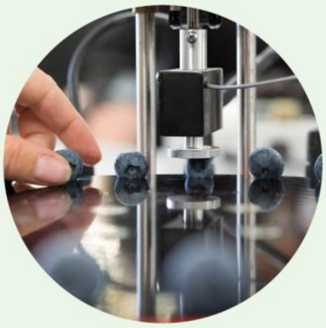







PFR SPTS No. 22727

Suitability modelling and life cycle analysis for almond cultivation in Hawke’s Bay and Poverty Bay

Cummins M, Vetharaniam I

July 2022

Confidential report for:

Central Hawke's Bay District Council

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PUBLICATION DATA

Cummins M, Vetharaniam I. July 2022. Suitability modelling and life cycle analysis for almond cultivation in Hawke's Bay and Poverty Bay. A Plant & Food Research report prepared for: Central Hawke's Bay District Council. Milestone No. 94407. Contract No. 40253. Job code: P/442101/01. PFR SPTS No. 22727.

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Executive summary

Suitability modelling and life cycle analysis for almond cultivation in Hawke's Bay and Poverty Bay

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We performed suitability modelling to identify locations that would be suitable for growing almonds in Hawke's Bay and Gisborne, and carried out climate change impact studies to investigate how suitability for almonds would change in these regions under two greenhouse gas emission pathways. We additionally performed a life cycle assessment (LCA) to evaluate the potential carbon footprint associated with growing almonds. This work is part of a larger effort to investigate the feasibility for establishing a New Zealand almond industry that produces high yields of a premium quality product while using sustainable agronomic practices to minimise environmental impacts.

Suitability modelling

- Suitability modelling was carried out for a number of criteria related to climate, soil and terrain considerations. Climate-related criteria included sufficiency of winter chill accumulation and warmth accumulation for flowering, adequacy of temperatures for pollination, frost risk, moisture-related disease risk, warmth accumulation for crop maturity, risk of rain damage to nuts around harvest, and adequacy of annual rainfall. Soil and terrain criteria included sufficiency of soil depth, sufficiency of drainage, steepness of land, and appropriate land use capability class.

- Continuous suitability models were used, with suitability criteria being assessed on a continuous scale of 0 (unsuitable) to 1 (highly suitable with no limitations). Lower scores indicate more mitigations are required to successfully grow the crop. Suitability scores for different criteria were combined using weighted geometric averaging to obtain an overall cultivation suitability score, with the value of the weights assigned to different criteria reflecting their relative importance. GIS climate and land databases were used to provide inputs to the models, allowing for construction of suitability maps for the Hawke's Bay and Gisborne regions.

- An existing almond phenology model that uses climate data as inputs was modified and parameterised to predict when key phenological stages (flowering, hull split and harvest maturity) occur in relation to potentially inclement weather. Limited New Zealand centric data were available from two Hawke's Bay almond orchards with a combined three years of observations and were used to parameterise the model for New Zealand. More comprehensive data would be needed to obtain a more robust parameterisation.

- The modelling results showed that a diverse suitability landscape for cultivating almonds existed across both Hawke's Bay and Gisborne regions. No locations were identified that would provide optimal conditions for almonds with few limitations to production. However a number of locations were identified that could provide good conditions for growing almonds, although subject to some limitations to achieving maximum production potential.

- Some locations in the Heretaunga Plains, especially around Hastings and Havelock North, were found to have the highest cultivation suitability scores, with a number of locations in Central Hawke's Bay District having slightly lower cultivation suitability scores. A number of locations around Poverty Bay and inland of the Poverty Bay Flats were also identified as having good suitability scores. Although these locations are likely to be subject to more limitations or extra mitigation costs, they are potential sites for successful almond orchards.

- Large areas of Central Hawke's Bay District and areas around Hastings and Napier were identified as having insufficient annual rainfall to obtain maximum yields without irrigation. However growers can choose not to irrigate almonds and accept low yields.

- The climate change impact assessment projected that under RCP 8.5, a high greenhouse gas (GHG) concentration pathway consistent with unabated emissions, cultivation suitability for almond would improve over time, at least to 2070. Under RCP 6.0, a GHG concentration pathway consistent with lower emissions than RCP8.5, cultivation suitability for almond was also projected to improve, but at a slower rate than under RCP 8.5.

Life Cycle Assessment

- A partial Life cycle assessment (LCA) showed that if irrigation were used, almonds at the farm gate would have a potential carbon footprint of 1.83 kg CO_2-eq/kg. For comparison, studies for almond production overseas found the potential carbon footprint to be between 1.6–1.9 kg CO_2-eq/kg.

- Irrigation was highlighted as a potential system hotspot and area of consideration for system improvements accounting for 68% of the total footprint. This is followed by machinery operations (13%) and fertiliser use (9%).

- Sensitivity analysis revealed that a reduction in the applied irrigation could significantly reduce the overall potential footprint. This may, however, have a negative correlation with the overall potential yield.

- Orchard specific data were limited, therefore, a number of assumptions have been made in the design of the LCA model. It is advised that LCA results are considered alongside other information.

- A review of the potential carbon footprint relating to other land uses was completed. However, LCAs are a relative measure and comparisons between land uses and products with different functions should be avoided.

- Future assessments should focus on data quality to improve the reliability and robustness of the current LCA model. Further considerations may include expanding the system boundary or the effect of bi-product utilisation for other processes.

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1 Introduction

This report details the outcomes of a study to perform suitability modelling and life cycle assessment (LCA) for almonds, in order to support the development of a new almond sector in the Hawke's Bay/Poverty Bay regions. This study is part of a larger project to investigate the feasibility for establishing a New Zealand almond industry that produces high yields of a premium quality product while using sustainable agronomic practices to minimise environmental impacts.

Ideal conditions for almonds are Mediterranean-like climates with slightly hot summers and cool winters, coupled with deep, loamy well-drained soils (Ahmed & Verma 2009). The New Zealand Tree Crops Association considers New Zealand climates to be relatively marginal for growing almonds, with the most suitable areas likely to be located in areas of Hawkes' Bay, Nelson, Canterbury and Otago (https://treecrops.org.nz/almond-factsheet/), which is likely reflected by a lack of commercial production, with only a few almond growers in the country. Development of an almond industry would be supported by the identification of promising areas as a first step before on-ground feasibility investigations. New Zealand's primary sector is subject to a number of weather-related risks and is potentially vulnerable to climate change which could bring about declining yields and profitability or alternatively provide new opportunities (Hopkins et al. 2015; Manning et al. 2015; Ausseil et al. 2016; Cradock-Henry et al. 2019). Thus an understanding of potential impacts of climate change is important when establishing a new almond industry.

Some consumers are likely to pay a price premium for sustainably and locally grown almonds (de-Magistris & Gracia 2016). Thus it would be invaluable to understand how New Zealand grown almonds would compare with imported almonds on sustainability issues, as well as with alternative land uses. Life cycle assessment (LCA) is a tool that can be used to assess the potential environmental performance of a production system and LCA methodology is intended to give an indication of the potential footprint along each step of a product's life cycle and highlight hotspots along the production chain. Inputs and associated outputs of a product system can then be quantified to give an indication of their potential environmental burden.

The aim of this study was to:

- Apply a model previously developed by Plant & Food Research (PFR) to evaluate the suitability of almond cultivation, using GIS-based information on soil, terrain, and weather, to identify the most suitable locations in Hawke's Bay and East Coast, and the most suitable almond phenotypes, for the production of sustainably produced almonds.
- Use LCA to evaluate the potential carbon footprint associated with growing almonds in Hawkes Bay, and identify 'hotspots' with the production systems.
- Investigate how climate change could impact the suitability of individual locations under different scenarios of future atmospheric greenhouse gas (GHG) concentrations (and thus different levels of global and regional warming).

1.1 Suitability modelling

The PFR suitability model uses essentially a fuzzy logic approach and calculates a suitability score on a continuous scale from 0 (totally unsuited) to 1 (suitable with no limitations) for each suitability criterion being considered. This approach has been applied to model location suitability for a number of perennial crops (Vetharaniam et al. 2021). Criteria scores are geometrically averaged to get an overall suitability score, with scores weighted to reflect their relative importance.

For modelling suitability with respect to climate-related criteria, the model simulates the temporal development of key phenology stages (e.g. budbreak, flowering period, hull split and maturity) as a function of weather data, in order to assess the timing of weather conditions that could be deleterious to particular phenology stages. For example, frost events or poor pollination conditions during the flowering period, or rainfall from the split hull stage through to harvest.

Thomas & Hayman (2018) noted that phenology-based models provide a means to explore how almonds will perform at new sites and in future climates. Those authors reported the development and evaluation of an almond phenology model driven by chill and heat accumulation, with particular phenological stages (10% and 80% flowering, 1% and 100% hull split, and harvest) dictated at precise amounts of heat and chill accumulation. A similar approach had also been reported by Parker & Abatzoglou (2017) a little earlier.

The PFR model takes a probabilistic approach and simulates the likelihood of a phenological stage having been reached, which can reduce the inconsistencies that occur with hard cut-offs. The model was theoretical for almonds in New Zealand, and has been parameterised based on published data from overseas trials that provided chill and heat accumulation for different phenological stages. Model simulations were formulated separately for three development groups: early, medium and late cultivars. For each phenology stage, the model simulated the percent of cultivars in each development group expected to have reached that stage.

There is a paucity of almond phenology data for New Zealand, and we had access to incomplete datasets for two separate orchard locations in Hawke's Bay, one having observations in two different growing seasons, and the other having observations in only one growing season. However, when testing the initial parameterisation these were sufficient to show that the overseas data were not suitable for modelling the New Zealand situation. This was not unexpected since the cultivars grown here were not represented in the overseas data, and furthermore, chill and heat accumulations for the same cultivar can vary with country.

We adjusted the PFR suitability model to simulate the phenology observations from the Hawke's Bay orchards, and sense checked predictions for phenological stages where data were available. There were insufficient data to parameterise the mode separately for early, medium and late developing cultivars, and so we used one parameterisation set that reflected the variation from early to late developing cultivars.

1.1.1 Interpreting continuous suitability scores

The use of continuous suitability scores is an alternative to using categories with hard cut-offs. A high suitability score (close to 1) for a criterion indicates that crop cultivation will have little or no limitation with respect that criterion. However, the lower the score is below 1, the greater the limitations that can be expected, and more mitigations would be needed to successfully grow the crop, or more losses tolerated. This approach generally does not rule a location as suitable or unsuitable – that becomes a management decision.

1.2 Life cycle assessment

The life cycle of a product may be evaluated from the extraction of raw materials to production, transport, consumer interaction, and recycling (i.e. cradle to grave), or as part of a product system (i.e. cradle to farm gate). Results and interpretation of an LCA can then be integrated with other assessment techniques to improve sustainability outcomes, improve management, or resource use efficiency (Klöpffer 1997; Finnveden et al. 2009; Hauschild et al. 2018).

The LCA framework, as defined by the International Organization for Standardisation (ISO 2006a, 2006b) has four main phases:

- *Goal and scope definition*: this includes the reason for carrying out the study, the intended application and audience. It is also here that the system boundary is defined (i.e. the extent or the cut-off of the production system being assessed) and the functional unit defined (i.e. base reference to compare products).
- *Life cycle inventory (LCI):* LCI is the collection and sum of all the inputs and outputs and associated flows of the product system.
- *Life cycle inventory analysis (LCIA):* aims to describe the environmental consequences of the loads quantified in the LCI, which are translated to potential impacts such as global warming potential (GWP), eutrophication potential or acidification potential.
- *Interpretation:* results from the previous phases are evaluated in relation to the goal and scope in order to reach conclusions and formulate recommendations.

There is increased awareness and concern regarding the potential impacts on society associated with climate change and global warming (Kerr 2007). LCA has been used extensively to assess the potential environmental impact of a variety of products and in more recent times has also been adopted to evaluate the performance of agricultural products (Hayashi et al. 2006; Roy et al. 2009; Caffrey & Veal 2013). Rather than addressing the immediate and most obvious concerns, LCA takes a holistic approach and allows us to evaluate the potential impact of various stages within a product's life cycle. The assessment and definition of environmental impact, when conducting an LCA, is at the discretion of those who are undertaking the study and what has been defined in the goal and scope. When reporting the results from LCAs, in relation to a carbon footprint, units of CO_2-equivalent (CO_2- eq) are often used. The emission of greenhouse gases, which are the result of a number of natural and human driven processes, has varying degrees of global warming potential (GWP) and therefore, CO_2- eq units provide a metric measure that allow us to compare different gaseous emissions on a common scale.

