth, D., Teixeira, E., Zyskowski, R., Hargreaves, J., Moot, D., 2014. Plant modelling framework: software for building and running crop models on the APSIM platform. Environ. Model. Softw. 62, 385–398. https://doi.org/10.1016/j.envsoft.2014.09.005

Daly, M.J., Martin, R.J., 1988. Oilseed Rape: The effects of rate, timing and form of nitrogen applications on a depleted Lismore soil, in: Proceedings Agronomy Society of N.Z. 18. 1988. pp. 97–102.

Dong, Z., Chen, M., Srivastava, A.K., Mahmood, U.H., Ishfaq, M., Shi, X., Zhang, Y., Moussa, M.G., Li, X., Hu, C., Zhang, F., 2024. Climate changes altered the citrus fruit quality: A 9-year case study in China. Sci. Total Environ. 923, 171406. https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.171406

Dudziec, P., Warmiński, K., Stolarski, M.J., 2024. Industrial Hemp As a Multi-Purpose Crop: Last Achievements and Research in 2018−2023. J. Nat. Fibers 21, 2369186. https://doi.org/10.1080/15440478.2024.2369186

FAR | Arable Industry Marketing Initiative, 2022. New Zealand survey of maize areas and volumes https://assets.far.org.nz/blog/files/a2cd1eb5-337f-500f-ab6b-3fac3b821a82.pdf. Summary at https://www.far.org.nz/resources/new-zealand-survey-of-maize-areas-and-volumes-june-1-2022. Access: 13 May 2025.

Gabzdylova, B., Raffensperger, J.F., Castka, P., 2009. Sustainability in the New Zealand wine industry: drivers, stakeholders and practices. J. Clean. Prod. 17, 992–998. https://doi.org/https://doi.org/10.1016/j.jclepro.2009.02.015

Holzworth, D., Huth, N.I., Fainges, J., Brown, H., Zurcher, E., Cichota, R., Verrall, S., Herrmann, N.I., Zheng, B., Snow, V., 2018. APSIM Next Generation: Overcoming challenges in modernising a farming systems model. Environ. Model. Softw. 103, 43–51. https://doi.org/https://doi.org/10.1016/j.envsoft.2018.02.002

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., Keating, B.A., 2014. APSIM - Evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw. 62, 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009

Huang, Y., He, J., Xu, Y., Zheng, W., Wang, S., Chen, P., Zeng, B., Yang, S., Jiang, X., Liu, Zishuang, Wang, L., Wang, X., Liu, S., Lu, Z., Liu, Ziang, Yu, H., Yue, J., Gao, J., Zhou, X., Long, C., Zeng, X., Guo, Y.-J., Zhang, W.-F., Xie, Z., Li, C., Ma, Z., Jiao, W., Zhang, F., Larkin, R.M., Krueger, R.R., Smith, M.W., Ming, R., Deng, X., Xu, Q., 2023. Pangenome analysis provides insight into the evolution of the orange subfamily and a key gene for citric acid accumulation in citrus fruits. Nat. Genet. 55, 1964–1975. https://doi.org/10.1038/s41588-023-01516-6

Huett, D., 2004. Macadamia physiology review: a canopy light response study and literature review. Aust. J. Agric. Res. 55, 609–624. https://doi.org/10.1071/AR03180

Jamieson, P.D., Cloughley, C.G., 1998. Chapter 5. Impacts of climate change on wheat production, in: Warrick, R.A., Kenny, G.J., Harman, J.J. (Eds.), CLIMPACTS Assessment Report. The Effects of Climate Change and Variation in New Zealand: An Assessment Using the CLIMPACTS System. International Global Change Institute (IGCI), University of Waikato, Hamilton, New Zealand, pp. 57–64.

Lilburne, L., Hewitt, A., Webb, T.H., Carrick, S., 2004. S-map – a new soil database for New Zealand. Reg. Inst. - Online Publ. http//www.regional.org.au/au/asssi/supersoil2004/s5/oral/1512_lilburne.htm.

Mullan, A.B., Sood, A., Stuart, S., Carey-Smith, T., 2018. Climate Change Projections for New Zealand: Atmosphere Projections based on Simulations from the IPCC Fifth Assessment, 2nd Edition. NIWA Client Rep. Minist. Environ. Updat. June 2016 Rep. with a Sect. Proj. Extrem. rainfall Chang. WLG2015-31.

Newsome, P.F.J., Wilde, R.H., Willoughby, E.J., 2008. Land resource information system data layers. Landcare Research Technical Report. Available at: https://lris.scinfo.org.nz/layer/76-nzlri-land-use-capability/. https://doi.org/http://doi.org/10.7931/DL1V88

Rutledge, D., Ausseil, A.-G.A.-G., Baisden, T., Bodeker, G., Booker, D., Cameron, M., Collins, D., Daigneault, A., Fernandez., Frame, B., Keller, E., Kremser, S., Kirschbaum, M., Lewis, J., Mullan, B., Reisinger, A., Sood, A., Stuart, S., Tait, A., Teixeira, E., Timar, L., Zammit, C., Fernandez, M., Frame, B., Keller, E., Kremser, S., Kirschbaum, M., 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.

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.

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.

Teixeira, E., Ausseil, A., Burgueño, B., Brown, B., Cichota, R., Davy, M., Ewert, F., Guo, J., Holmes, A., Holzworth, D., Hu, W., de Ruiter, J., Hume, E., Jesson, L., Johnstone, P., Powell, J., Kersebaum, K.C., Kong, H., Liu, J., Lilburne, L., Meiyalaghan, S., Storey, R., Richards, K., Tait, A., van der Weerden, T., 2020. A spatial analysis framework to assess responses of agricultural landscapes to climates and soils at regional scale, in: Lothar Mueller, L., Mirschel, W. (Eds.), Innovations in Landscape Research. Springer Berlin, Berlin.

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

Teixeira, E.I., George, M., Herreman, T., Brown, H., Fletcher, A., Chakwizira, E., de Ruiter, J., Maley, S., Noble, A., 2014. The impact of water and nitrogen limitation on maize biomass and resource-use efficiencies for radiation, water and nitrogen. F. Crop. Res. 168, 109–118. https://doi.org/10.1016/j.fcr.2014.08.002

Tsimba, R., Edmeades, G.O., Millner, J.P., Kemp, P.D., 2013. The effect of planting date on maize grain yields and yield components. F. Crop. Res. 150, 135–144. https://doi.org/http://dx.doi.org/10.1016/j.fcr.2013.05.028

Vetharaniam, I., Stanley, J., Cummins, M., Dijssel, C., Müller, K., 2024. Modelling Climate Change Impacts on Location Suitability for Cultivating Avocado and Blueberry in New Zealand. Land 13, 1753. https://doi.org/10.3390/land13111753

Wheeler, T.R., Batts, G.R., Ellis, R.H., Hadley, P., Morison, J.I.L., 1996. Growth and yield of winter wheat (Triticum aestivum) crops in response to CO2 and temperature. J. Agric. Sci. 12, 37–48.

Wilson, D.R., Johnstone, J. V, Salinger, M.J., 1994. Maize production potential and climatic risk in the South Island of New Zealand. New Zeal. J. Crop Hortic. Sci. 22, 321–334. https://doi.org/10.1080/01140671.1994.9513841

5 Annex

The figures below (A1 to A33) show absolute yield changes due to climate change for all region by crop by time-slice combinations.

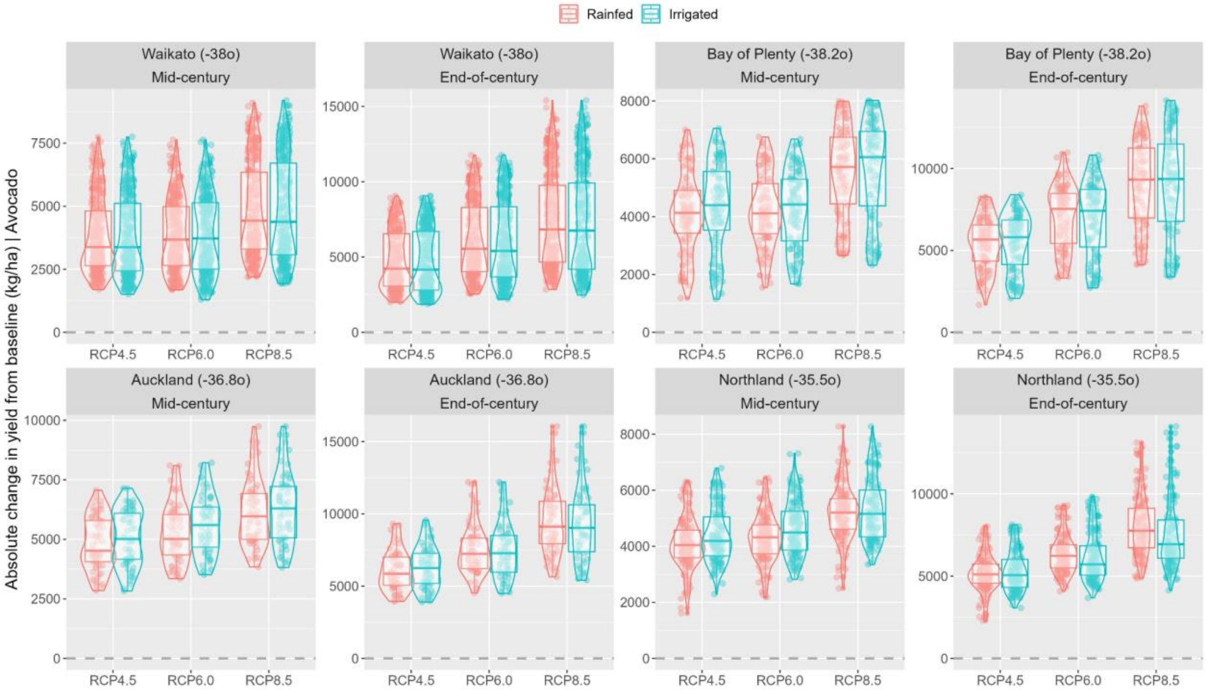

Figure A1 Yield differences under climate change Representative Concentration Pathways (RCP) for Avocado across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

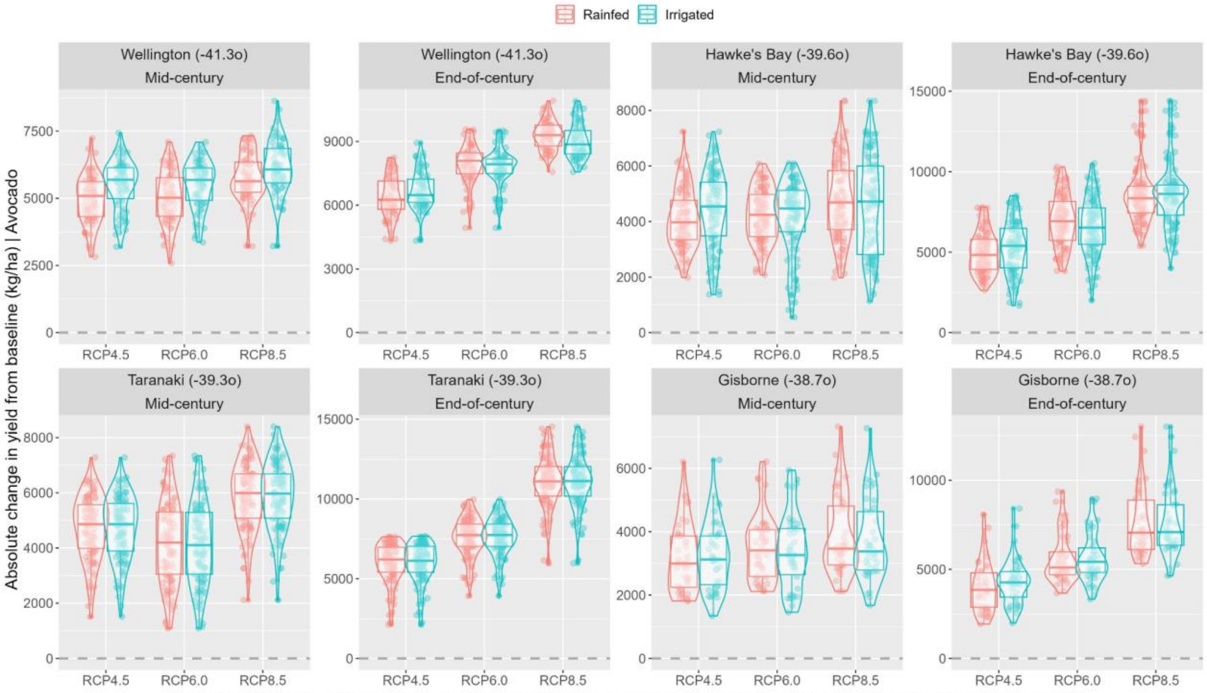

Figure A2 Yield differences under climate change Representative Concentration Pathways (RCP) for Avocado across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

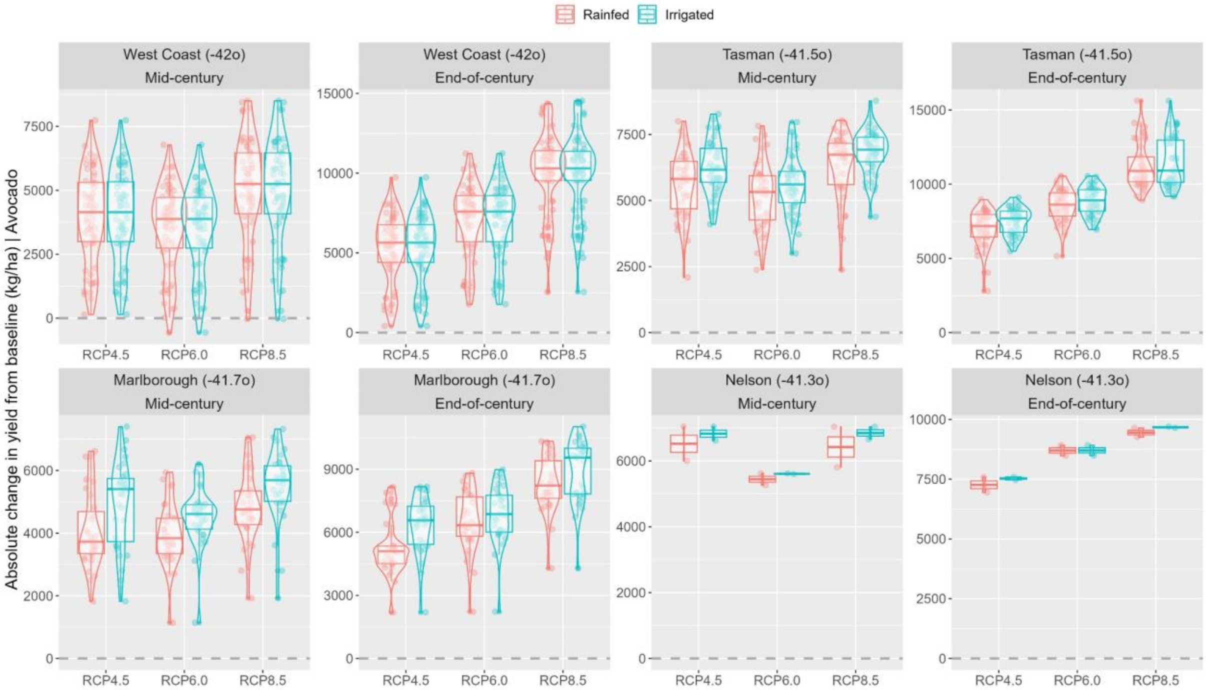

Figure A3 Yield differences under climate change Representative Concentration Pathways (RCP) for Avocado across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

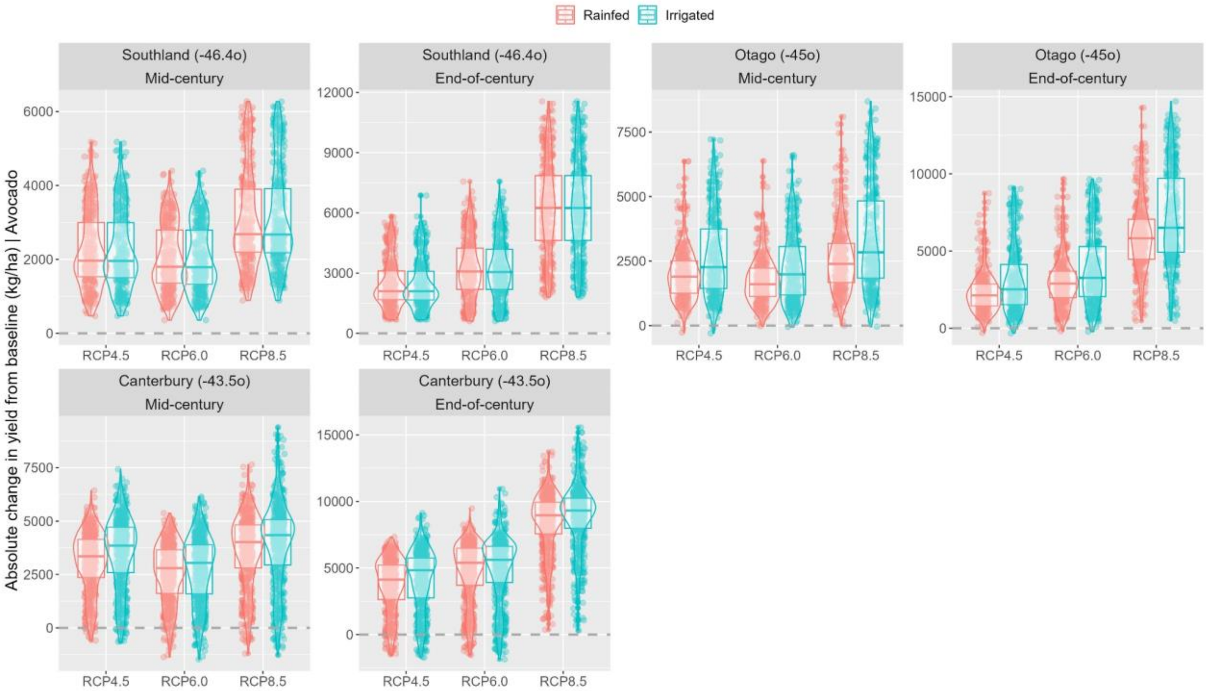

Figure A4 Yield differences under climate change Representative Concentration Pathways (RCP) for Avocado across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

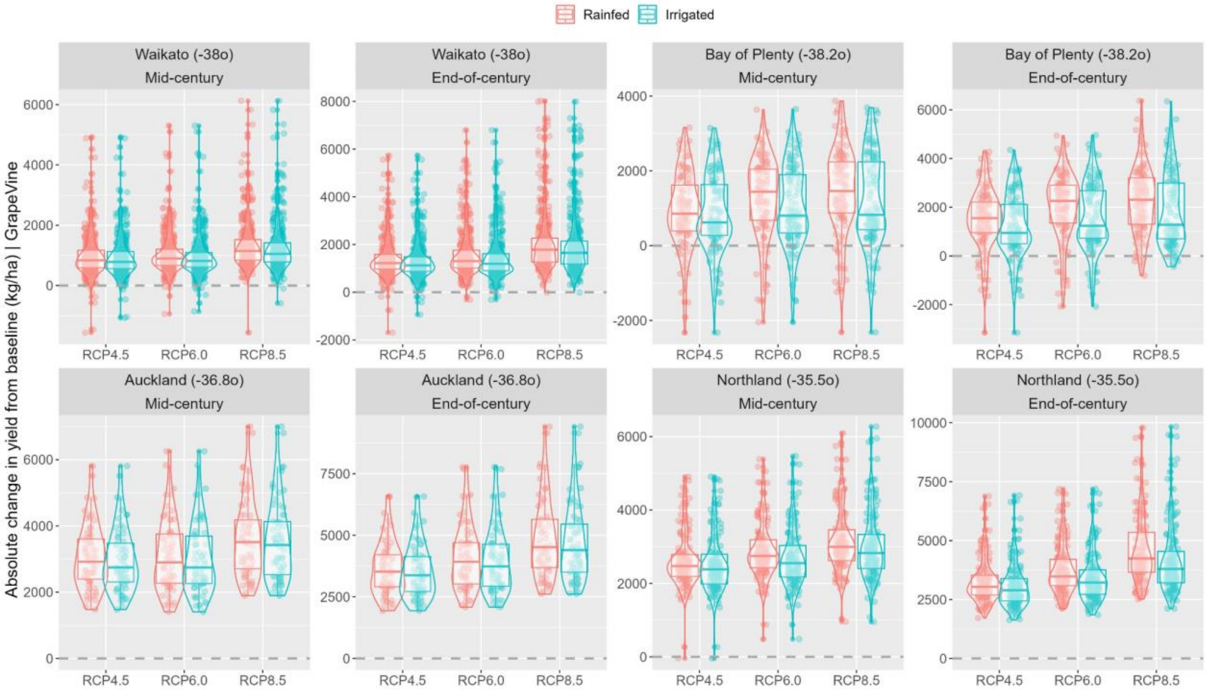

Figure A5 Yield differences under climate change Representative Concentration Pathways (RCP) for GrapeVine across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

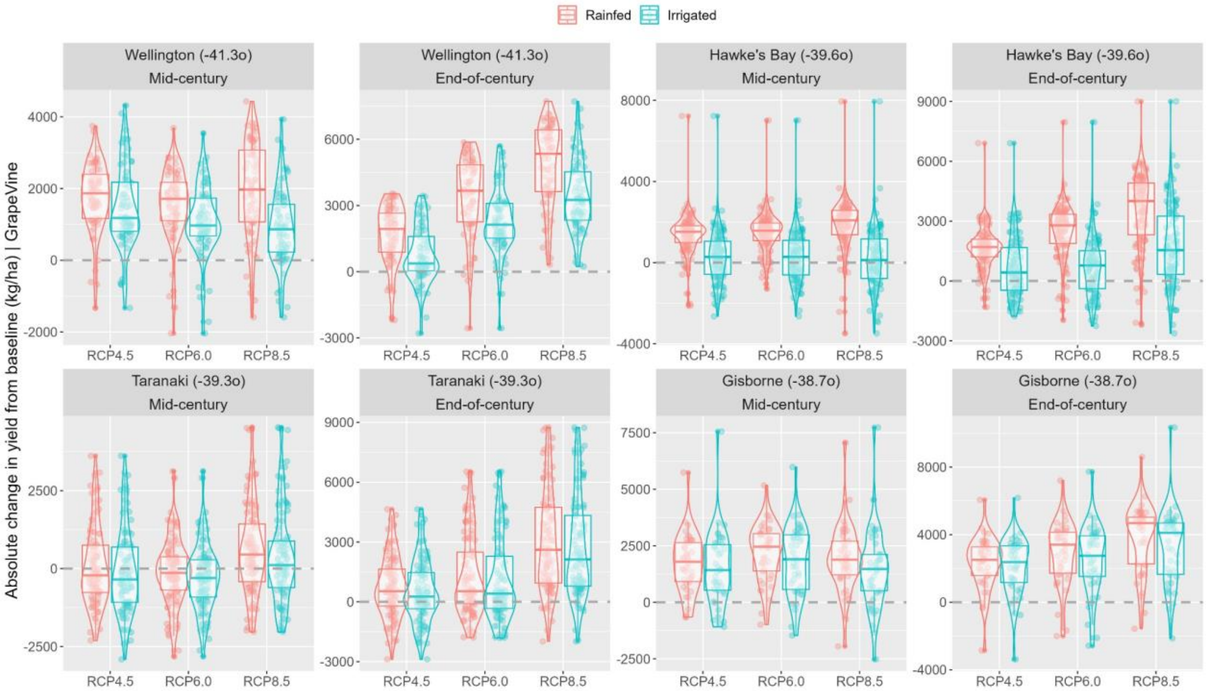

Figure A6 Yield differences under climate change Representative Concentration Pathways (RCP) for GrapeVine across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