2 Methodology

2.1 Suitability modelling

A number of climate- and soil/land-related suitability criteria were identified by Hall et al. (2018) for a range of temperate tree crops related to climate, soil and terrain considerations, and are applicable to almond cultivation. These include adequacy of winter chill to ensure a sufficient and compact flowering, sufficient warmth during the growing season for the crop to reach maturity, risk to production from frost damage, soil drainage class, soil depth to a root-impermeable layer, and the slope of the land. In addition to these suitability considerations, Vetharaniam et al. (2021) included land use capability (LUC) class descriptors as suitability criteria that could be used for a range of crops, and also developed a generic disease-risk suitability model for pathogens favoured by high moisture availability combined with warm temperatures. We have included all the above as suitability criteria for almonds.

Thomas et al. (2019) listed a number of risk factors of concern identified during workshops with Australian almond growers. Excluding criteria mentioned above, these included rain at harvest, heatwaves, and wind damage, non-synchronised flowering, adequacy of rainfall for growing requirements, temperatures being too cold for pollination, and hail damage. Of these, we have included rain around harvest, adequacy of rainfall and cold temperatures during pollination in our suitability considerations.

There is a lack of quantitative data on the impact of heatwaves, and heatwaves are less likely to be a problem in New Zealand compared with Australia, especially in the current climate, and thus this was a risk that we modelled. The risk of wind damage was not modelled since the historic and simulated future climate data contain average daily wind speeds but not gusts or storm events. We did not have data on historic hail events in our historic climate database, and hail events cannot be projected with any confidence in future climate projection data, and thus hail risk was excluded as a modelled suitability criterion. Non-synchronised flowering between main varieties and pollinator cultivars is related to low chill accumulation, and risks can be reduced by using self-fertile varieties (Thomas et al. 2019). Since we included chill consideration in the modelling, we did not model non-synchronised flowering as a specific criterion.

The temporal development of almonds was modelled in terms of the probabilities that key phenology stages including budbreak, flowering period, hull split and maturity had been reached at different stages of the growing season, with these probabilities expressed as functions of accumulated chill and/or warmth over the course of the growing season. Climate-related suitability scores were calculated with respect to the rate of phenological progression, separately for each year. Scores for individual climate criteria were averaged over a period to get a representative mean score. Overall climate suitability was calculated first on a yearly basis by taking the weighted geometric mean of individual climate criteria scores for each year, and then averaging the yearly climate suitability scores over a period. Land-related suitability scores were calculated separately for each criterion, and then could be geometrically averaged using weights to get an overall suitability score for land-related criteria. The suitability scores for land and for climate could be then geometrically averaged using weights to get an overall suitability score than balanced across all criteria. Weights used in geometric averaging were chosen to reflect the relative importance of individual criteria.

Suitability scores for the contemporary period were calculated using data on historic weather. Suitability scores for future periods required the use of projection data from climate models.

2.1.1 Data

Observed, historic climate data

We used NIWA's VCSN database to provide estimates of historic values of daily climate variables. These data are gridded with a resolution of approximately 5 x 5 km, covering the entire country. The VCSN data are estimates of daily climate variables based on spatial interpolation of actual observations made at climate stations spanning the country (Tait et al. 2006; Tait 2008). We used daily maximum and minimum temperatures, relative humidity (RH) and rainfall data for the period 2001 to early 2021. The maximum temperature for each day is the maximum recorded **from** 9 a.m. of that day; the minimum temperature corresponds to the minimum recorded **to** 9 a.m. of that day; RH is humidity at 9 a.m.

Projected climate data

We used the "SLM RCP" datasets which had been specifically bias and variance adjusted for horticulture-related climate projection by Vetharaniam et al. (2021) and are derived from modelled climate data that were supplied by NIWA for the Sustainable Land Management and Climate Change (SLMACC) project 'Analysis of potential climate change impacts on horticulture's spatial footprint' (#34671).

The NIWA data were derived from NIWA's high resolution Regional Climate Model (RCM), which was run in alternative simulations with boundary conditions that were provided by outputs from six CMIP5 (Coupled Model Intercomparison Project (CMIP) Phase 5) global climate models (GCMs): BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-EL-R, HadGEM2-ES and NorESM1-M. Simulations were performed under four Representative Concentration Pathways (RCPs) which represent different scenarios of future atmospheric greenhouse gas (GHG) concentrations, and thus four different levels of global and regional warming. The simulations were run for the years 1972 to 2100, and beyond for some GCMs, with a hindcast period of 1872 to 2005. The simulations are described in detail by the Ministry for the Environment (2018).

Of the four RCP pathways, RCP 2.6 and RCP 8.5 are the extremes: RCP 2.6 represents a low greenhouse gas (GHG) concentration pathway consistent with significant emissions reductions, and RCP 8.5 represents a high GHG concentration pathway consistent with unabated emissions. The two intermediate RCP pathways are RCP 4.5 and 6.0 with RCP 4.5 corresponding to more emissions reductions than RCP 6.0.

For projecting climate change impacts, we used RCP 8.5 since it is closest to the current emissions trajectory and additionally we included RCP 6.0.

Land and soil information

We used the FSL and NZLRI databases to get data on the potential rooting depth (PRD, https://lris.scinfo.org.nz/layer/48110-fsl-potential-rooting-depth/) provided by the soil, soil drainage (https://lris.scinfo.org.nz/layer/48104-fsl-soil-drainage-class/), and land use capability (LUC) class (https://lris.scinfo.org.nz/layer/48076-nzlri-land-use-capability/). Slope information was obtained from Land Environments of New Zealand (LENZ, https://lris.scinfo.org.nz/layer/48081-lenz-slope/).

Locations of public conservation areas were obtained from the Department of Conservation (DOC) Public Conservation Areas database (https://koordinates.com/layer/754-doc-public-conservation-areas/). Data on the location of urban areas, quarries, rivers and lakes were available in the NZLRI database. Information from these databases had been extracted and then resampled onto a grid resolution of approximately 1 x 1 km in the SLMACC project 'Analysis of potential climate change impacts on horticulture's spatial footprint' (#34671).

Limitations when using gridded data

There can be significant variation in microclimates and weather variables within the approximately 25 km^2 area represented by each VCSN grid cell. For example Ellenwood (1941) found differences of 1.7 to 2.2°C between locations in neighbouring apple orchards that had no more than a 7.5 m difference in elevation. Such variation is not represented in the VCSN database, which provides a single daily value per grid for each weather variable that it contains. Similar limitations apply to databases for soil and terrain properties. These limitations should be borne in mind when considering outcomes from GIS-based models.

Elevation data

Although we have not used elevation information directly, an elevation map (Figure 1) for the locations being modelled can be useful for sense-checking predictions.

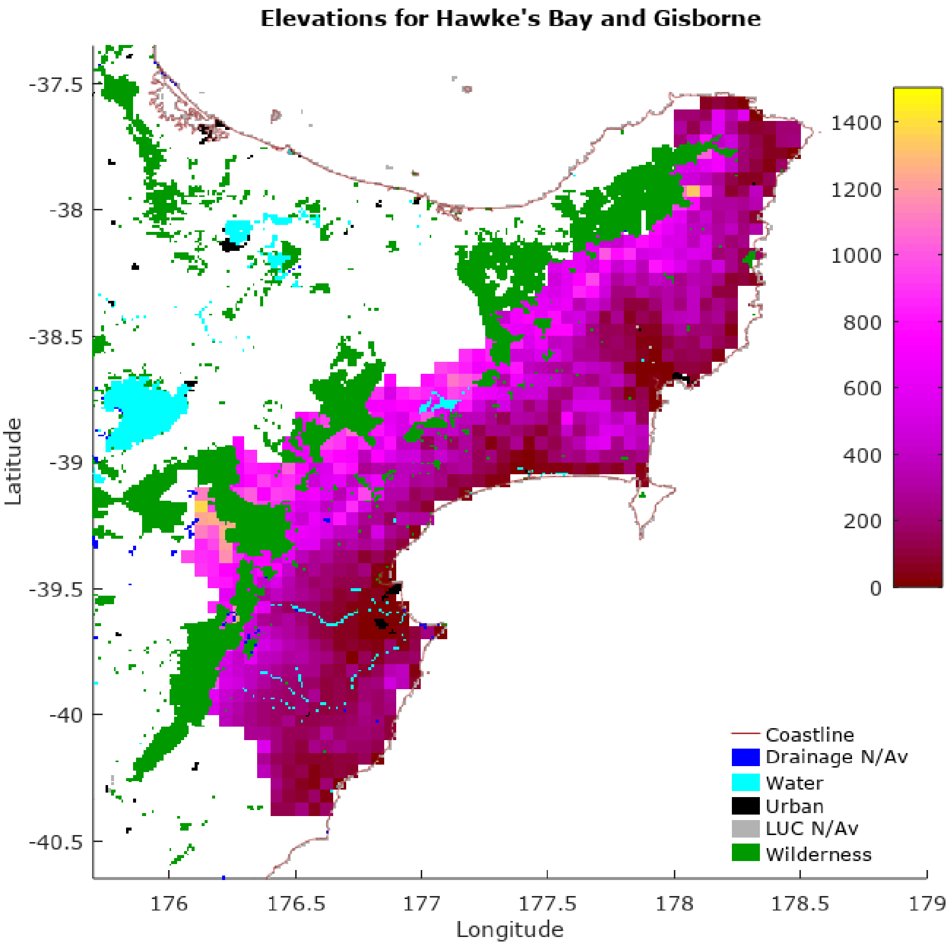

Figure 1. Elevations of locations across the Hawke's Bay and Gisborne Regions, using data provided in the Virtual Climate Station Network (VCSN) database.

2.1.2 Modelling phenological development

Parker & Abatzoglou (2017) described a mechanistic model approach in which key phenology stages (1%, 50% and 100% bloom, 1% and 100% hull split, and harvest maturity) were reached at specified thresholds of chill or warmth accumulations, and associated with different levels of cold hardiness, which was expressed as percent damage below specified threshold temperatures. We adapted this approach by introducing variance into the thresholds for chill and warmth accumulation. We additionally replaced the fixed cold damage thresholds with continuous sigmoidal damage responses as described by Vetharaniam et al. (2021), and this is elaborated on in the section on frost risk below.

Chilling, forcing and flowering

The most common chilling models used for fruit trees are the Utah (or Richardson) Chill Units Model (Richardson et al. 1974), the Dynamic Model (Fishman et al. 1987a, b; Erez et al. 1990) and the simple model of chilling hours between 0 and 7°C. The Utah model has been used in conjunction with growing degree hours (GDH) to predict the transition in almonds from endodormancy to ecodormancy and the time to reach full bloom (opening of 50% of flowers) in several studies (Egea et al. 2003;

Alonso et al. 2005; Alonso et al. 2010). The Dynamic model has also been used to model blooming time in almonds (Gaeta et al. 2018; Thomas & Hayman 2018; Díez-Palet et al. 2019; Thomas et al. 2019). There are contrasting views on which of these two models is better. (Luedeling 2012; Measham et al. 2017) and Covert (2011) found that none of chilling hours, the Utah model or the Dynamic model stood out as better for predicting flowering time.

We used the Utah (Richardson) model together with GDH accumulation, in a "chill-force" model of flowering. This model assumes that chilling is needed for a flower bud to transition from a state of endodormancy to a state of ecodormancy after which its progression to flowering is forced by heat accumulation. The Utah model uses temperature thresholds of 1.5, 2.5, 9.2, 12.5, 16 and 18°C and assigns chill units (CU) of respectively 0.5, 1, 0.5, 0 and -0.5 for each hour that temperature was in the intervals defined by the thresholds. No CU are assigned for temperatures below 1.5°C and -1 CU assigned for each hour above 18°C.