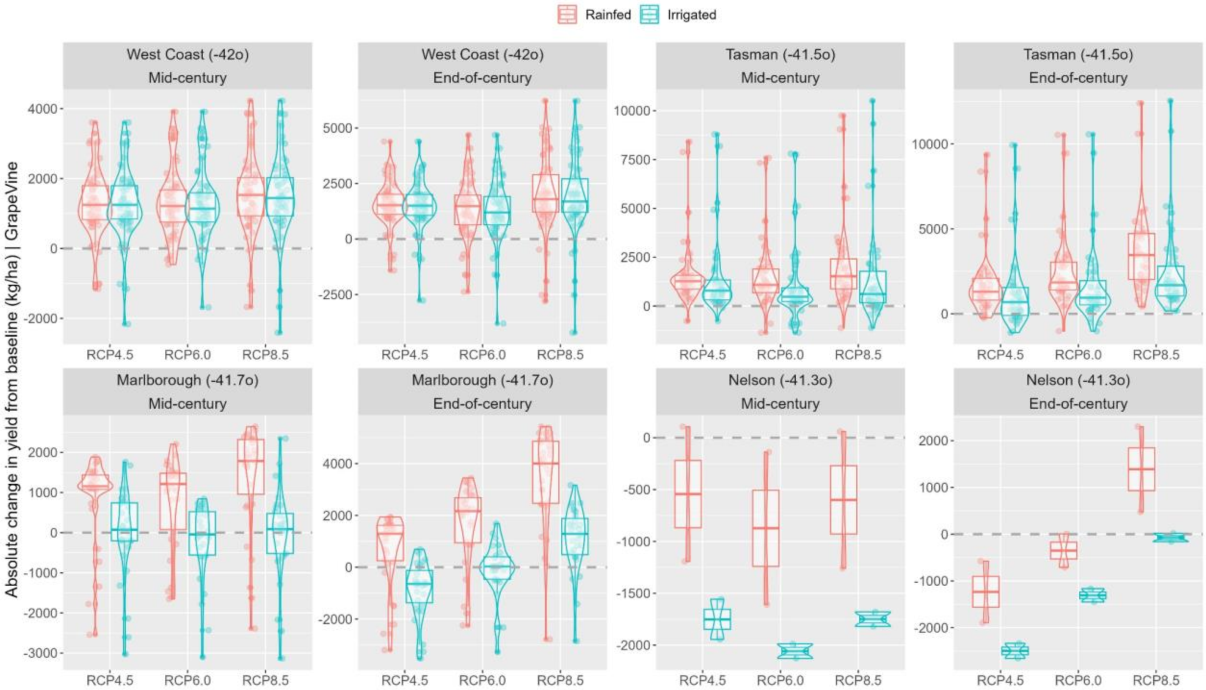

Figure A7 Yield differences under climate change Representative Concentration Pathways (RCP) for GrapeVine across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

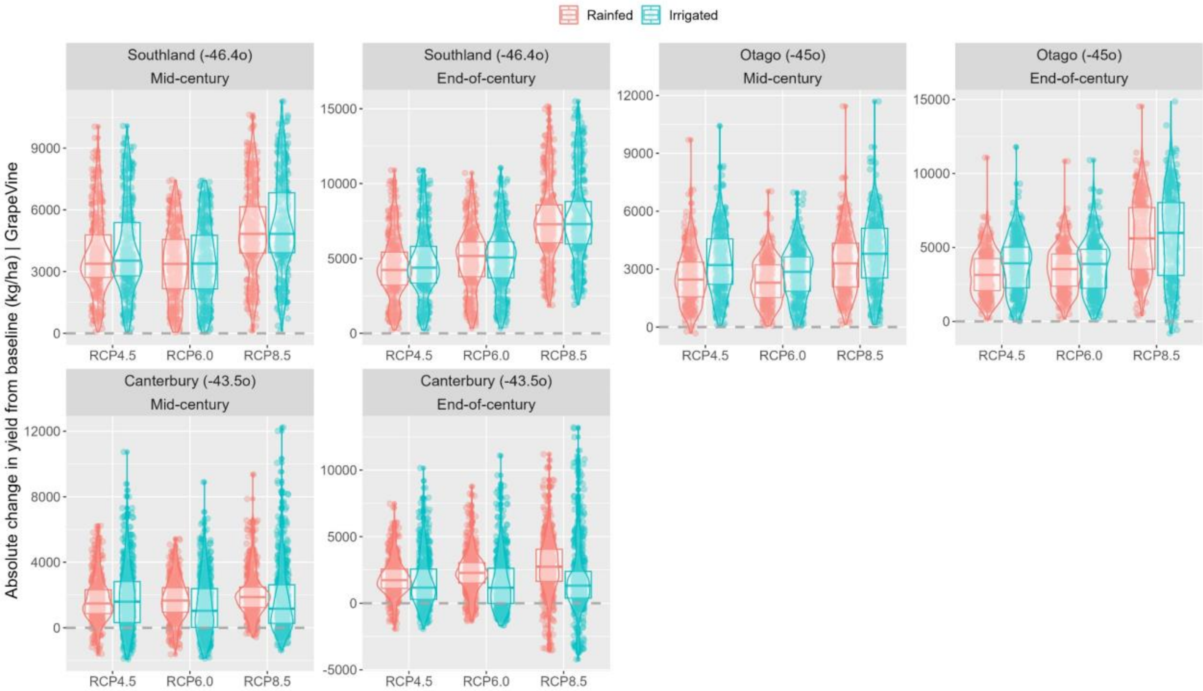

Figure A8 Yield differences under climate change Representative Concentration Pathways (RCP) for GrapeVine across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

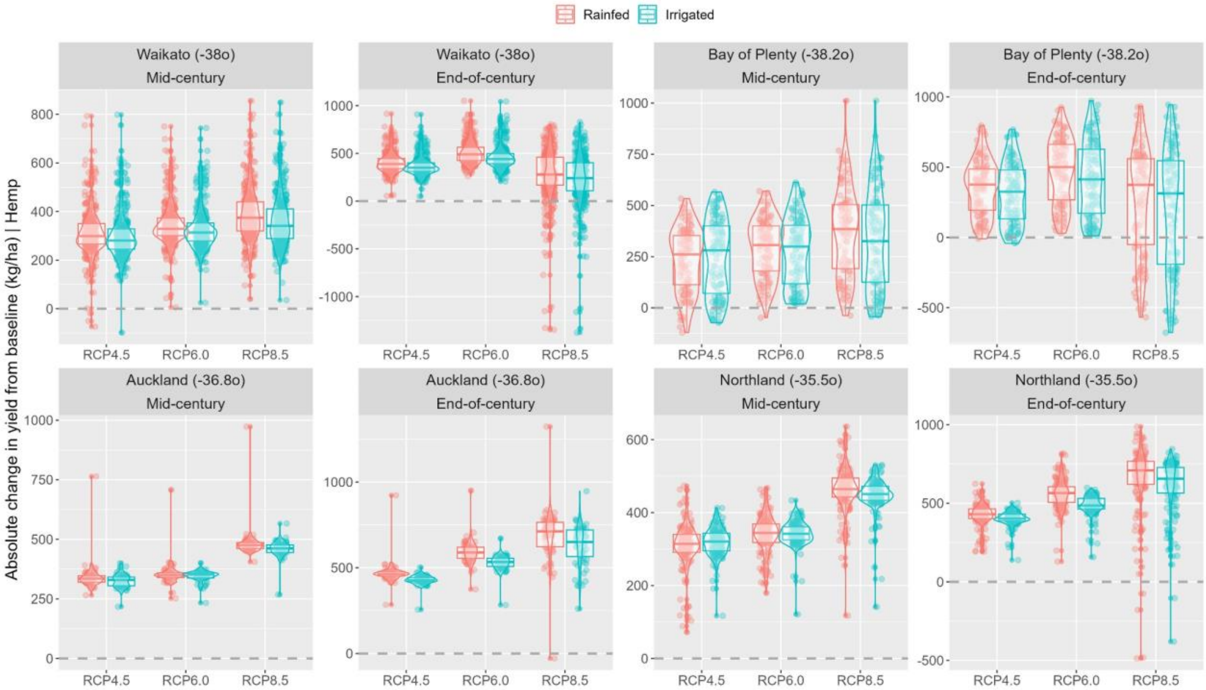

Figure A9 Yield differences under climate change Representative Concentration Pathways (RCP) for Hemp across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

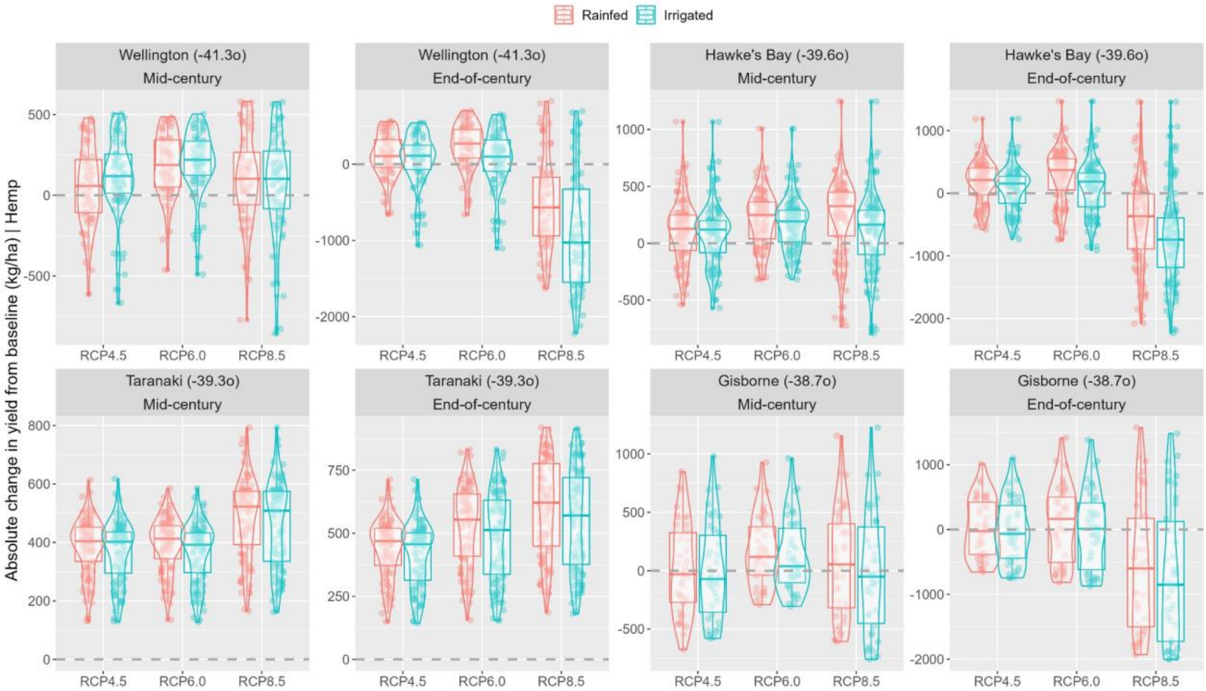

Figure A10 Yield differences under climate change Representative Concentration Pathways (RCP) for Hemp across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