In the Utah model, GDH with respect to a base of 4.5°C are normally calculated by capping hourly temperature at 25°C and then subtracting 4.5 from each hourly temperature above 4.5°C, then summing across the day. However almonds prefer summer temperatures of 30 to 35°C (Ahmed & Verma 2009) and thus 25°C is likely too low for an upper accumulation temperature. Thus we followed Thomas et al. (2019) who used an upper accumulation temperature of 36°C when calculating GDH.

Reported chill and heat accumulation requirements for almonds to transition from endodormancy to full bloom (F50 or 50% of flowers having opened) varied between different studies and between cultivars. Egea et al. (2003) found that 10 cultivars ranged in their chilling and heat requirement from 270 to 1000 CU and 5940 to 7580 GDH respectively. Alonso et al. (2005) found that 44 cultivars had chill requirements ranging from 360 to 480 CU and heat requirement ranging from 5350 to 9350 GDH, while Alonso et al. (2010) found that nine cultivars had a similar range in chill requirement from 330 to 500 CU but a much larger range in heat requirement of 2870 to 10230 GDH.

In a study of three cultivars, Ramírez et al. (2010) found that CU requirements were 35–49% lower but GDH requirements 42– 71% higher than those found by Alonso et al. (2005) for the same cultivars. Similarly comparing results for cultivars common to the studies of Egea et al. (2003) and Alonso et al. (2005), differences in chill requirement were opposite to differences in heat requirement. This may reflect that increased chill could require decreased forcing, or that decreased chill could be compensated for by increased GDH.

To reflect the variability in reported chill requirements, the PFR model uses a function to express the proportion of chill requirement across cultivars that is obtained from a given value of accumulated CU, based on the mean and standard deviation of the published results discussed above. This would for example allow modelling the days by which the 5th, 50th and 95th percentiles of cultivars would have had their chill requirements met and the days by which the 5th, 50th and 95th percentiles of cultivars would have experienced full bloom. To reflect that decreased chill could be compensated by increased GDH accumulation and vice versa, we used a sigmoidal chill function that increased from 0 to 1 as accumulated CU increased, and the daily value of the chill function was used to eight daily GDH when calculating accumulated GDH.

We applied the assumption by Hayman & Thomas (2017) that for almonds in Australia, chill accumulation occurs only from late April, and calculated chill accumulation starting from the last week of April. Calculation of CU requires hourly temperature values, and in order to calculate CU from maximum and minimum temperature, it was assumed that temperature had a sinusoidal variation through the day. The hours spent below a temperature threshold T_{crit} is then given by:

$$\frac{24}{\pi}\left(1-\mathrm{real}\left(\mathrm{acos}\left(2\frac{T_{\mathrm{crit}}-T_{\mathrm{min}}}{T_{\mathrm{max}}-T_{\mathrm{min}}}-1\right)\right)\right). \quad (1)$$

To model the occurrence of the F1 and F100 stages (respectively 1% and 100% bloom) we followed Parker & Abatzoglou (2017) who worked in growing degree days (GDD) base 4.5°C and modelled these stages as occurring when heat accumulation was respectively 80% and 135% of the heat accumulation at F50 (50% bloom). We applied these factors to the probability means and standards for GDH calculated above, allowing us to predict for example the days by which the 5th, 50th and 95th percentiles of cultivars would have experienced the F1 and F100 stages.

Data for testing the models were sparse. We had access to 10 weekly observations recorded from 21 July to 29 September 2021 for two cultivars ('All-In-One' and 'Monovale') from a trial planting near Havelock North. These observations indicated whether budbreak had occurred, and stages of flowering including completion of flowering. We also had observations on flowering from an almond orchard near Waipukurau for the years 2016 and 2021. There were two observations for 2016 (made on 28 August and 10 September) that recorded which of eight cultivars had yet to bloom, had just started to bloom or were in full bloom. For the Waipukurau orchard in 2021, there was a record of when the earliest cultivar had its first flowers (24 July), and a suggestion that the latest variety may have finished flowering 5 weeks later in late August. The grower had some qualitative information on the differences in flowering time between the eight cultivars, but this was not sufficient for quantitative modelling.

The chill-force model was run using an initial parameterisation from the published CU and GDH requirements, and with weather data inputs from the VCSN database that corresponding to the locations of the two orchards providing data and for the growing seasons in which observations were made. This exercise revealed that initial parameterisation predicted a much earlier flowering than was observed. This is unsurprising since the published studies were from overseas trials in continental climates, and used different cultivars from those grown in New Zealand. An adjustment in parameterisation was required to delay model predictions for flowering stages and improve their alignment with observation. The 'All-In-One' and 'Monovale' flowering observations for Havelock North were used as indicators of very early and very late flowering cultivars.

The sigmoidal chill function used to weight daily GDH was specified give values of 0.05 0.5 and 0.95 for accumulations of respectively 28, 400 and 1200 CU. A sigmoidal function predicting the fraction of cultivars reaching the F1 stage was parameterised to give values of 0.05, 0.5 and 0.95 for accumulations of respectively 5000, 5350 and 5700 chill-weighted GDH. Similarly sigmoidal functions were parameterised to give values of 0.05, 0.5 and 0.95 at chill-weighted GDH accumulations of respectively 7488, 8000 and 8512 h°C for the F50 stage and respectively 10295, 11000 and 11705 h°C for the F100 stage.

The logistic curve was used to model sigmoidal curves, and takes the form below, where y is the suitability value, x is the criterion value, and parameter c determines the 0.5 value of x, and k determines the rate at which suitability changes with the criterion variable:

$$y=\frac{1}{1+\exp(k(x-c))}. \quad (2)$$

Ripening and maturity

Two important phenological stages before harvest maturity are the 1% and 100% hull split (HS1 and HS100) stages. Connell et al. (2010) published data on number of days between HS1 and HS100 for different cultivars, and Thomas et al. (2019) used this information to estimate GDD requirements to transition between these phenological stages. The observations of Connell et al. (2010) together with other published observations were similarly used by Parker & Abatzoglou (2017) to estimate GDD requirements from the start of ecodormancy to 1% HS, 100% HS and harvest, providing a continuation to their values for GDD requirements for different stages of bloom.

We had no data on hull split for either the Havelock North or Waipukurau orchards' harvests of 'All-In-One' and 'Monovale' with which to compare model predictions. Harvests of these cultivars were recorded for Havelock North at different times in March and May 2022 (corresponding to the flowering in 2021), but we could not model up to this time period since the VCSN database that we accessed provided information for dates only up to February 2022. However, for the Waipukurau orchard, the maturation of the earliest nuts on the earliest trees was recorded on 2 April 2017 although no further harvest data were available for that year. The grower considered that on average, harvest would occur around mid-April to the end of April. Based on these considerations and the GDH accumulations to these dates in 2017 for that orchard location, we parameterised a sigmoidal function specifying the fraction of cultivars whose crop would have matured to provide values of 0.05, 0.5 and 0.95 for GDH accumulations of respectively 61430, 63450 and 65470 h°C. Applying the ratios between the GDD requirements used by Parker & Abatzoglou (2017) for the HS1, HS100 and harvest stages to our GDH requirements, we then parameterised our hull split functions to give values of 0.05, 0.5 and 0.95 at respectively 42885 44900 46915 h°C for the fraction of cultivars reaching HS1 and at respectively 53385, 55400 and 57415 h°C for the fraction of cultivars reaching HS100.

Simulation of phenology

The New-Zealand-centric observations that were available were not sufficient to model separately early and late cultivars, and one simulation across the spread of cultivar development times was performed. With the new parameterisation for the phenology model, the simulation gave results that were approximately in line with the observations for the two orchards (Figure 2). The VCSN database contained information up to mid-February 2021 and thus while the entire 2016 growing season was simulation, the 2021 growing year was simulated only up to mid-February.

For the Havelock North orchard, the starts of stages F1, F50 and F100 line up with the observations for 'All-In-One' for those stages, and the ends of these stages line up with corresponding observations for 'Monovale' (Figure 2). This is expected since the model parameterisation was designed to achieve this. Similarly the model parameterisation was that for the Waipukurau orchard in 2016, the model predictions for when the earliest and latest cultivars become harvestable coincide with grower observations for the start and end of the harvest period (Figure 2).

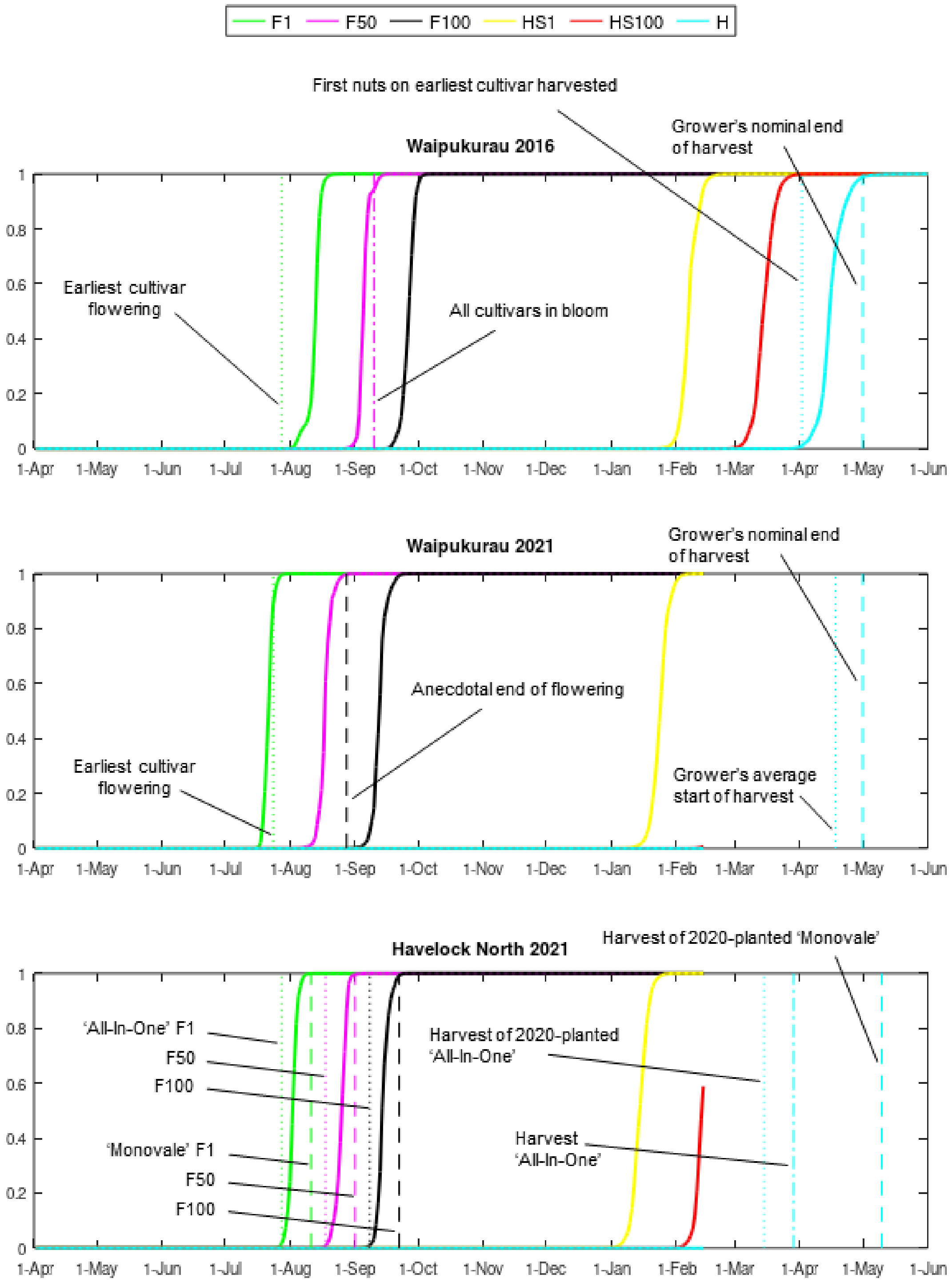

Figure 2. Model predictions of phenological stages of almonds for Waipukurau and Havelock North orchards. Solid curves show the fraction of cultivars predicted to have reached the 1%, 50% and 100% bloom stage (respectively F1, F50 and F100), the 1% and 100% hull split stage (respectively HS1 and HS100) and harvestable stage (H). Vertical lines indicate grower observations. Simulations used the Virtual Climate Station Network (VCSN data) and were run only to mid-February 2022 because weather data were not available after that time.