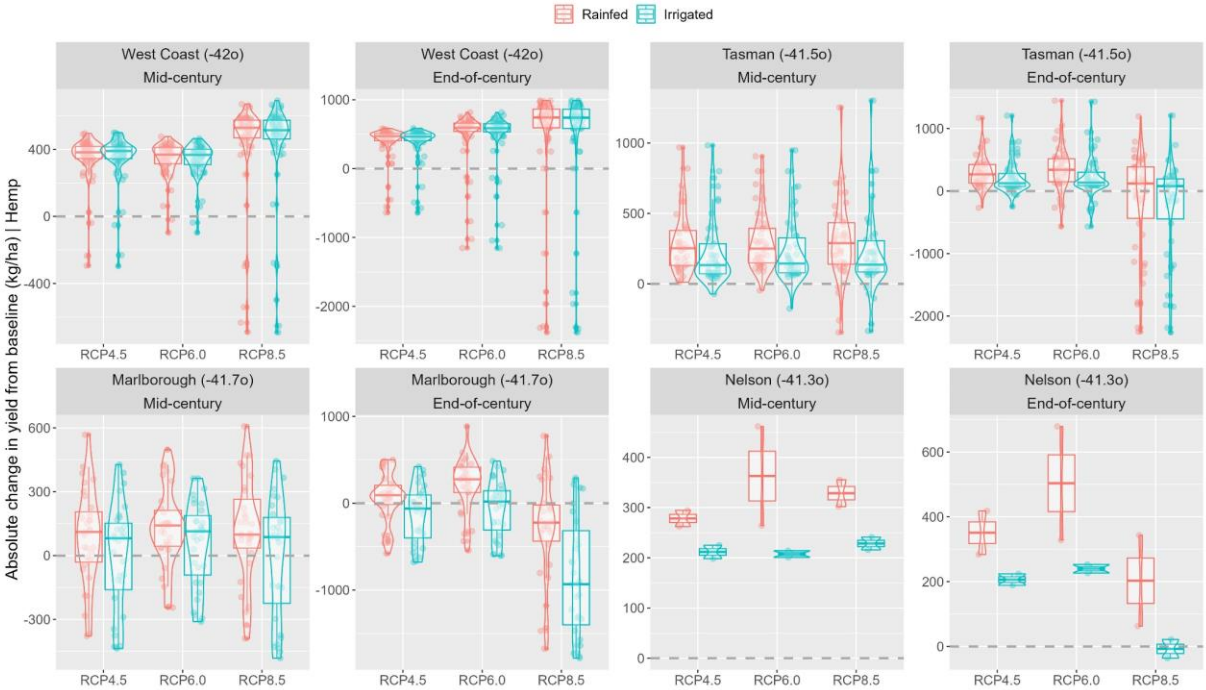

Figure A11 Yield differences under climate change Representative Concentration Pathways (RCP) for Hemp across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

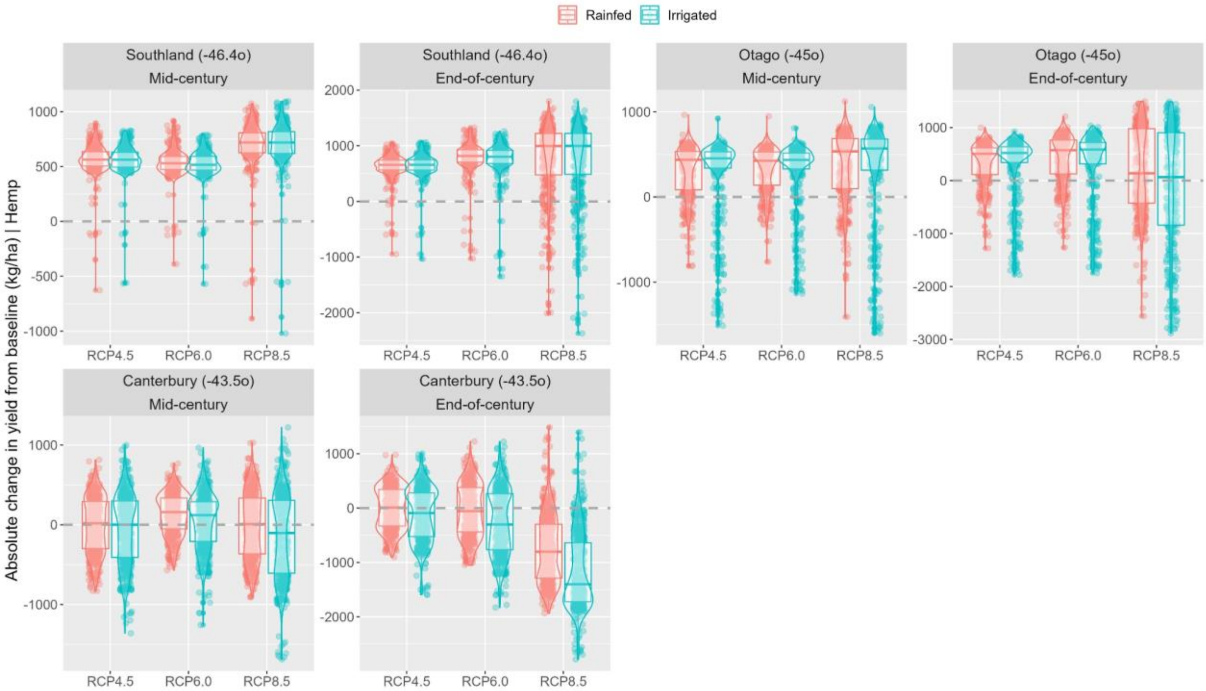

Figure A12 Yield differences under climate change Representative Concentration Pathways (RCP) for Hemp across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

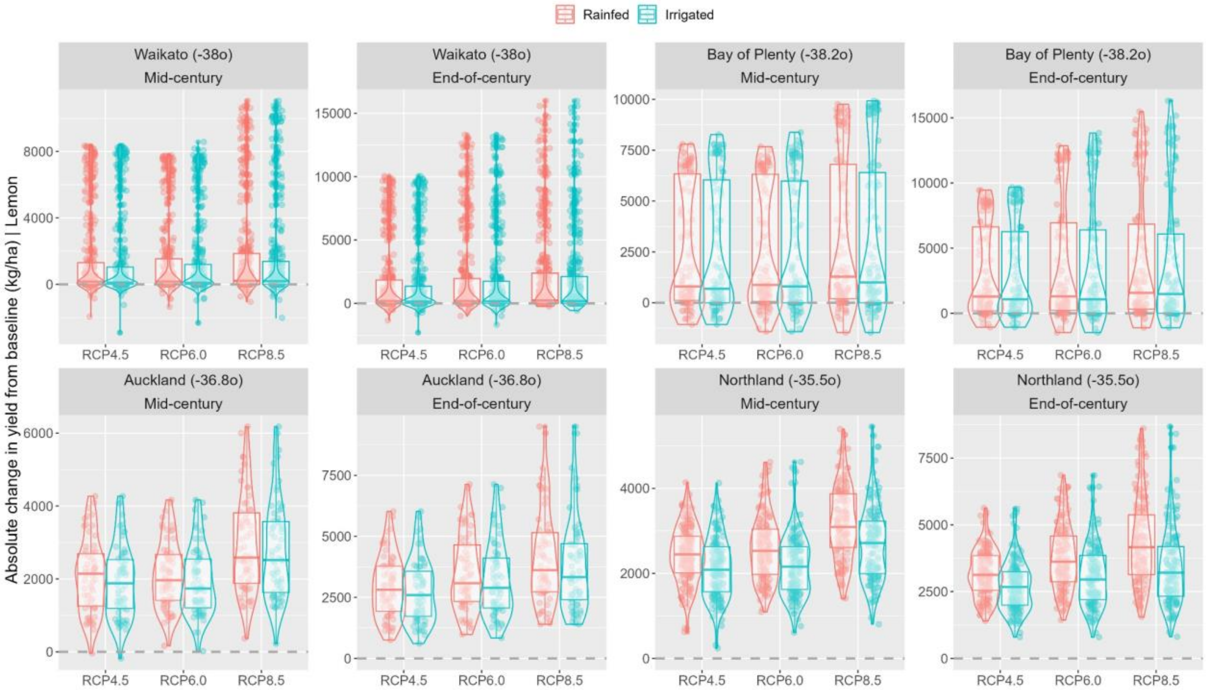

Figure A13 Yield differences under climate change Representative Concentration Pathways (RCP) for Lemon across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

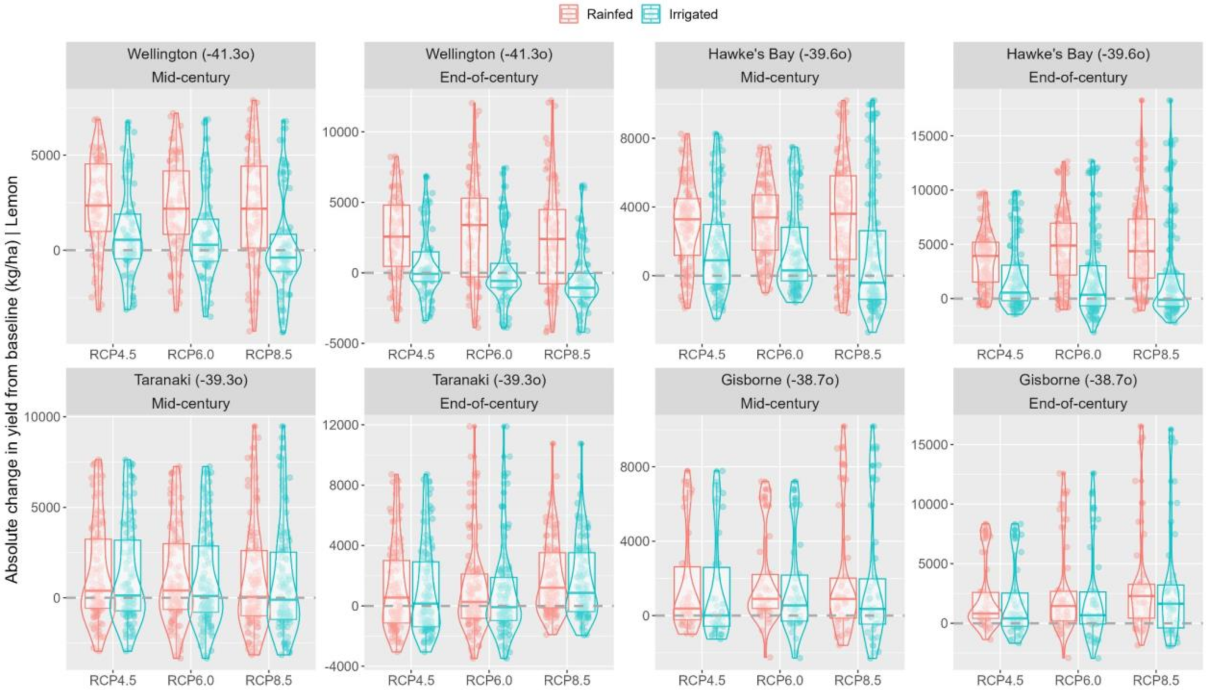

Figure A14 Yield differences under climate change Representative Concentration Pathways (RCP) for Lemon across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

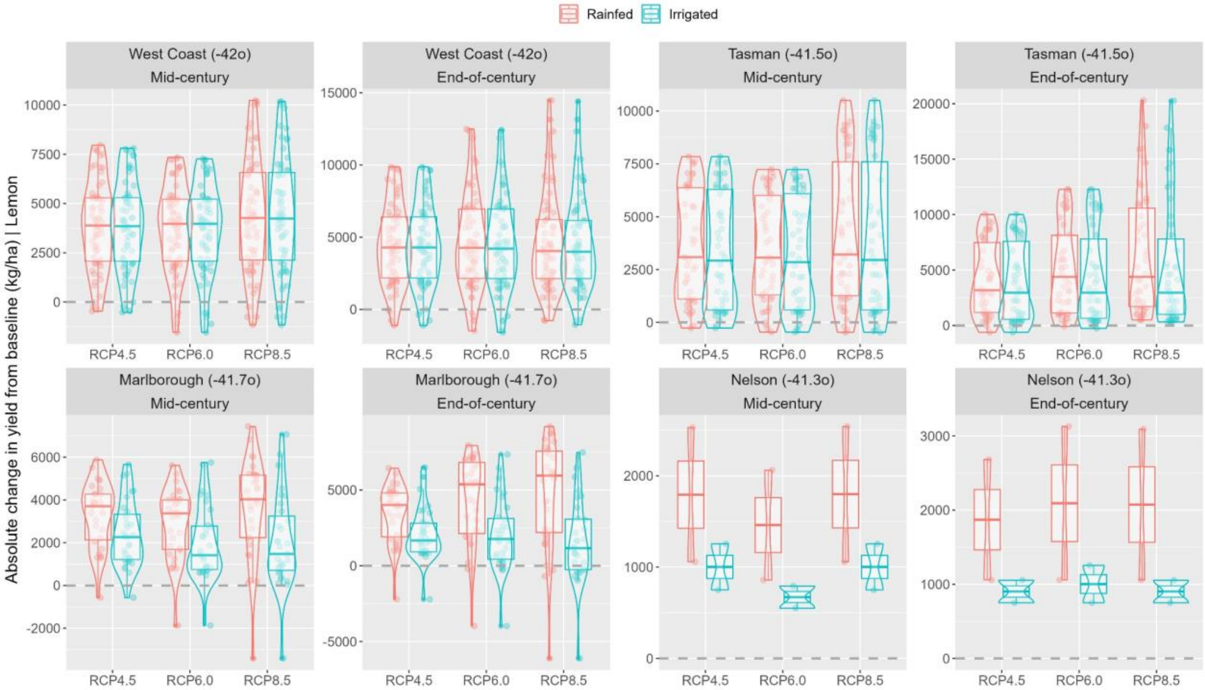

Figure A15 Yield differences under climate change Representative Concentration Pathways (RCP) for Lemon across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

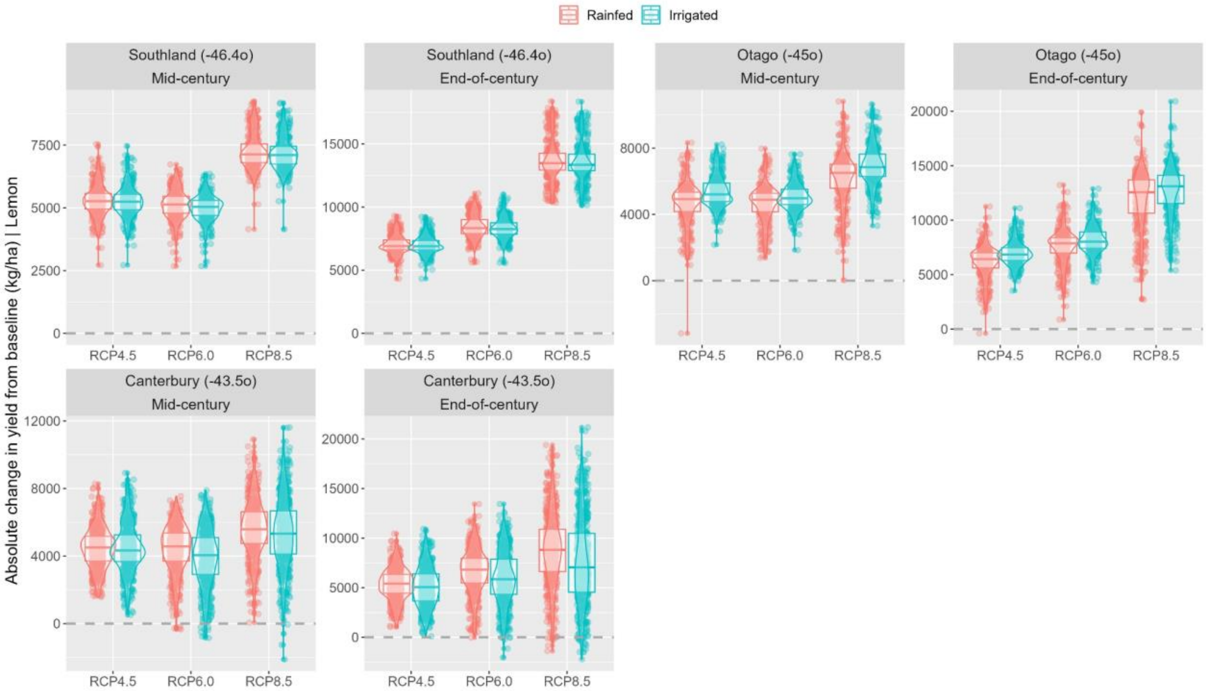

Figure A16 Yield differences under climate change Representative Concentration Pathways (RCP) for Lemon across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

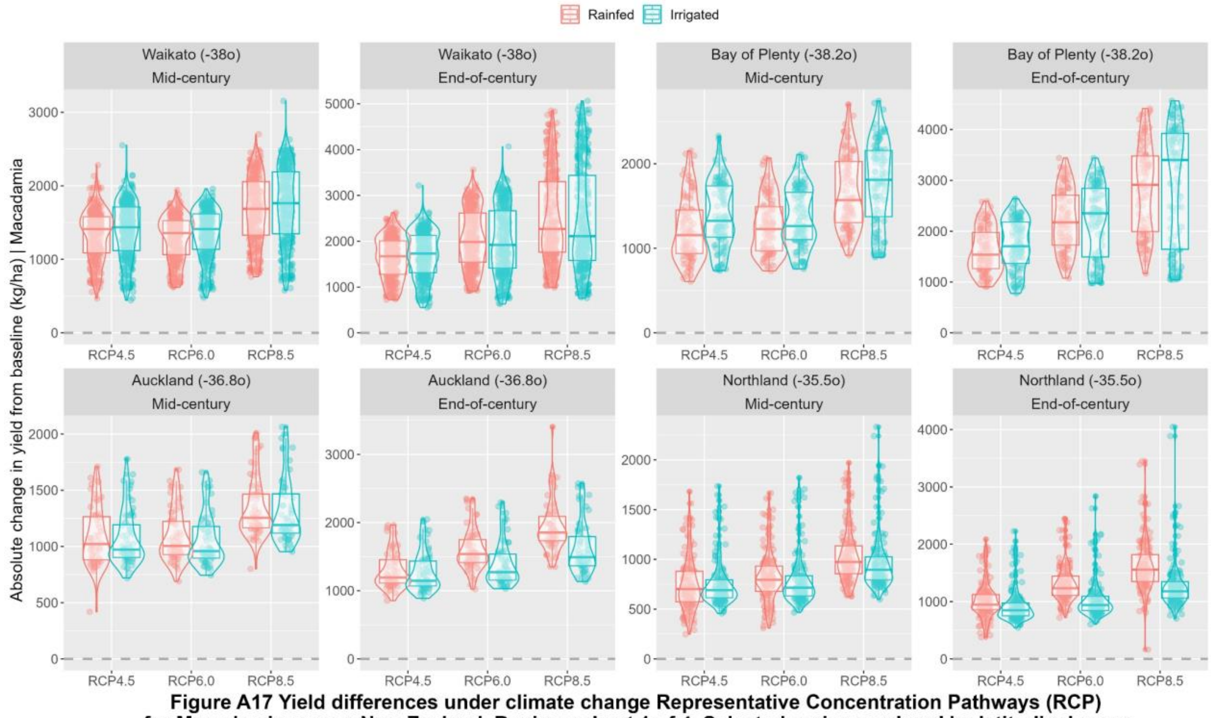

Figure A17 Yield differences under climate change Representative Concentration Pathways (RCP) for Macadamia across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

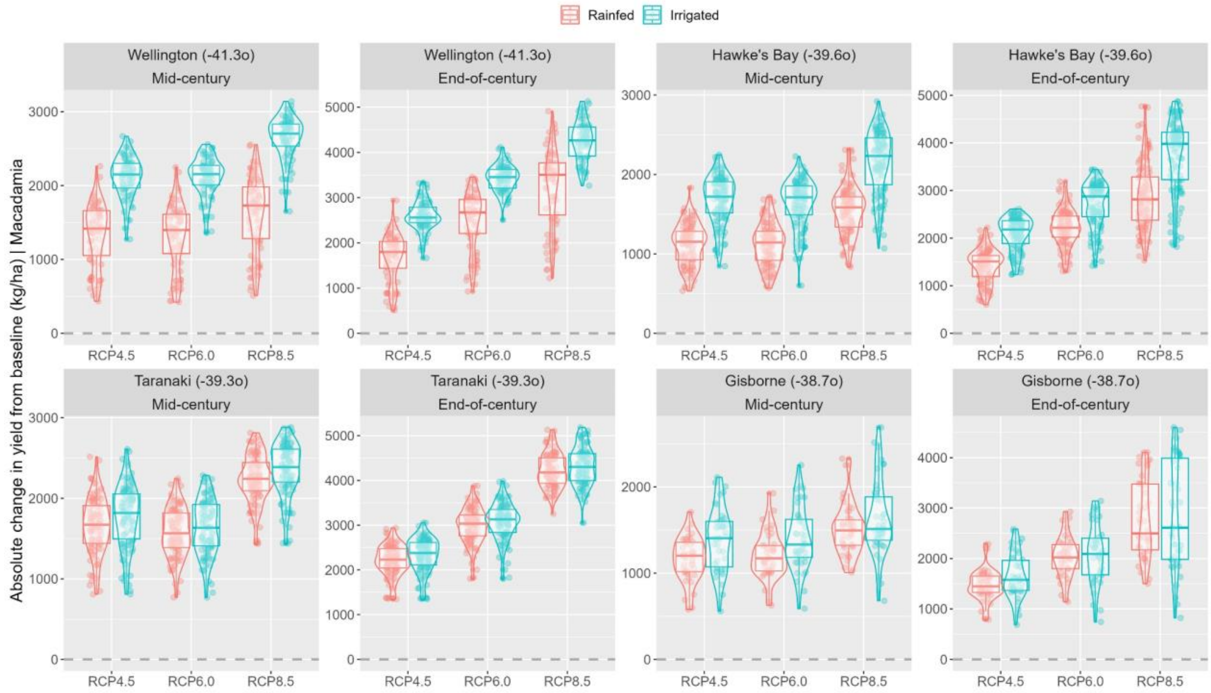

Figure A18 Yield differences under climate change Representative Concentration Pathways (RCP) for Macadamia across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

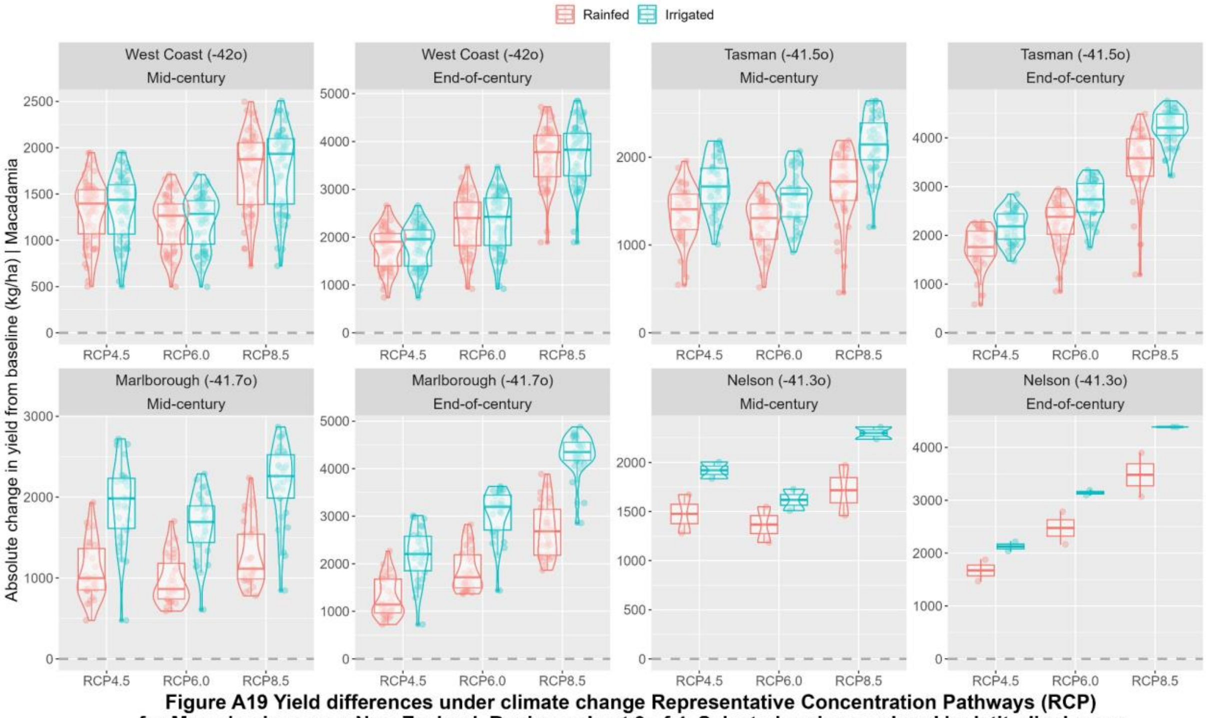

Figure A19 Yield differences under climate change Representative Concentration Pathways (RCP) for Macadamia across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