For the Waipukurau orchard, the model prediction for the start of the F1 period in 2016 occurred a few days before the earliest flowering observation, while for 2021 the model predicted that most cultivars would have reached F1 by the time the first flowers of the earliest cultivar were observed (Figure 2). Possible reasons for this discrepancy include that the parameterisation of the model lacks robustness due to insufficiency of data, or that the orchard is in a microclimate not represented by the VCSN weather data for that grid. No observations were made for the 2016 F100 stage for the Waipukurau orchard. While the end of flowering observation for 2021 occurred earlier than predicted (Figure 2), that observation was anecdotal and corresponds to a far more compact flowering period that occurred in 2016. Thus it is difficult to gauge the degree of model discrepancy from this F100 comparison.

There were no observations from the Waipukurau or Havelock North orchards to compare with the model predictions for the HS1 and HS100 stages. However in Australian observations, HS1 was found to occur from the very end of December to very early February and HS100 from the last week of January to the mid-March (Thomas & Hayman 2018). The model predictions do not significantly depart from this, and suggest that HS1 and HS100 would occur slightly later for the New Zealand orchards (Figure 2).

The model was parameterised to predict that for 2016, the earliest almonds would reach harvest maturity on the day that the Waipukurau grower first harvested nuts, and to predict that for 2016 all almonds would have reached harvest maturity on the nominal last day of harvest. We note however that the day of harvest does not necessarily coincide with the days almonds reach maturity. The harvest of 'All-In-One' at Havelock North at the end of March 2021 is earlier than predicted for Waipukurau, and this is consistent with prediction of hull split occurring earlier at Havelock North (Figure 2). The earlier harvest of 'All-In-One' from trees planted in 2020 and the very late harvest of 'Monovale' from trees also planted in 2020 (Figure 2) can be regarded as atypical since the phenology of young trees can be quite different from mature trees, according to the grower.

The phenology model was run for all locations across Hawke's Bay and Gisborne for the growing years 2001–2002 through to 2020–2021, using weather data from the VCSN database.

2.1.3 Suitability modelling

Chill-force suitability score

The cut-off by which flowering should have been completed was 30 September. For each location, the fraction of cultivars having completed flowering on any day during a growing year is given by the F100 value for that day and location. Thus we used the F100 value for 30 September as a "chill-force" suitability score to indicate how well almond requirements for flowering were met by the combination of chilling and warmth at each GIS location in the VCSN database.

Pollination suitability score

Honey bee colonies tend to have small populations during the late winter/early spring period that almonds flower, and this can make pollination challenging, as can inclement weather (Danka et al. 2006). Almond nectar secretion rate is likely to be a primary driver for foraging activity, and honey bees evaluate the profitability of nectar rewards against environmental conditions (Alqarni 2015). In very cold winters, almond nectar secretion may be too low to be attractive to honey bees (Farkas & Zajácz 2007). Honey bees will forage for water at temperatures as low as 5°C (Kovac et al. 2010) and for a range of resources at temperatures up to as high as 43°C, (Abou-Shaara et al. 2017) .

Covert (2011) considered that for good pollination of almonds, wind speeds should be under 24 km/h and temperatures between 15 and 38°C, with an absence of both rain and cloudy weather. However, Szabo (1980) found that RH and wind speed had little effect on flight activity of honey bees and that ambient temperature and solar radiation were the most important factors. Similarly, Clarke & Robert (2018) found that variation in temperature and solar radiation together explained 78% of egress rate of honey bees from their hives.

Although high temperatures can reduce the effective pollination period of almonds by reducing stigma receptivity, this is countered by a longer effective pollination period in almonds compared with other fruit trees (Ortega et al. 2004), and high temperatures are unlikely to be a concern when almonds flower in New Zealand.

Flight activity in *Apis mellifera* was found to increase 10-fold when temperatures increased from 10°C to 12°C. Based on a four-hour foraging window (10 am to 2 pm) for almond (Danka et al. 2006), we calculated the proportion of time that temperature in this period was above 12°C for each day.

The pollination suitability score was then calculated as the weighted mean of this proportion, where the weight used was the probability that the almonds were in flower. This probability was calculated as the proportion of cultivars having reached the 1% bloom stage minus the proportion having reached the 100% bloom stage.

Frost suitability score

Thomas et al. (2019) considered frost risk to almonds in terms of the number of nights colder than 2°C, these being considered prone to frost. The PFR model uses a different approach to frost risk and calculates expected damage as a function of minimum temperature, following the approach described by Vetharaniam et al. (2021). This requires knowledge of damage versus temperature at different phenological stages.

Connell & Snyder (1996) found that the small nut stage was the most vulnerable to frost damage, with a 100% damage rate at -3.3°C but negligible damage at -1.1°C, with a lethal cold temperature (LCT) for 50% kill between -2.2 and -2.8°C. The full bloom stage was the second most vulnerable to frost with reported damage rates ranging from 1 to 5% at -2.2°C, from 70 to 100% at -3.3°C and from 80 to 100% at -3.9°C (Connell & Snyder 1996). This contrasts with a 20% damage rate at -3.9°C and 75% damage rate at -5.6 °C given by Parker & Abatzoglou (2017). For the pink bud stage, reported damage rates averaged 52% at -3.9°C (20 to 70% damage). Based on a sparse amount of data from two cultivars, the green bud stage appeared much hardier with average losses of 5, 5 and 7.5% at temperatures of -3.9, -5.6 and -6.7°C (Connell & Snyder 1996). Dormant shoots are hardier still, with an LCT for 50% kill in the range -18.0 to -24.5 °C.

We assumed temperatures would rarely be cold enough to cause significant damage to the green bud stage or earlier, and used the frost susceptibility values for the full bloom stage as an approximate average of susceptibilities across the pink, full bloom and nut stage. We constructed a sigmoidal frost-damage function with damage rates of 5%, 50% and 95% at temperatures of -2.2, -3.0 and -3.8°C (Figure 3), to simulate the susceptibility of almonds to frost from the pink bud stage onwards.

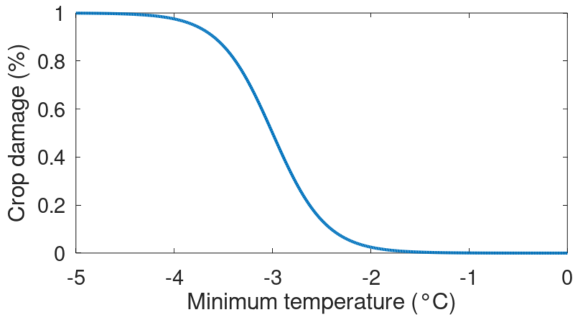

Figure 3. Curve used to model crop damage as function of minimum temperature.

We did not model the occurrence of the pink bud stage, and so used the F1 curve as an indicator or a switch from low frost susceptibility to high frost susceptibility. The harvestable stage curve was used as an indicator of when there was no longer a frost risk. Daily expected losses were calculated from the frost-damage function using minimum daily temperature as an input, and were then weighted by the daily difference between the F1 curve and the harvest stage curve. Weighted losses were accumulated over the growing season and the portion of crop surviving was expressed as a fraction to give the frost suitability score.

Sufficiently warm growing season

A nominal cut-off date of 30 April was taken for nuts to ripen to maturity and be harvestable. For each location, the fraction of cultivars having reached the harvestable stage is given by the harvest maturity curve value for that day and location. Thus we used the value for the harvest maturity curve on 30 April as a GDH suitability.

Rain damage to nuts

Almond growers in Australia identified rain at harvest as their primary concern (Thomas et al. 2019). Under wet conditions *Salmonella* can migrate from soil through the hull and shell of shaken almonds lying on the ground to the almond kernel (Danyluk et al. 2008) and the risk of high concentrations of this pathogen is increased (Uesugi & Harris 2006). Harvesting onto a cover would reduce this risk. *Aspergillus* infection can occur during hull split, especially if there is high humidity (or insect injury) and has the potential to contaminate almonds by producing aflatoxins (Picot et al. 2017). Rain at harvest can also prevent harvesting operations, impose additional costs to dry wet fruit, or cause loss in the harvest year by causing hull rot or, in subsequent years, by causing the death of spurs (Thomas et al. 2019). We found no information that quantified crop damage as a function of rainfall. Therefore we constructed a harvest-rain suitability score function relative to 50mm of rain falling in the period between hull split and harvestable stage, to which we assigned a suitability value of 0.5. A weighted risk window for rain damage to fruit was calculated for each location as the proportion of cultivars having reached the 100% split hull stage subtracted from the proportion having reached the harvest stage. For each grid location, daily rainfall data were multiplied by the daily risk window weightings and summed to obtain a "risk-weighted rainfall" value for each year. We assigned a harvest-rain suitability curve having values of 0.95, 0.5 and 0.05 for 25, 50 and 75 mm of risk-weighted rainfall.

Disease risk

There is a large variation between different plant pathogens in their optimal environments, and their requirements factors such as temperature and moisture (DeLucia et al. 2012; Juroszek & von Tiedemann 2015). Thomas et al. (2019) indicated that almond pathogens are favoured by high moisture conditions (e.g. rainfall or high RH). Certainly the majority of plant pathogens are favoured by high-moisture conditions (Velásquez et al. 2018). Different pathogens have different optimal growing temperatures and thus there will be a microbial threat across a band of temperatures (see Vetharaniam et al. 2021). Those authors calculated a generic disease suitability score as a function of both temperature and RH, and assumed pathogens risk would be a threat only within a temperature band. However for this project we have not considered temperature as a limiting factor to disease, and modelled disease risk in terms moisture alone. Some studies have found that RH was a more reliable indicator of disease risk than rainfall (Creasy 1980), and RH has been used as an predictor in some models of disease threat (e.g. Wilks & Shen 1991; Beresford et al. 2016). Thus we used a sigmoidal suitability score for disease risk that was a function of RH alone, taking values of 0.05, 0.5 and 0.95 at RH values of respectively 77, 85 and 93%.

The risk of root disease resulting from waterlogging is reflected in suitability considerations around soil drainage.

Annual rainfall deficit

Although almonds are considered among the more drought tolerant of perennial tree crops, there is a variation between cultivars in the sensitivity of yield to water deficit stress (Ghrab et al. 2002; Gutiérrez-Gordillo et al. 2020). Estimated evapotranspiration (ET) for almond orchards was 1100–1350 mm for California (Goldhamer & Fereres 2017) and 1450 mm for the south-east of Australia (Stevens et al. 2012). Tree density and the nature and density of ground vegetation will have an impact on crop ET.

In regions averaging 118 mm of rain per year, almond yield was maximised (3900 kg/ha) when 1250 mm of water was applied, while yields of 3250 kg/ha were obtained for 1000 mm of applied water. By contrast, in the Waipukurau orchard with no irrigation, very low inputs and an average annual rainfall of about 750 mm, yields obtained were much lower; we estimated yield was in the order of 500 kg/ha based on discussions with the grower on nuts harvested per tree. Differences in yield can be affected by differences in cultivars, management practices and intensity of fertiliser use, as well as by rainfall deficits.

Based on published ET values above, we worked with an average annual ET for almonds of 1300 mm, and based on the yield to water response found by Goldhamer & Fereres (2017), we constructed a sigmoidal annual rainfall suitability score function that gave suitability values of 0.18, 0.83 and 1.0 for annual rainfalls of respectively 750, 1000 and 1300 mm.

Potential rooting depth

The depth of soil to an impermeable layer, referred to as the potential rooting depth (PRD), is an important criterion identified by Hall et al. (2018), since this determines the ability of the tree to develop a strong vigorous root structure, and trees in deeper soil can have more tolerance of drought than trees in shallow soil.

The depth of almond roots can be affected by irrigation and the type of irrigation (Ben-Asher et al. 1994). Romero et al. (2004) found that subsurface irrigation stimulated deeper root development (40–80 cm) compared with surface irrigation (0–40 cm), and that that root density below 80 cm was almost nil, with 75% of fine roots in the upper 70 cm of soil, although in that trial the soil properties below 80 cm may have presented a barrier to deeper root penetration. Young, trickle-irrigated almond rootstocks had root depths down to one metre, but the majority of roots occurred in the top 60 cm of soil (Franco & Abrisqueta 1997). Ben-Asher et al. (1994) found that almond roots may exceed 1.5 to 2 m in depth, even with trickle irrigation.