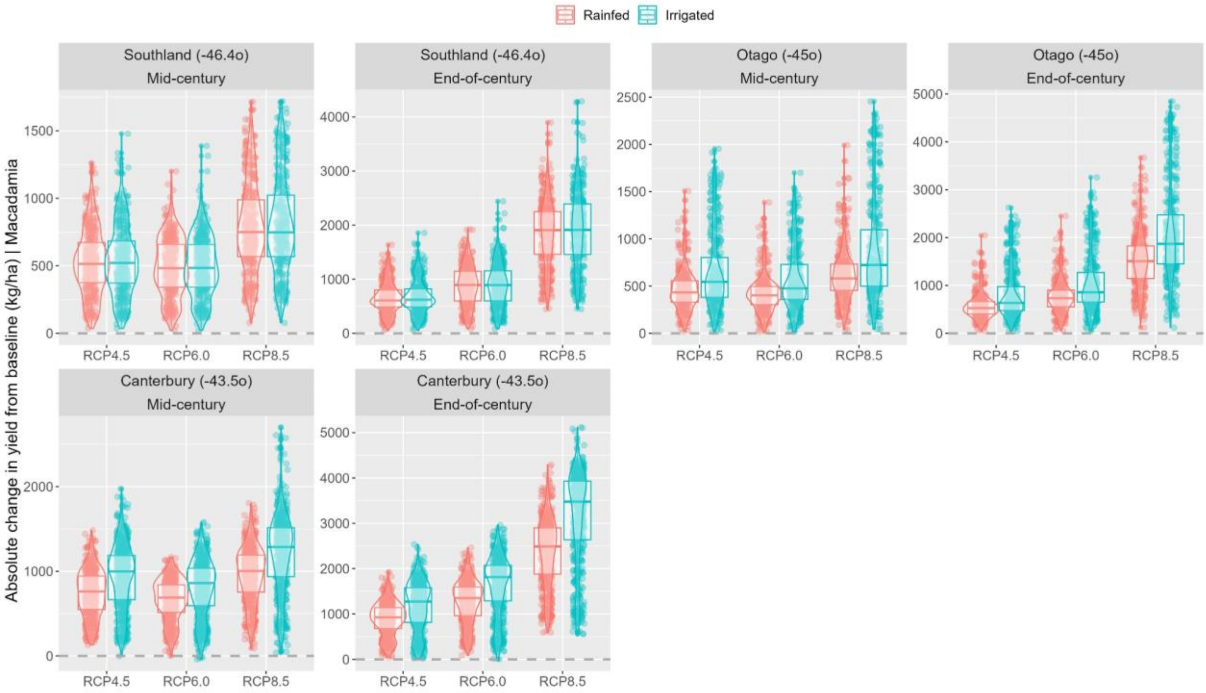

Figure A20 Yield differences under climate change Representative Concentration Pathways (RCP) for Macadamia across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

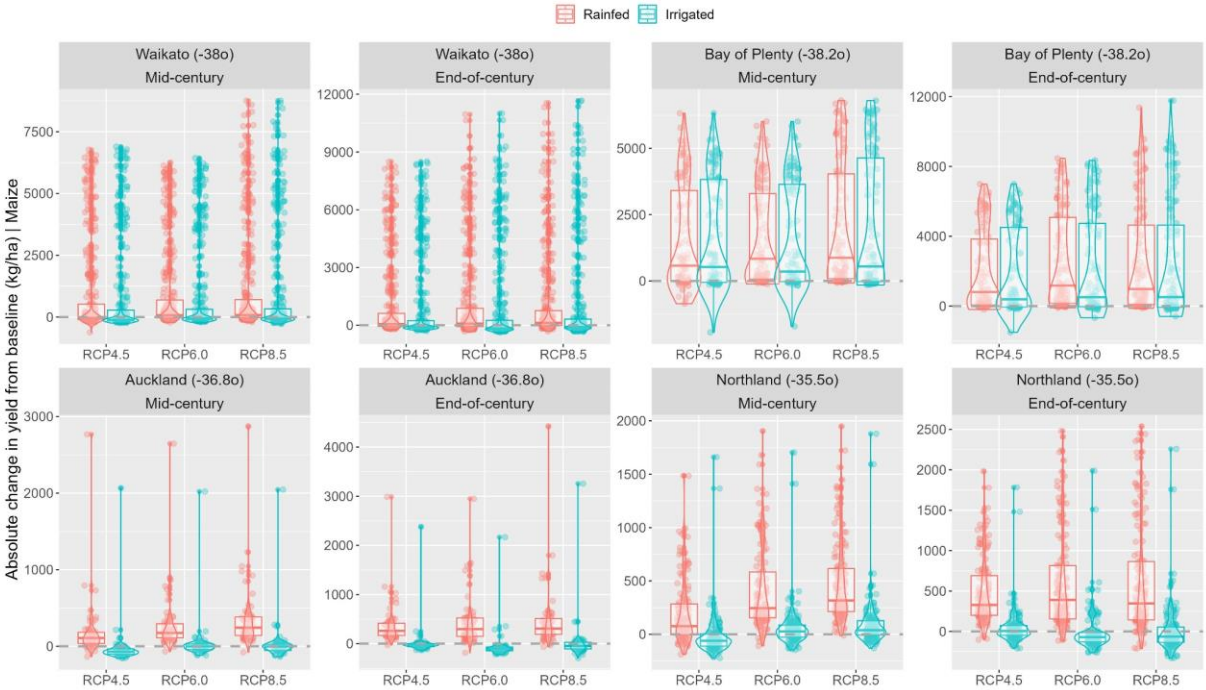

Figure A21 Yield differences under climate change Representative Concentration Pathways (RCP) for Maize across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

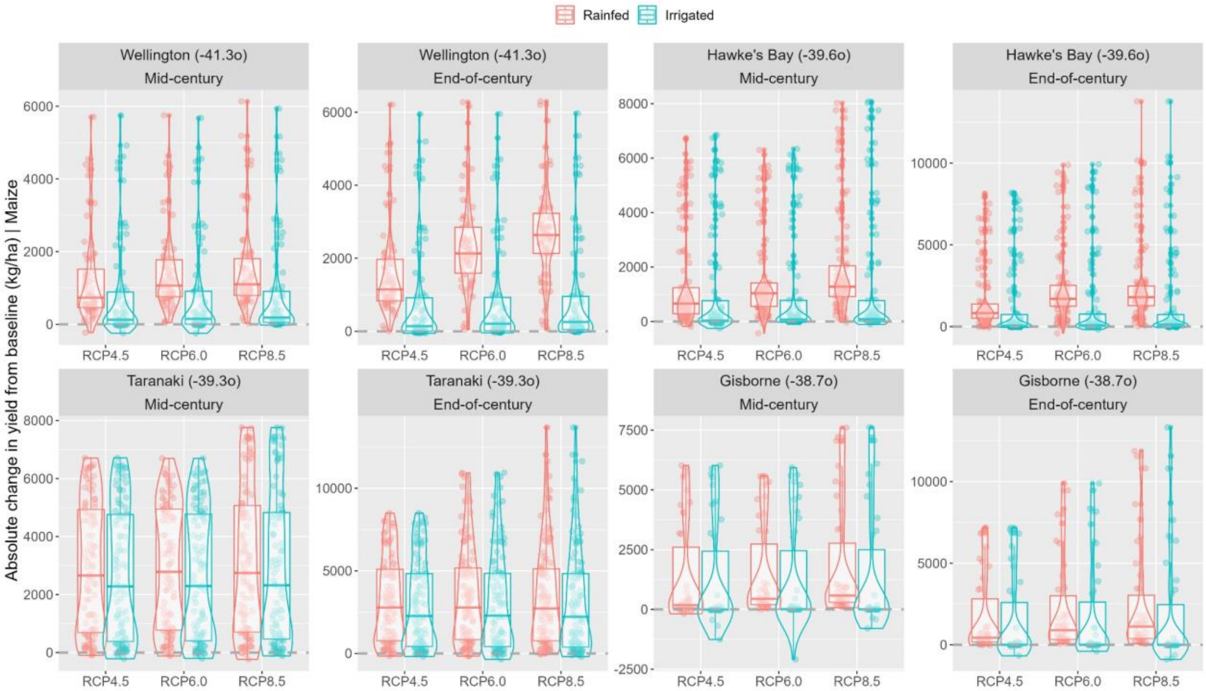

Figure A22 Yield differences under climate change Representative Concentration Pathways (RCP) for Maize across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

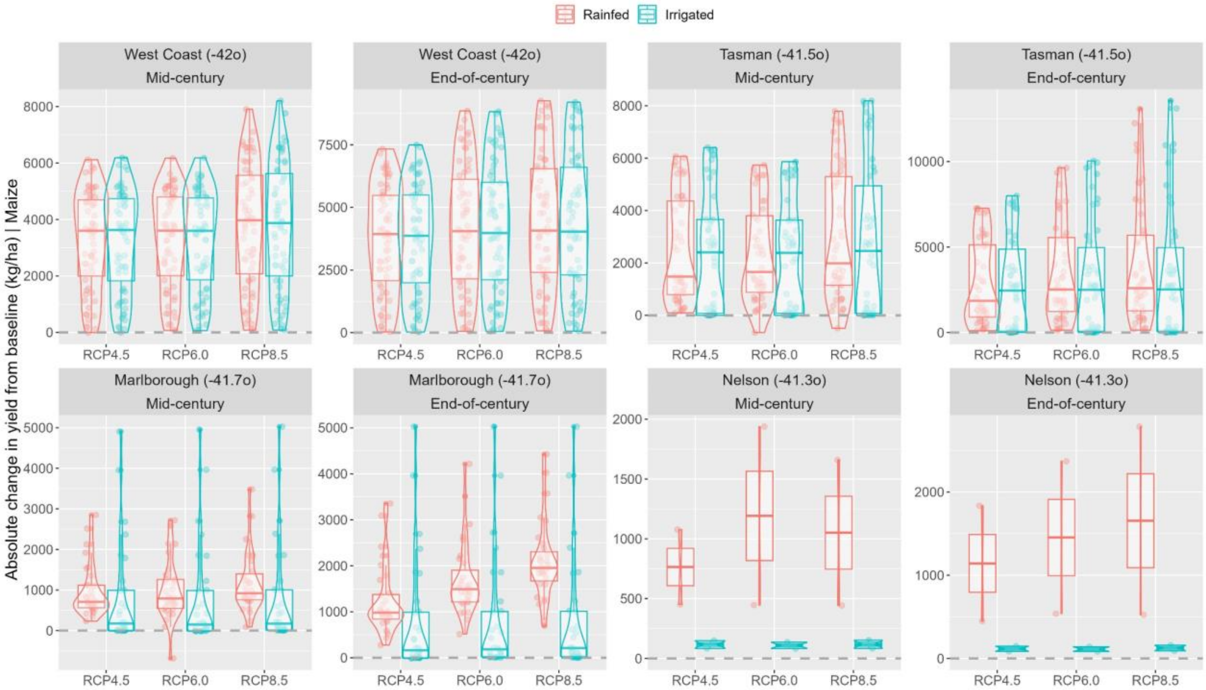

Figure A23 Yield differences under climate change Representative Concentration Pathways (RCP) for Maize across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

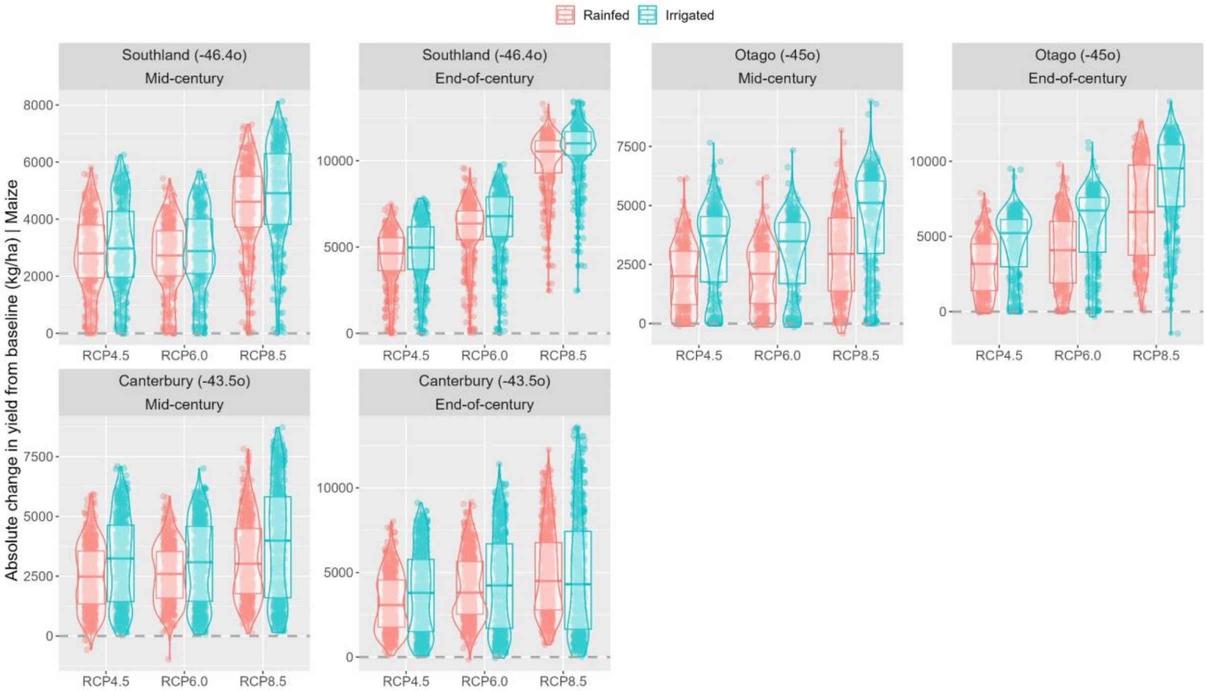

Figure A24 Yield differences under climate change Representative Concentration Pathways (RCP) for Maize across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

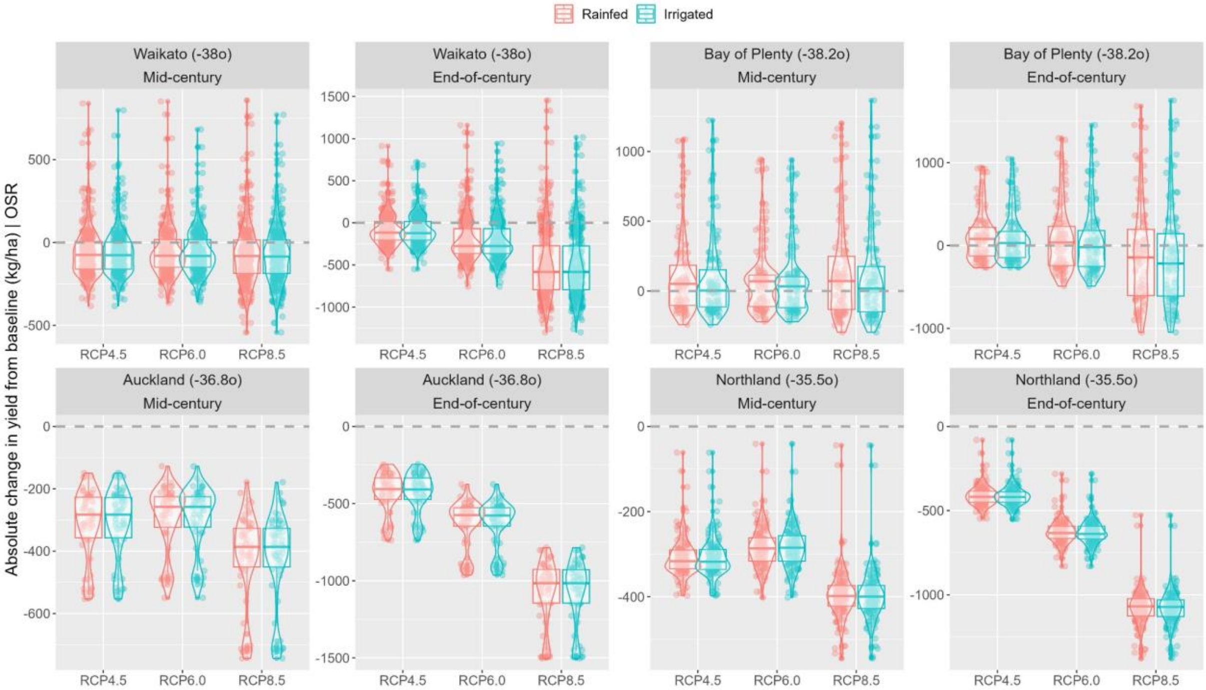

Figure A25 Yield differences under climate change Representative Concentration Pathways (RCP) for OSR across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

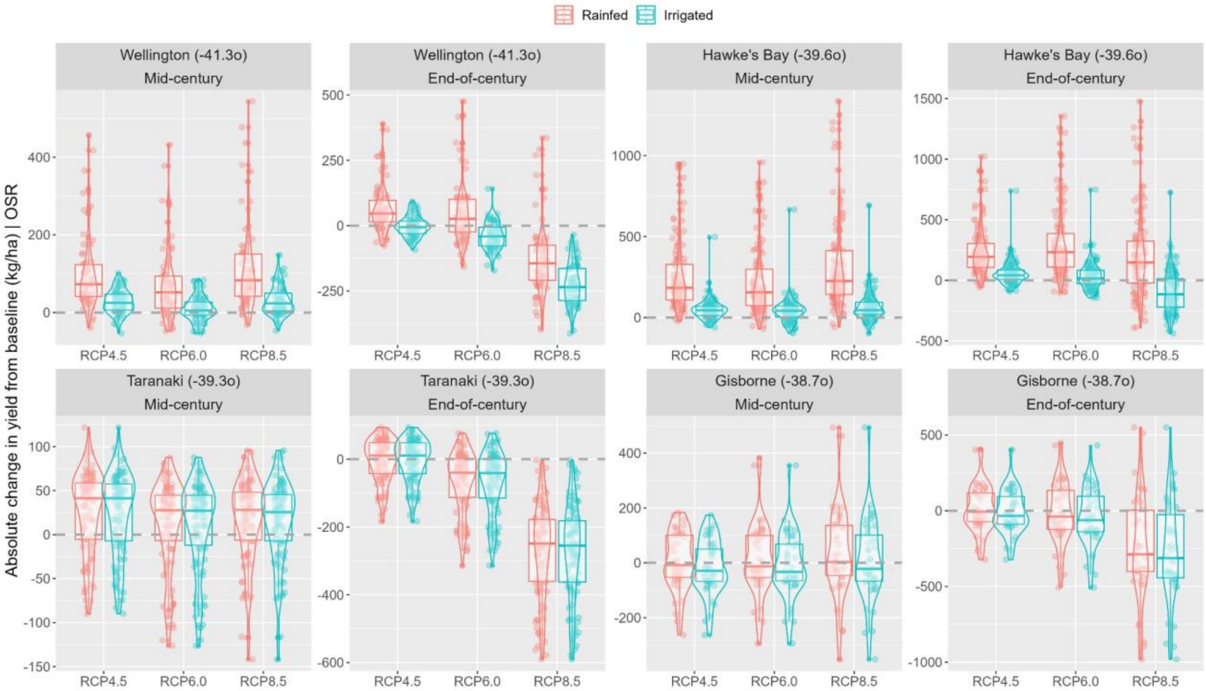

Figure A26 Yield differences under climate change Representative Concentration Pathways (RCP) for OSR across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

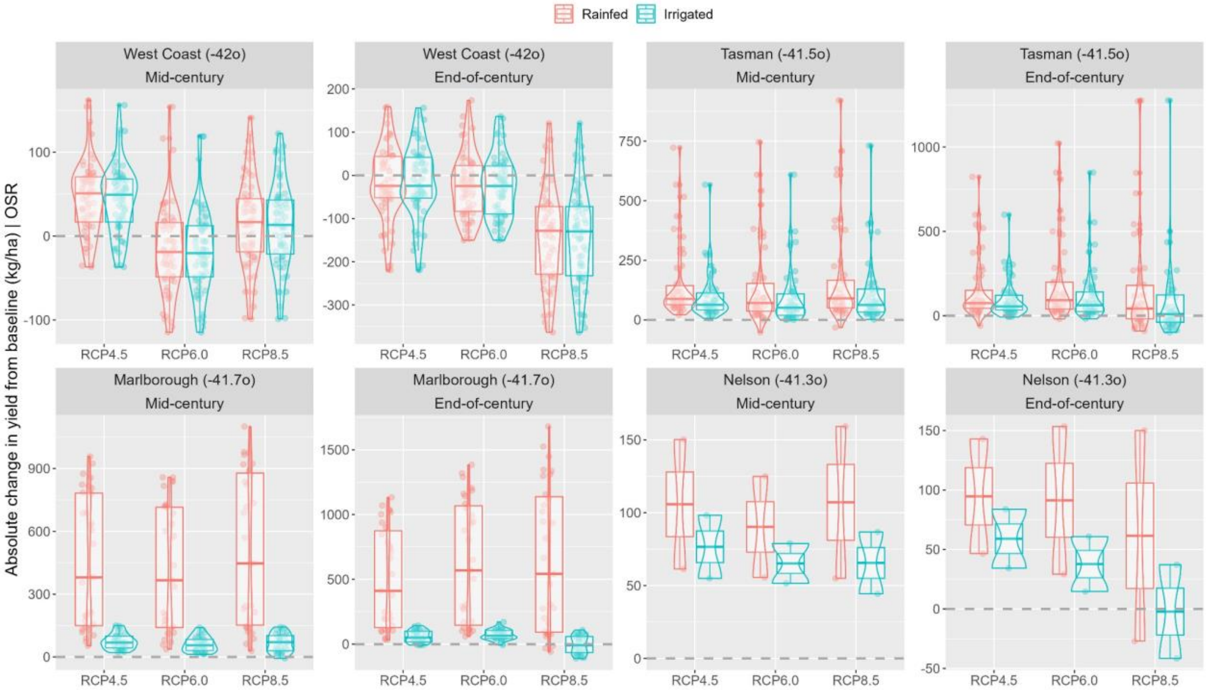

Figure A27 Yield differences under climate change Representative Concentration Pathways (RCP) for OSR across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

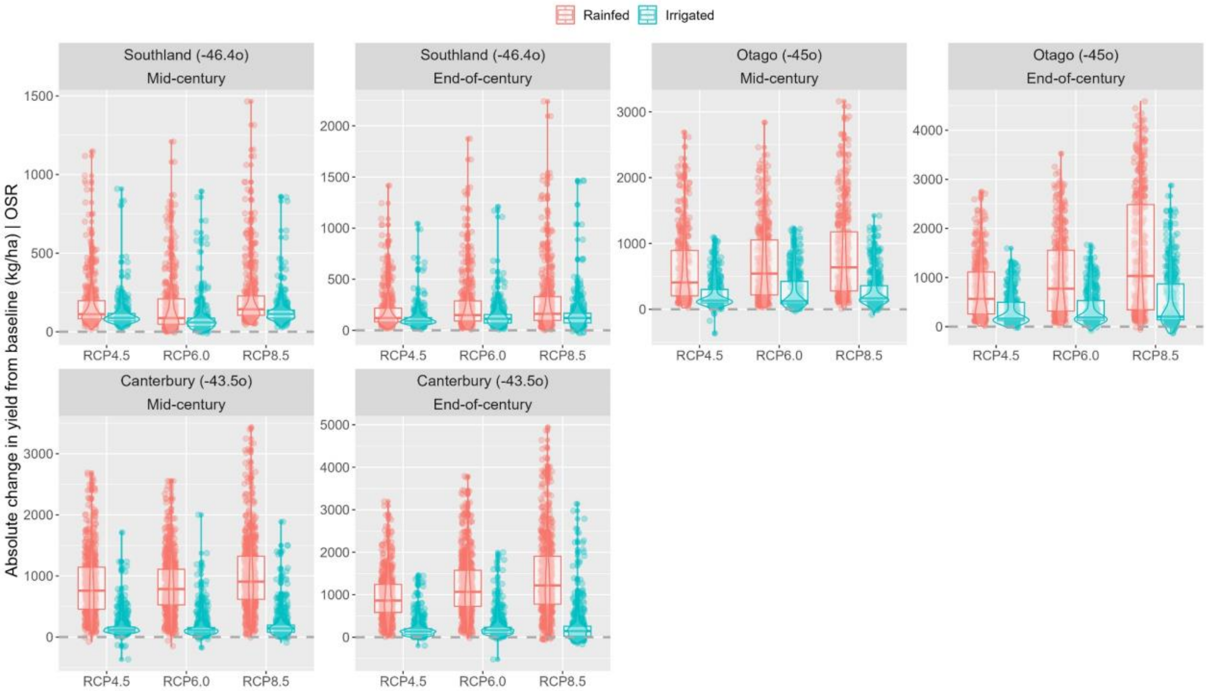

Figure A28 Yield differences under climate change Representative Concentration Pathways (RCP) for OSR across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