For constructing a suitability score, we noted that Long & Kaiser (2013) considered that soil depths of 3 to 5 feet (0.9 to 1.5 m) are required for semi-dwarfing root stocks of cherry, and thus almonds will likely require at least a similar root depth. Thus we assigned a suitability curve with values of 0.05, 0.5, 0.95 and 1 for potential rooting depths of 0.2, 0.5, 0.95 and 1.5 m.

Slope

For many crops, considerations of slope of the land from the viewpoints of erosion risk or suitability for machinery give 30° as generally being an upper limit (Rowland et al. 2016). However, since harvesting almonds involves shaking fruit from the tree and gathering from the ground, a flat surface would pose significant advantages. However, almond orchards have been established on steeply sloping land, though tree vigour decreased with increased slope (García et al. 2010). We assigned a continuous sigmoidal suitability function that had a value of 1.0, 0.97, 0.5 and 0.0 for slopes of respectively 0, 5, 10 and 20°.

Drainage

Many almonds and almond × peach hybrids used for rootstocks have a low tolerance to asphyxia caused by waterlogging (Felipe 2009). In New Zealand, 'Golden Queen' peach is often used as a rootstock, and also prefers well-drained conditions. Moist soil conditions can increase susceptibility to a number of diseases such as crown gall (*Agrobacterium tumefaciens*), oak root fungus (*Armillaria mellea*) and attacks by a number of *Phytophthora* species (Gradziel 2009).

Drainage information for individual locations was available in terms of classifications that took into account a number of factors, including soil structure, depth, and permeability, and water table depth. These classifications had the following qualitative descriptors: well, moderately, imperfectly, poorly and very poorly drained. Reflecting the requirement that good drainage is essential for almonds, we assigned suitability scores of respectively 1.0, 0.9, 0.3 0.1 and 0 to these drainage categories.

Land use capability class

Land Use Capability (LUC) class descriptors are divided into eight main categories (numbered 1 to 8), with 1 indicating land classes with virtually no limitations for arable use and 8 indicating land classes with very severe limitations or hazards that make it unsuitable for agriculture or forestry. Following Vetharaniam et al. (2021) we used LUC class as a suitability criterion, despite some overlap between LUC class descriptors and other land information such as slope, PRD and drainage, since LUC class also contains extra information on soil. We assigned suitability scores to LUC classes to develop a graduated scale, with Classes 1 to 8 assigned scores of 1, 0.95, 0.9, 0.8, 0.65, 0.5, 0.05 and 0.

Calculation procedures for suitability scores

Climate related suitability scores for calculated for each growing year for the growing years 2001–2002 through to 2020–2021, using data from the VCNS database. A representative score for each climate-related criterion was obtained taking the arithmetic mean of yearly scores calculated for the 20-year period.

Overall climate suitability

Scores for individual climate criteria were combined for each year by taking their weighted geometric means provide an overall climate suitability score for that year. A higher weight reflects a higher significance placed on that factor. We chose weights of 2.0 for the chill-force, GDH, frost and pollination suitability scores, and a weight of 1.0 for harvest rain suitability and a weight of 0.5 for the disease suitability score. The early climate suitability scores were averaged over a period of years using arithmetic means to provide a climate suitability score for the period.

The annual rainfall suitability score was kept separate from the overall climate suitability since this was developed from the perspective of maximising yield, whereas a grower may prefer a low input system with lower yields as part of a niche industry.

Overall cultivation suitability

Climate suitability and soil criteria suitability were combined by weighted geometric averaging to give an overall cultivation suitability map. The weightings used were, respectively, the sum of the climate criteria weights and the soil criteria weights.

2.1.4 Projecting suitability changes in future climates

The SLM RCP datasets were used to project suitability scores for two two-decade periods: 2031 to 2050 and 2051 to 2070. Although the projection data extend to 2100, uncertainty increases with increased projection date, and the projection period that we have used will easily encompass the productive lifetime of an almond orchard.

For each of the RCP datasets (6.0 and 8.5) that we used in the climate projection dataset, the suitability models were run separately for the corresponding six SLM RCP datasets (corresponding to forcing by six GCMs). This gave six alternative values for each suitability criterion score at each GIS location, for each RCP. The six alternatives scores were averaged and standard deviation calculated for each suitability score, separately for each RCP. This procedure was carried out for each of the two future periods.

SLM RCP data for the period 1971–2005 are considered to be historical simulations and are referred to as 'SLM RCP Past', and for each CMIP5 model, all RCP datasets share the same RCP Past dataset. To provide a reference from which to gauge projected change, the suitability models were run separately for the six SLM RCP Past datasets, for the period 1981 to 2000. Means were calculated from the six suitability calculations for use as a reference.

2.2 Life cycle analysis

From a New Zealand context, LCA methodology has been used to evaluate a number of land use systems. Barber et al. (2011) found that potential carbon emissions associated with a selection of crops from New Zealand's arable sector, specifically wheat, maize silage, maize grain, ryegrass seed, were 340, 125, 190 and 1325 kg CO_2-eq/tonne, respectively. Results from the assessment showed that emissions associated with the manufacture and application of synthetic fertilisers were the biggest contributors to the overall potential emissions. Milà i Canals et al. (2006) found that the environmental impacts associated with commercial apple production in Hawke's Bay and Central Otago ranged from 40 to almost 100 kg CO_2-eq/tonne of grade 1 and 2 apples. The majority of the associated emissions where due to mechanisation, activities such as spraying, irrigation, frost protection and harvesting, and also to the application of fertilisers. Overall emissions where found to be higher for apple production in central Otago than that of Hawke's Bay due to the greater energy demand associated with frost protection and fertiliser use.

Basset-Mens et al. (2005), found that emissions associated with dairy production in New Zealand were 50–80% lower than that in Europe, with an estimated 718 g CO_2-eq/kg milk produced in New Zealand. Emissions of methane, from on farm pasture digestion, and production of feed, accounted for 46 and 40% of the total emissions respectively. The authors noted that the lower results of New Zealand's dairy production compared to that of Europe was likely due to New Zealand's high-producing perennial pastures and all-year grazing, compared with the supplementary feeding systems of Europe. Ledgard et al. (2016) found that emissions associated with dairy production in the Waikato increased with stocking rate intensification. However, the total emissions between the low-, medium-, and high-intensity systems were not too dissimilar, ranging from 0.75–0.8 kg CO_2-eq/kg of fat and protein corrected milk for the low-, medium-, and high-intensity systems. In a study comparing beef production in New Zealand and Uruguay, López et al. (2013) found that New Zealand beef production had a potential carbon footprint of 8–10 kg CO_2-eq/kg of live weight compared to 18–21 kg CO_2-eq/kg of live weight in Uruguay. However, on a per hectare basis, New Zealand's potential footprint was much higher than Uruguay, these being 3013–6683 kg CO2eq/ha/year and 1895–2226 kg CO2eq/ha/year, respectively. The greater amount of emissions was attributed to the more intense stocking rates found here in New Zealand.

In a recent review of the potential carbon footprint of commercial kiwifruit production, McLaren et al. (2021) found that the carbon footprint of kiwifruit delivered to a retailer in Germany was 1.24 kg CO_2-eq/kg. This was found to be a 24% decrease compared to those results of Mithraratne et al. (2010) who attributed 1.64 kg CO_2-eq/kg of kiwifruit delivered to a retailer in Germany. Shipping and pack house operations were found to be the greatest contributors to the overall emissions, while at the orchard phase of kiwifruit production, the majority of the total emissions were found to be attributed to the production and application of lime and fertilisers, and energy consumption from diesel and electricity.

While LCAs have not been undertaken for almonds within New Zealand, previous LCA studies of almond production, specifically in the USA, have indicated potential carbon emissions in the range of 1.76 kg CO_2-eq/kg, 1.6 kg CO_2-eq/kg, 1.92 kg CO_2-eq/kg (Marvinney et al. 2014; Kendall et al. 2015; Volpe et al. 2015). Nutrient management and energy consumption related to irrigation were highlighted as the main hotspots and greatest contributors to the overall total emissions within the production system.

2.2.1 Goal and scope

The main objective of this study was to evaluate the potential environmental impact associated with growing almonds in the Hawke's Bay, focusing on the potential carbon footprint. To assess the potential footprint, we conducted a partial LCA compliant with the framework defined by the International Organization for Standardisation (ISO 2006a, 2006b). GaBi Professional software (https://www.thinkstep-anz.com/) and its associated databases where utilised to assist with the modelling of the almond production system.

In the wider context, this research set out to investigate the feasibility for the establishment of a New Zealand almond industry and to assess the potential hotspots (i.e. areas with the greatest contribution to the overall impact) within the almond production system using internationally recognised methodology. The intended use of the LCA results is to help inform future decisions on management strategies to improve environmental performance and strive towards a premium product.

Under the LCA framework, the system boundary defines the processes, inputs, and outputs of the production system. Here, this was considered to be from the cradle to the farm gate. This included, where data were available, processes relating to the extraction of raw materials, production and transport of goods from overseas (i.e. fertilisers, pesticides), through to the cultivation and harvest of the final product. The final product in this context also defines our functional unit, which was chosen to be 1kg of shelled and hulled raw almond kernel.

Lack of New Zealand specific data relating to almond production meant we did not have sufficient information to conduct a satisfactory LCA. Hence, due to the hypothetical nature of the study, information used for modelling purposes relied solely on data obtained from literature and personal communications. The LCA model was designed to represent a "typical" orchard with conventional practices. To compare the effects of management practices and inputs into the orchard system, a sensitivity analysis was performed on areas within the production chain that were identified as potential hotspots. Further details of the orchard system are given below.

2.2.2 Model Design

The LCA model of the conventional system has been designed to represent a typical almond orchard according information obtained from literature. Much of the data used were specific to the production of almonds but in some instances the data have been adapted or modified, where appropriate, to provide the best estimate or approximation. Where information or data required to model a particular process were not available, the software package GaBi Professional and its associated databases have been used. The following key assumptions have been made regarding the design of the almond orchard:

- The model represents the inputs and potential environmental impact over a typical growing season.
- The orchard is a mature orchard (7+ years) so is expected to be in full production.
- Machinery, i.e. harvesters, mowers, sprayers etc., are considered to be an asset already present at the orchard.
- Irrigation is required to maximise productivity and is assumed to already be established.
- Pesticides and synthetic fertilisers are used as standard management practice, some of which are derived from overseas.
- Total yield is based on 2.5 t/ha of raw almond kernel.

2.2.3 Life Cycle Inventory (LCI)

Life cycle inventory (LCI) is the collection and sum of all the inputs, outputs and associated flows of a product system Inputs to the orchard system and sub system. Model inputs and data sources are summarised in Appendix 1, pages 59–60.

2.2.4 Pesticide Production and Transport:

Herbicides, fungicides, and insecticides are typically used for growing almonds under conventional settings (Gradziel 2017). Specific LCI data were not available for the production and formulation for the majority of pesticides considered in this study and were therefore modelled using a generic database from GaBi Professional as a proxy. Due to the lack of supply chain information, it was assumed that these pesticides where produced in the EU (Germany) and imported through Australia to New Zealand, following Müller et al. (2011). GaBi Professional databases where used for train, truck, and shipping for transport inputs. However, emissions associated with the production, formulation and transport of glyphosate to New Zealand have been calculated (Müller et al. 2011) and have been included in the model.

2.2.5 Fertiliser production and transport

The production of each fertiliser was modelled using databases from GaBi Professional. For transport of the final product, it was assumed that the urea fertiliser was made in Kapanui, Taranaki, New Zealand and then transported to Napier via truck. For the production and shipment of potassium chloride (KCL), it was assumed that the product was shipped directly from Hamburg, Germany, to Napier, New Zealand. Databases for transport (i.e. trucks, trains, ships) were modelled as described above for pesticides.

2.2.6 Orchard management

Orchard management includes inputs and activities that occur during the growing season and at harvest. This includes, for example, the application of pesticides and fertilisers, operation of machinery and application of irrigation. No data were found regarding the use of diesel for specific machinery tasks but was given as a total input. Therefore, it was assumed that this total amount included all operations relating to machinery throughout the growing season and during harvest. Databases for diesel and gas production where used from GaBi Professional. Similarly no specific data were available regarding the energy requirements and operation of irrigation systems. This was also modelled using a database available in GaBi Professional.

2.2.7 Estimation of field emissions relating to fertiliser use

Nitrous oxide emissions from soil are associated with both direct and indirect sources, including volatilisation and leaching of synthetic fertiliser through the soil profile. Total emissions associated with the use of synthetic fertiliser applications were calculated according to IPCC guidelines (IPCC 2006) and following Barber et al. (2011). The IPCC approach assumes that a proportion ($Frac_{LEACH}$) of anthropogenic N applied as synthetic fertiliser (N_{FERT}) to soils is leached or runs off (N_{LEACH}). The IPCC default value of $Frac_{LEACH}$ is 0.3, and New Zealand's country-specific $Frac_{LEACH}$ value is 0.07 (Ministry for the Environment 2017a). We use the IPCC default value $Frac_{LEACH}$ of 0.3 in the main analysis of the total emissions from fertilisers. Emissions associated with the use and combustion of diesel and gas during orchard activities where calculated using the emission factors provided by the Ministry for the Environment (Ministry for the Environment 2017b).

2.2.8 Components excluded from the system boundary

All processes beyond the farm gate were excluded in this LCA. For example, the transport of the harvested goods to processing facilities as well as all processing of the crops, such as drying, were not considered. Farm capital including machinery, trucks, tractors, sheds, and equipment such as irrigation infrastructure were already considered to be an asset within the orchard.

It was assumed that ground cover and crop residue was kept to a minimum through regular mowing and herbicide applications. Therefore potential emissions associated with crop residues have been excluded. Similarly, the effects of carbon sequestration associated with soils have also been excluded within the LCA model. In general, soils can act as a source and a sink of greenhouse gasses (Oertel et al. 2016), and it was assumed that the carbon content would remain relatively stable over the time frame considered for the LCA.

3 Results

3.1 Suitability score modelling for Hawke's Bay and Gisborne

3.1.1 Chill-force suitability score

The model calculates that large areas of Hawke's Bay and Gisborne away from mountain areas currently have very high levels of chill-force suitability, and there should be no issue with regard to flowering of all cultivars in these locations (Figure 4). In particular, in Hawke's Bay chill-force suitability was very high from north of the Heretaunga Plains through to the Takapau Plains, and in some coastal regions. In Gisborne, suitability was very high in the Poverty Bay area as well as further north through to East Cape.

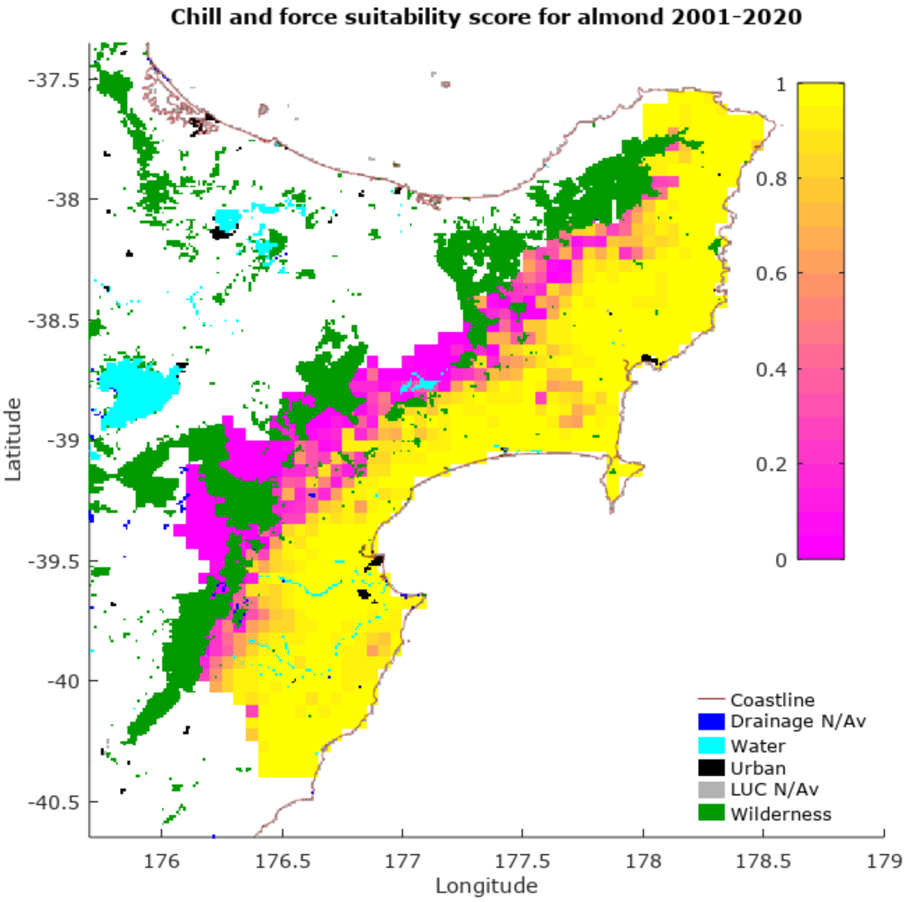

Figure 4. Adequacy of winter chill to progress flower buds to ecodormancy and subsequent warmth to force flowering, expressed as a suitability score from 0 to 1 and mapped for locations across the Hawke's Bay and Gisborne regions, for growing years 2001 to 2020. Suitability scores were calculated using Virtual Climate Station Network (VCSN) data.

3.1.2 Pollination suitability score

Pollination suitability was found to be generally low in many mountainous locations, and moderate in most other locations, with for example scores in the Poverty Bay area being in the order of about 0.7 and scores in the Heretaunga Plains being about 0.6 or less (Figure 5). The highest scores were for some locations around East Cape. This result suggests that in many locations of Hawke's Bay and Gisborne, the winter climate during almond flowering periods would allow pollination to occur but would not be sufficiently warm for very high honey bee activity on almond flowers. This may result in an incomplete pollination of flowers and a reduced yield in many locations. However, microclimates that are not captured by the VCSN data may provide more clement pollination weather.

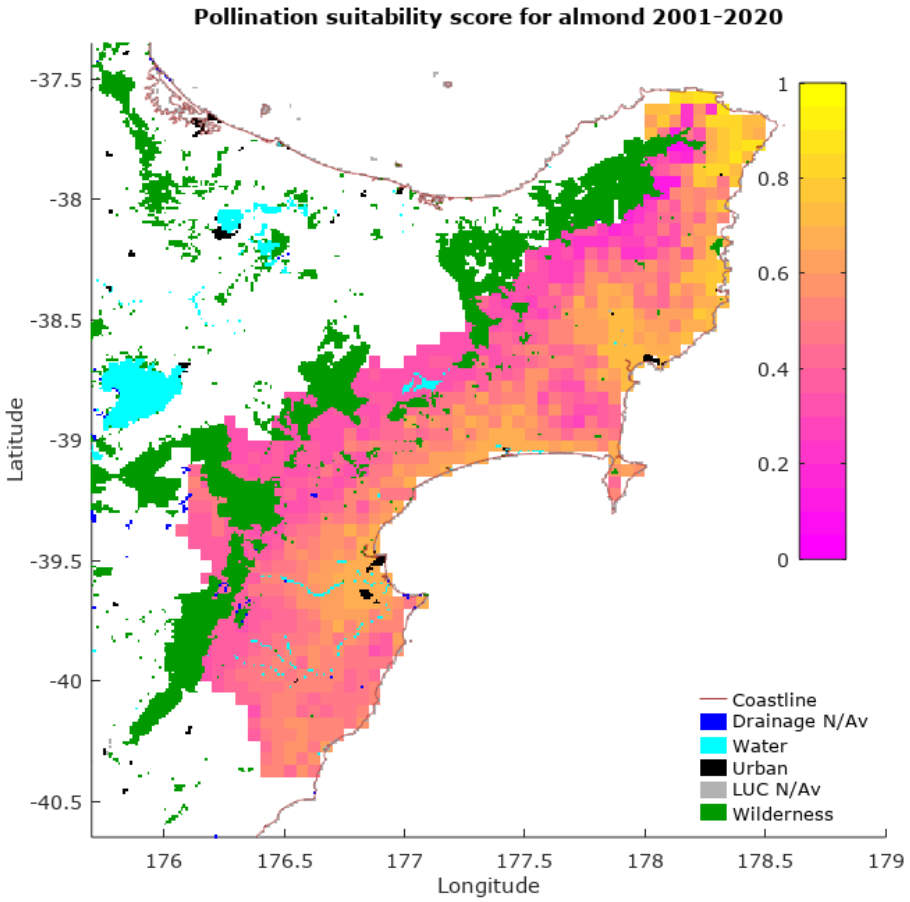

Figure 5. Adequacy of temperatures during flowering for the pollination of almonds by honey bees, expressed as a suitability score from 0 to 1 and mapped for locations across the Hawke's Bay and Gisborne regions, for growing years 2001 to 2020. Suitability scores were calculated using Virtual Climate Station Network (VCSN) data.

3.1.3 Frost suitability score

Frost was found not to be a significant threat areas for locations from Tangoio through to East Cape excluding mountainous locations to the west (Figure 6). The Heretaunga Plains around Napier were also found to have high frost suitability, with the risk of frost damage increasing further inland, northward up to Tangoio and south of Hastings (Figure 6). Frost protection methods such as with irrigation may be beneficial in the latter areas.

The locations with better frost suitability have a degree of correlation with locations with better pollination suitability scores (comparing Figure 6 with Figure 5).

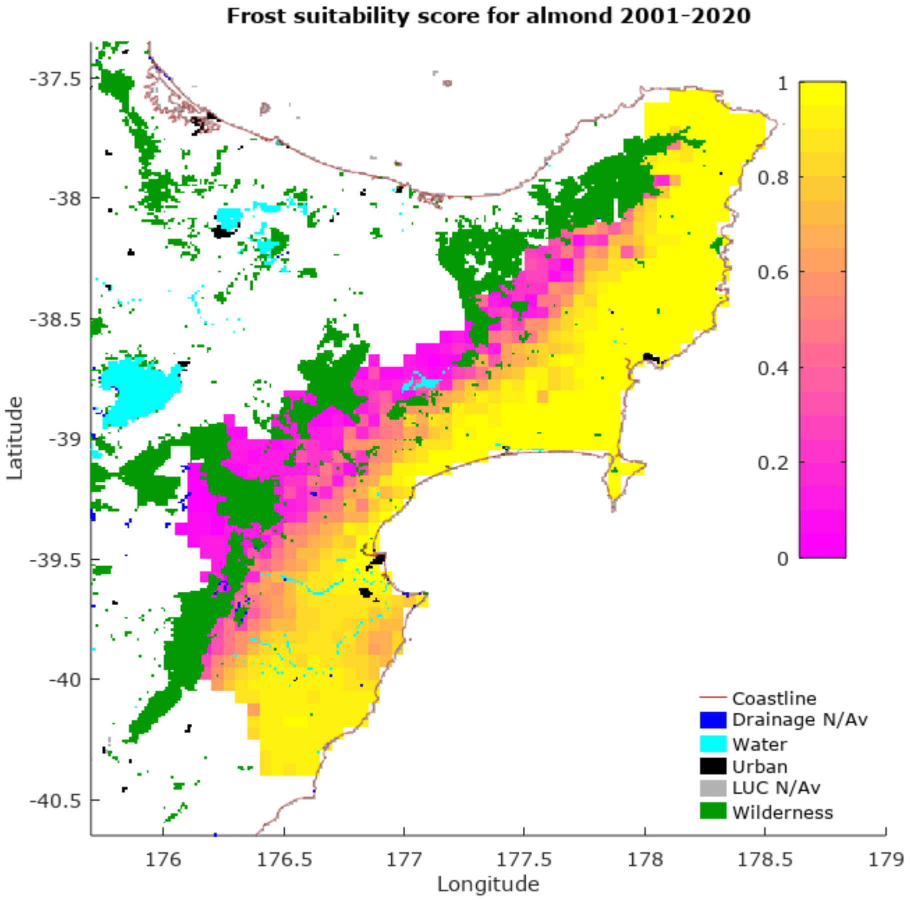

Figure 6. Risk of crop damage from frost expressed as a suitability score from 0 to 1 and mapped for locations across the Hawke's Bay and Gisborne regions, for growing years 2001 to 2020. Suitability scores were calculated using Virtual Climate Station Network (VCSN) data.