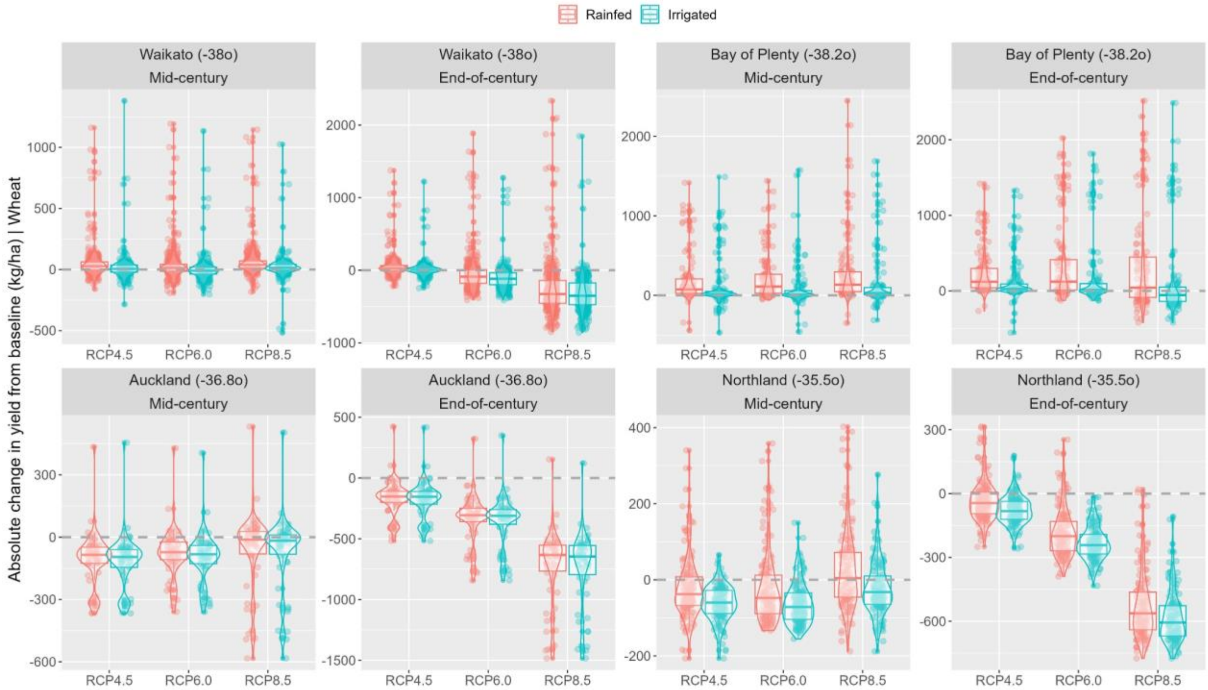

Figure A29 Yield differences under climate change Representative Concentration Pathways (RCP) for Wheat across New Zealand. Region-subset 1 of 4. Selected regions ordered by latitudinal range.

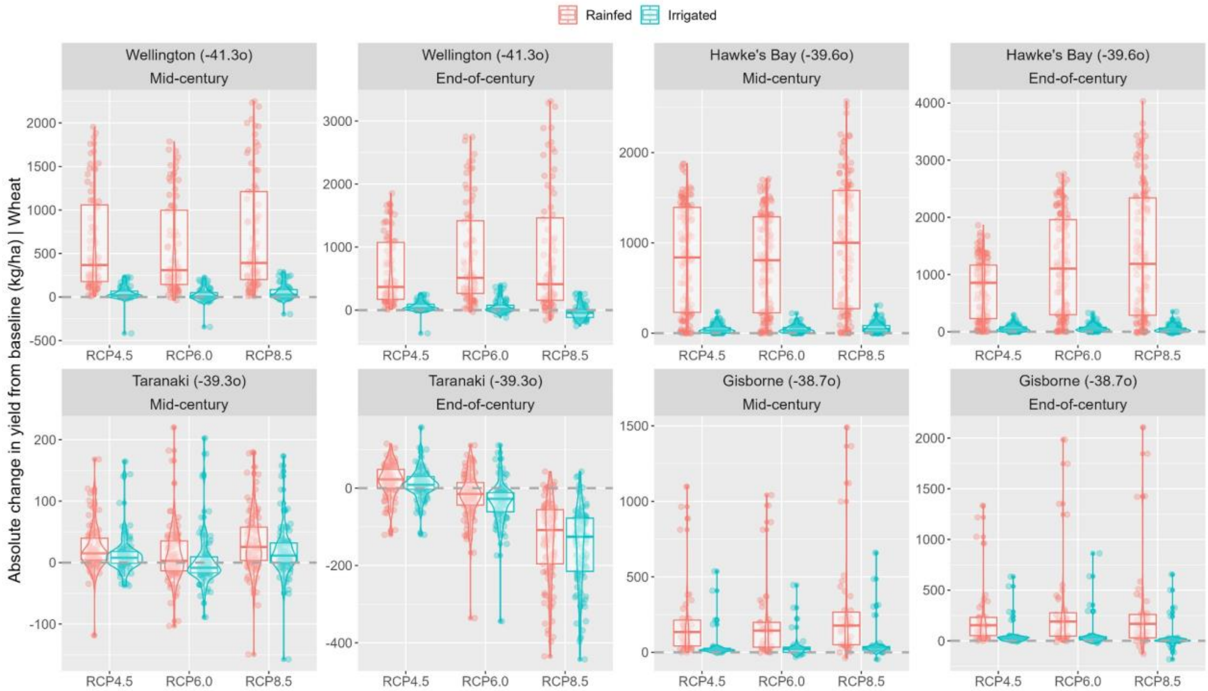

Figure A30 Yield differences under climate change Representative Concentration Pathways (RCP) for Wheat across New Zealand. Region-subset 2 of 4. Selected regions ordered by latitudinal range.

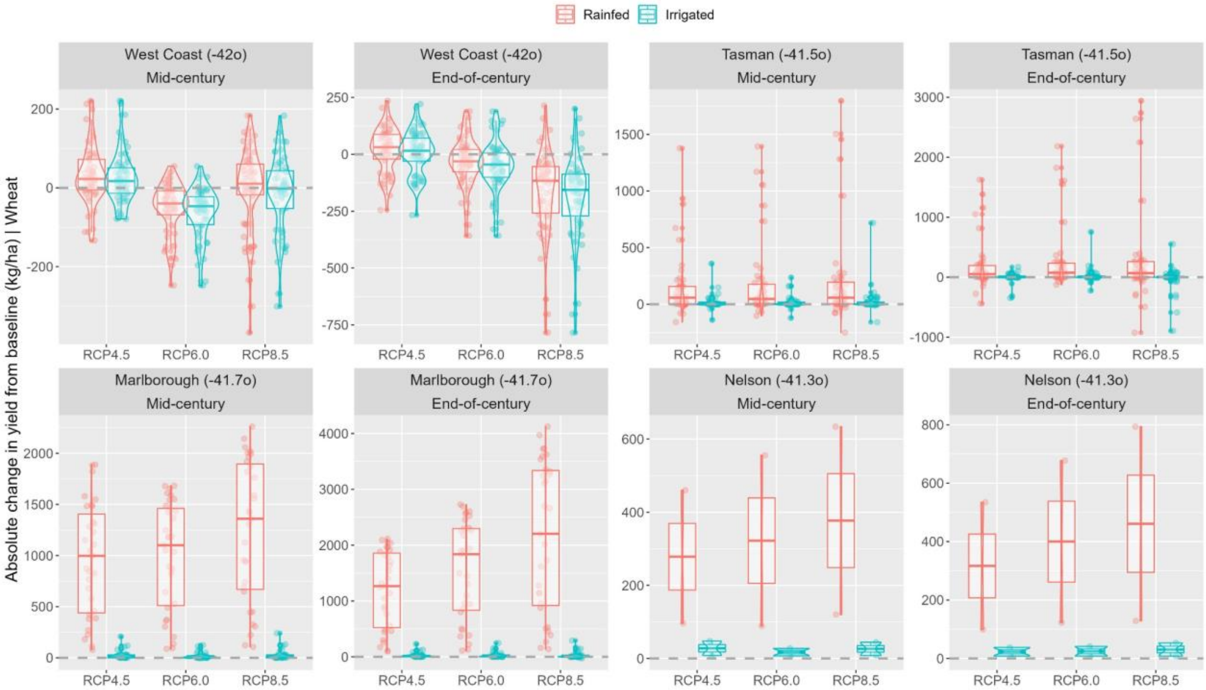

Figure A31 Yield differences under climate change Representative Concentration Pathways (RCP) for Wheat across New Zealand. Region-subset 3 of 4. Selected regions ordered by latitudinal range.

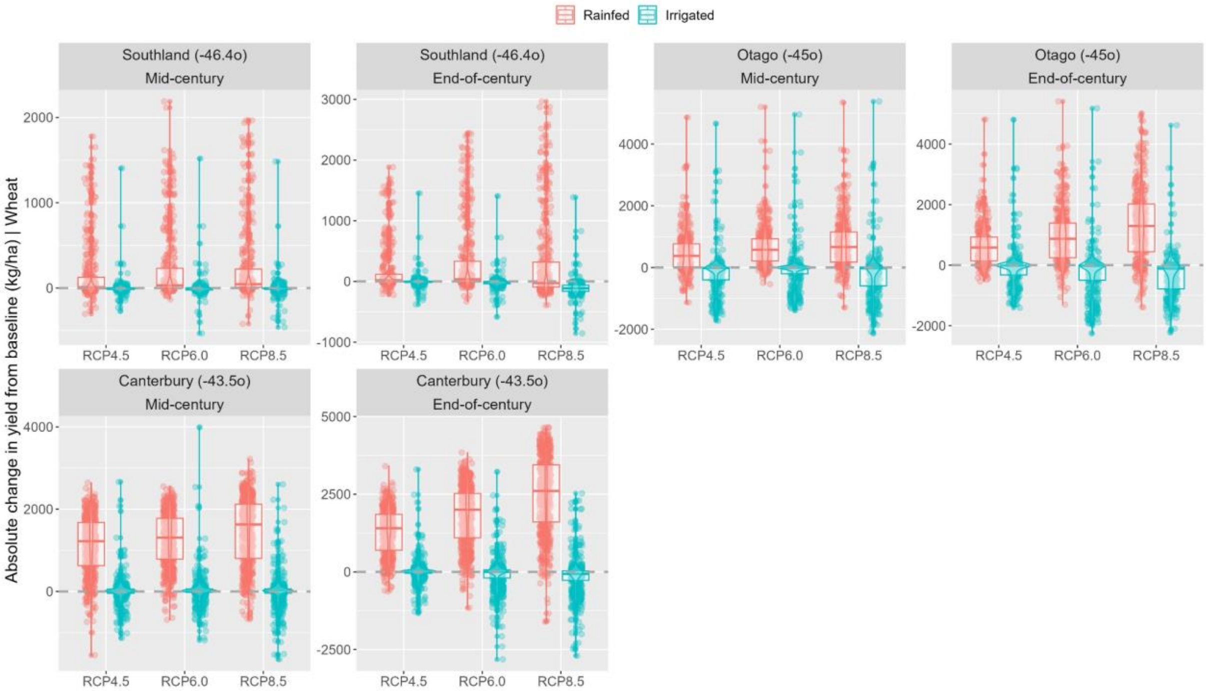

Figure A32 Yield differences under climate change Representative Concentration Pathways (RCP) for Wheat across New Zealand. Region-subset 4 of 4. Selected regions ordered by latitudinal range.

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