3.1.4 Sufficiently warm growing season

For most locations apart from those in mountainous areas, GDH suitability was found to be very high (Figure 6). A high GDH suitability score requires high enough accumulation of GDH to ensure that all cultivars have reached harvest maturity by the end of April. Since GDH accumulation within the model first requires that adequate winter chill has been achieved, some locations that are too warm to provide adequate winter chill may receive a low GDH suitability score, despite being warm locations.

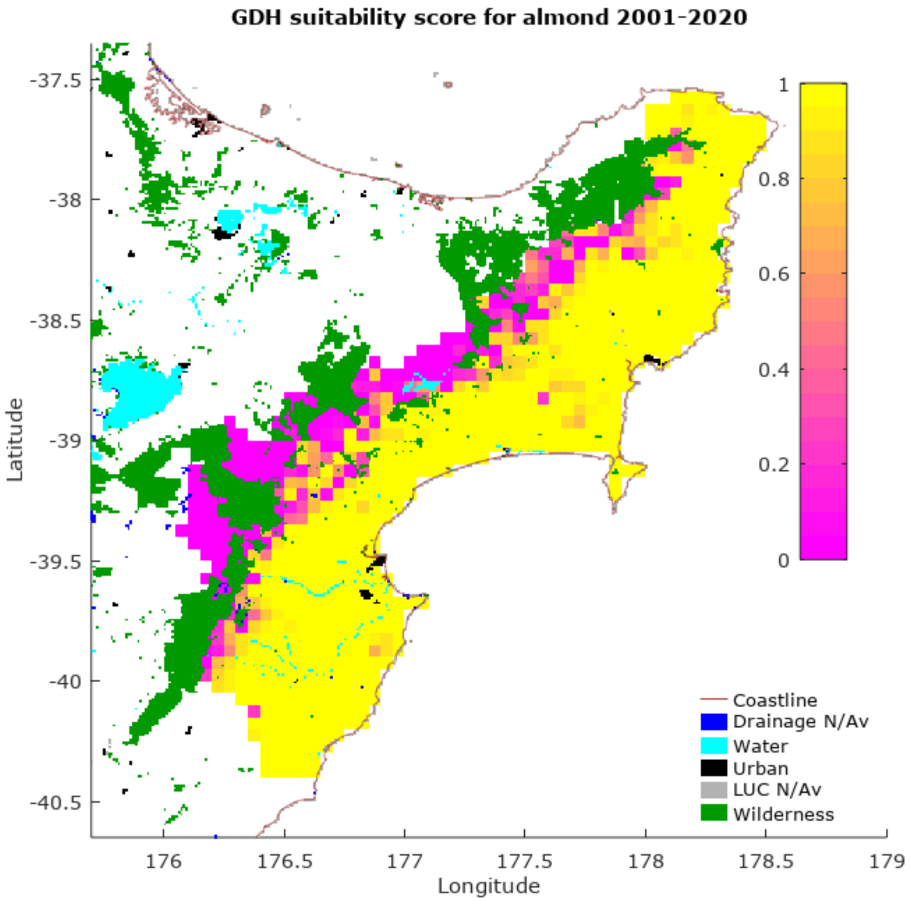

Figure 7. Adequacy of growing-season warmth, calculated as a growing degree hour (GDH) suitability score from 0 to 1 and mapped for locations across the Hawke's Bay and Gisborne regions, for growing years 2001 to 2020. Suitability scores were calculated using Virtual Climate Station Network (VCSN) data.

3.1.5 Disease risk

All locations modelled were found to have a degree of general disease risk from pathogens favoured by moist conditions occurring throughout the year. This excludes the specific risks caused by rain at harvest time, which has its own score. General disease risk scores varying from about 0.5 to about 0.8, with suitability tending to be lower in more mountainous areas (Figure 8). Since this suitability score is generic and does not address specific pathogens, it can be interpreted as illustrative of variation in potential risk between locations.

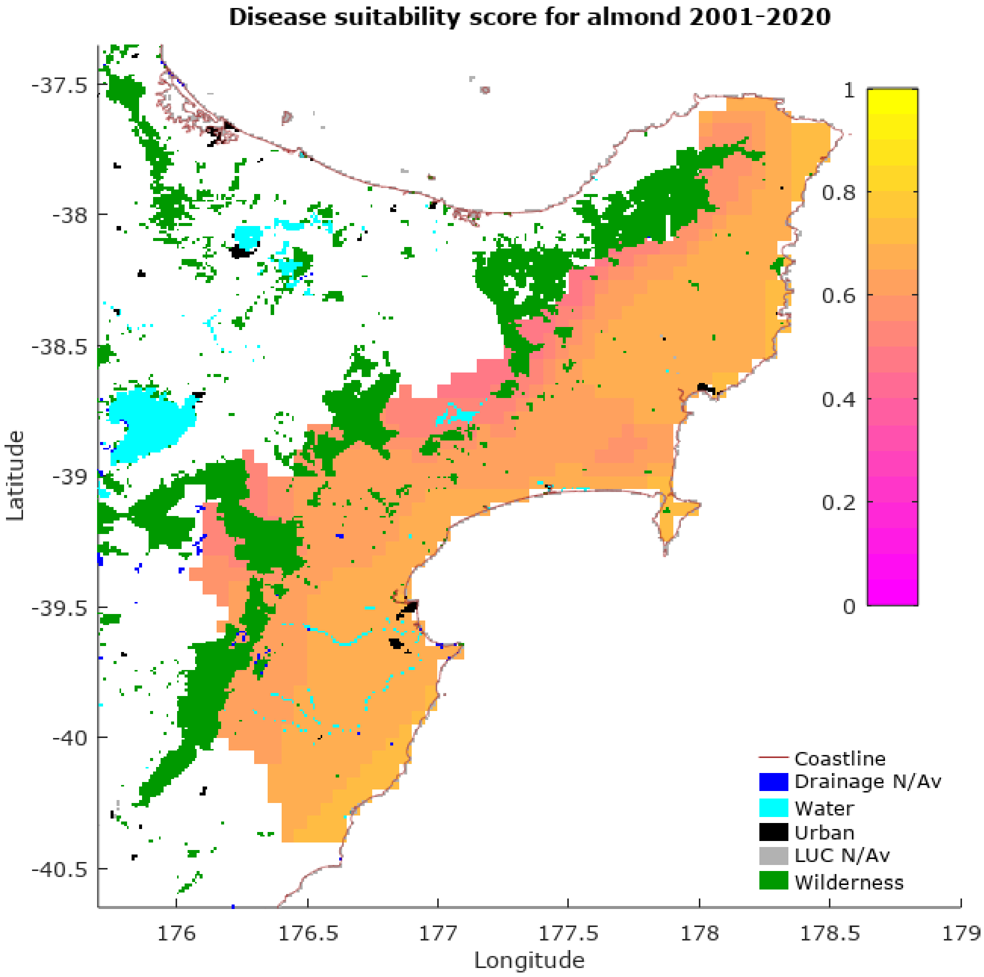

Figure 8. Risk to almonds from pathogens favoured by high moisture availability, expressed as a disease suitability score from 0 to 1 and mapped for locations across the Hawke's Bay and Gisborne regions, for growing years 2001 to 2020. Suitability scores were calculated using Virtual Climate Station Network (VCSN) data.

3.1.6 Harvest rain suitability

Many areas that scored highly in suitability scores for winter chill and forcing, frost risk, and GDH during the growing season were found to have low to very low harvest rain suitability, indicating a high risk of rain damage from between hull split and harvest, while anomalously some areas that had scored very low for winter chill and forcing, frost risk and GDH were found to have very high suitability (Figure 9). The explanation for the anomalous high harvest rain suitability is that those locations would be too cold for hull split or harvest to occur. The Poverty Bay area is indicated as one where rain around harvest could be a problem, while for locations from around the Heretaunga Plains to the locations around Waipukurau, the problem of harvest rain would be less severe, but likely to impose some yield losses or additional costs on growers.

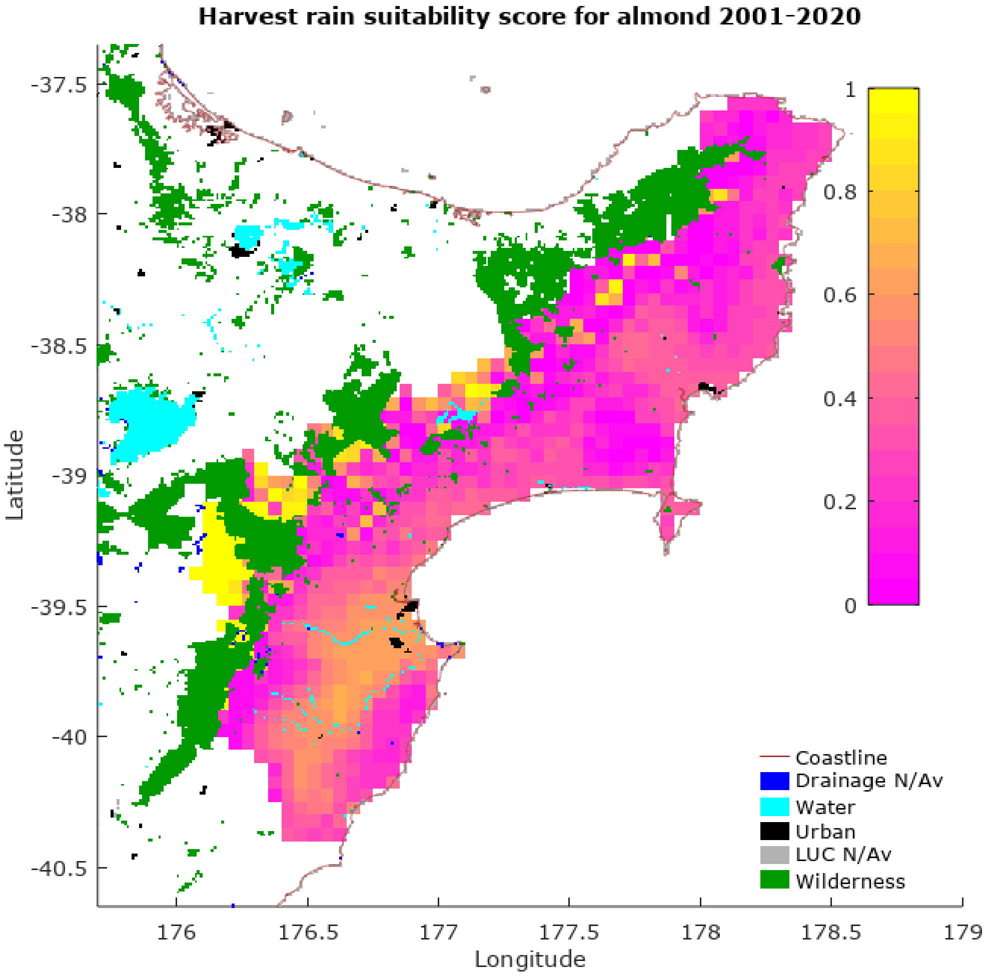

Figure 9. Risk to nuts from rain occurring between hull split and harvest, expressed as a harvest rain suitability score from 0 to 1 and mapped for locations across the Hawke's Bay and Gisborne regions, for growing years 2001 to 2020. Suitability scores were calculated using Virtual Climate Station Network (VCSN) data.

3.1.7 Annual rainfall deficit suitability

Annual rainfall suitability was identified as being high to very high for the majority locations, with the notable exception of locations from the Heretaunga Plains through to and around Waipukurau and to a lesser extent in the Poverty Bay area (Figure 10). With the exception of the anomalous areas in Figure 9 discussed above, Figure 9 and Figure 10 are close to mirror opposites, reflecting the trade-off between two criteria that are both dependent in different ways on rain.

Growers in a location of low annual rainfall suitability would have the option of mitigating the deficit in rainfall by irrigation, or could manage their orchards without irrigation and accept lower yields, as one grower has done. Therefore annual rainfall suitability was not included in the criteria used to calculate an overall climate suitability score, and is intended to be used stand-alone as an indicator of potential irrigation requirements.

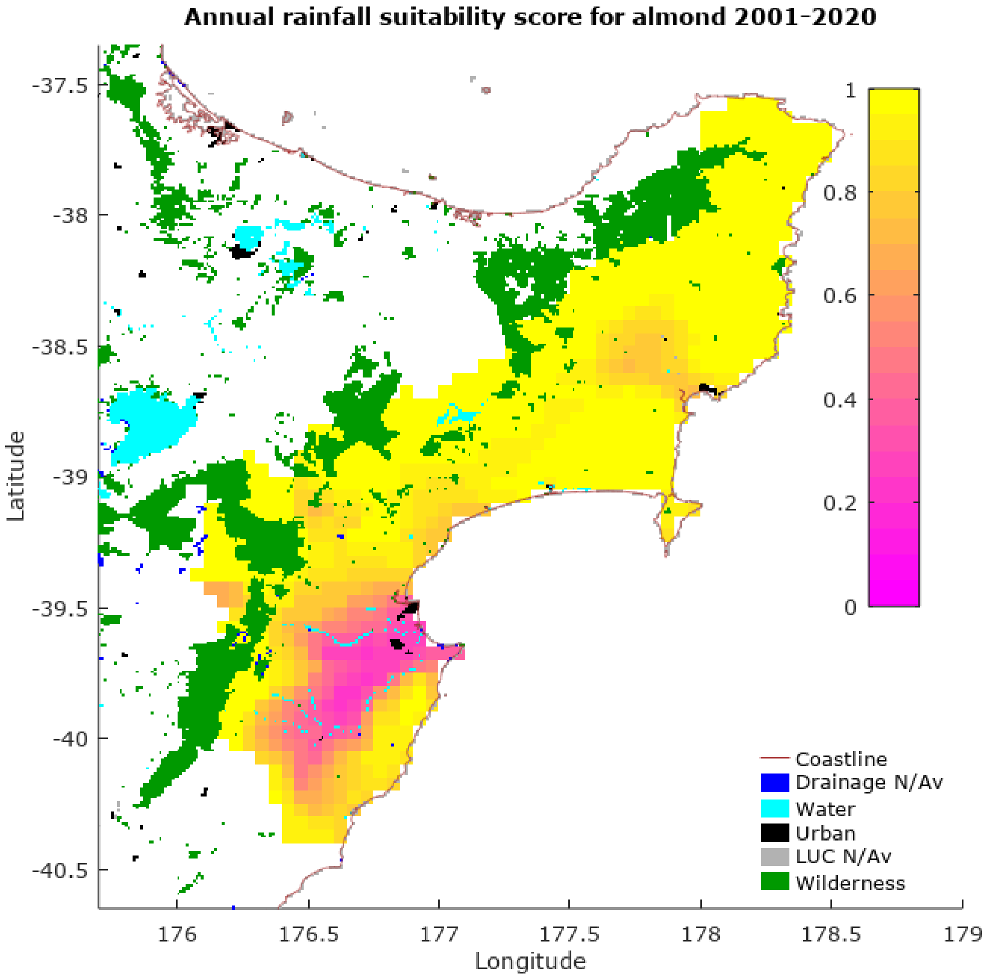

Figure 10. Adequacy of annual rainfall to meet the growing needs of almonds, expressed as an annual rainfall suitability score from 0 to 1 and mapped for locations across the Hawke's Bay and Gisborne regions, for growing years 2001 to 2020. Suitability scores were calculated using Virtual Climate Station Network (VCSN) data.

3.1.8 Overall climate suitability

Combing individual climate criteria by taking year-by-year weighted geometric means before arithmetic averaging over the 20-year period of the simulation provides an overall climate suitability score for that year (Figure 11). The chill-force, GDH, frost and pollination suitability scores were given weights of 2 reflecting a (subjectively) greater importance placed on them compared with the harvest rain suitability score which had a weight of 1. A weight of 0.5 was used for the disease suitability score because of the generic nature of the risk it calculated.

Annual rainfall suitability was excluded from the overall climate suitability, since it was intended that annual rainfall suitability be used as an indicator of irrigation requirements rather than as a determiner of location suitability.

Locations around and peripheral to Hastings are indicated as being among the more suitable locations in the Hawke's Bay and Gisborne regions. Some locations between Hastings and Waipukurau are indicated as having similar suitability to locations around Hastings, while some locations in Poverty Bay are indicated as posing only slightly more climate limitations for almond than the best sites (Figure 11).

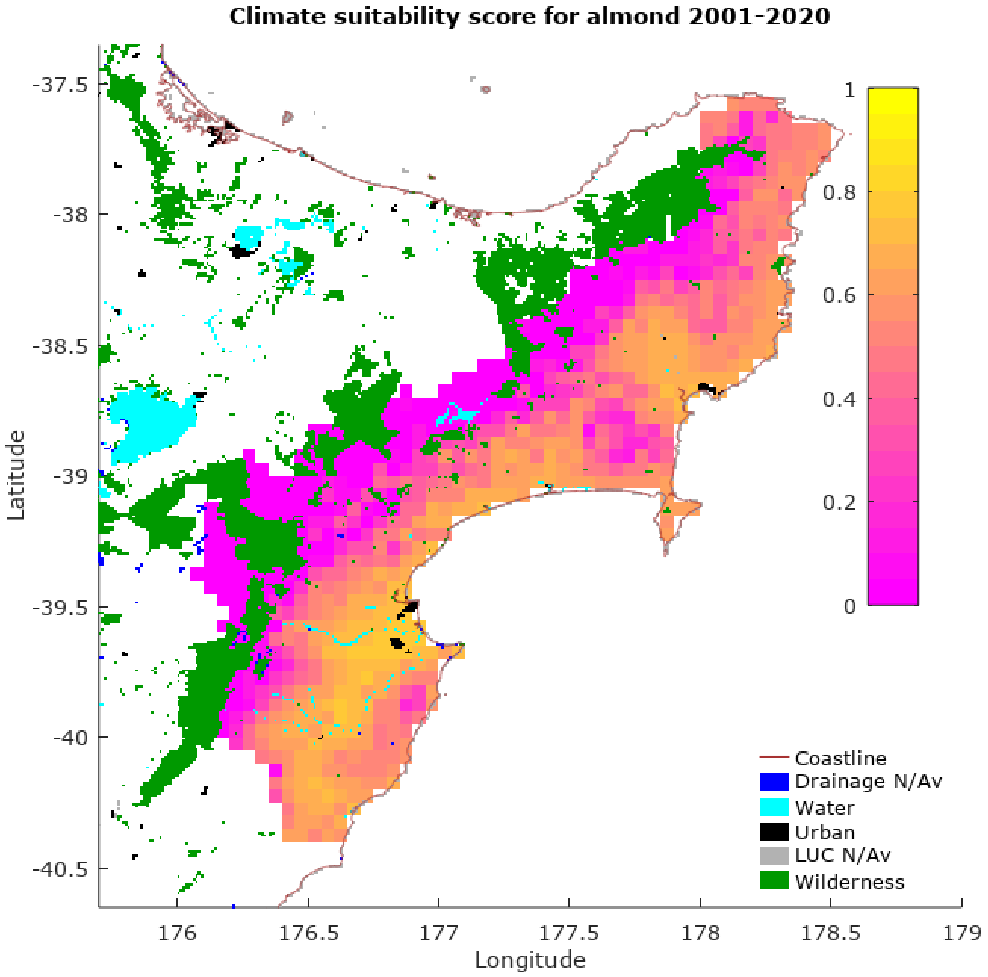

Figure 11. Overall climate suitability score from 0 to 1 that balances multiple climate-related criteria and mapped to show how well locations across the Hawke's Bay and Gisborne regions meet the climate requirements for almond. Scores were calculated for the growing years 2001 to 2020, using Virtual Climate Station Network (VCSN) data.

3.1.9 Potential rooting depth

Most areas of the Gisborne region were identified as having high suitability for PRD, although some locations in or around the Poverty Bay Flats area were identified as having shallow soils and thus low PRD suitability (Figure 12). Significant areas of land around Napier and to the west and north were found to have PRDs of low suitability for almonds, although with scattered areas of high suitability, while a large area around Hastings was found to have high suitability. Further south, large areas of Central Hawke's Bay were found to have low PRD suitability scores, but with significant areas of high

PRD suitability around the Takapau Plains and in the south-east (Figure 12). A low PRD can increase susceptibility to drought, and could be mitigated by irrigation or mounding.

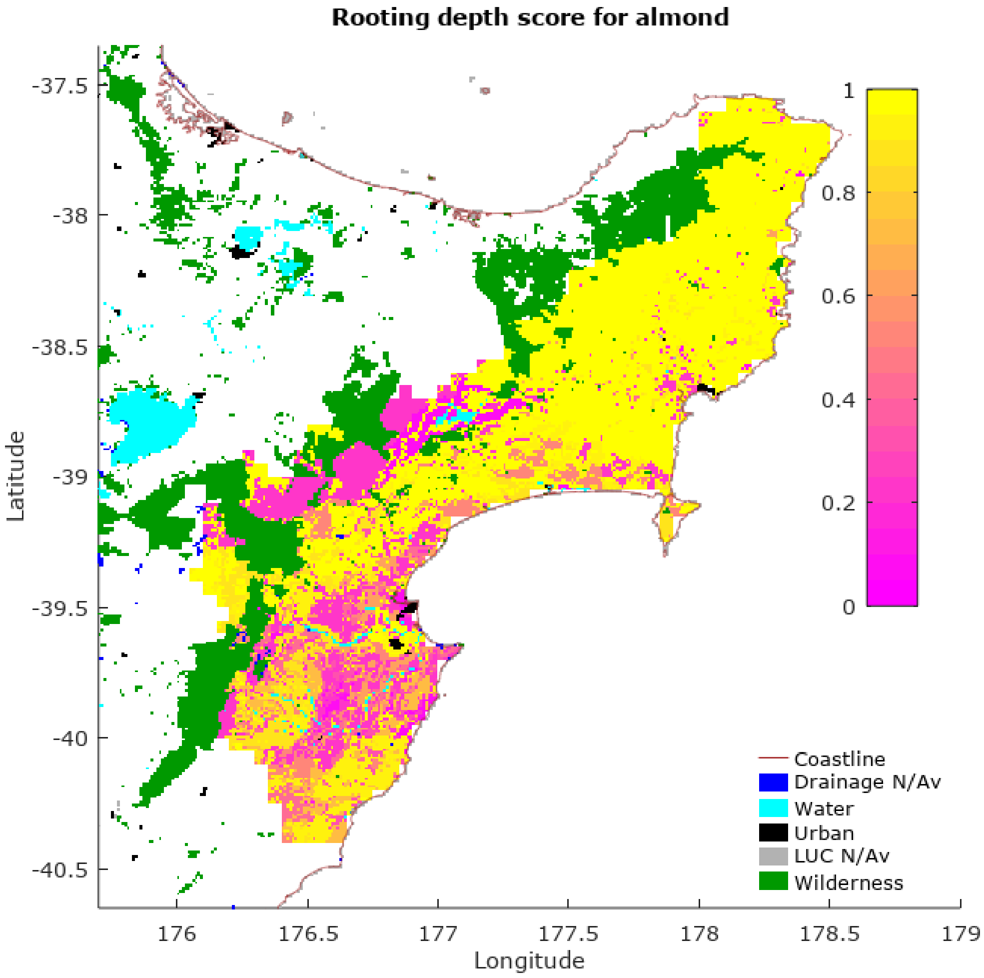

Figure 12. Rooting depth suitability scores for locations across the Hawke's Bay and Gisborne regions indicating the suitability of soil depth for growing almond.

3.1.10 Slope suitability

The majority of locations in Gisborne and the area of Hawke's Bay north of Napier were found to have very low slope suitability, although there are still a large number of high slope suitability locations scattered in this area, and a large contiguous area of highly suitable land in the Poverty Bay Flats extending inland (Figure 13). South of Napier the majority of locations have high slope suitability, with a number of low suitability areas in Central Hawke's Bay (Figure 13). Land with low slope scores corresponds to steeper slopes which may not be conducive to machine shaking to harvest almonds. However, manual shaking of almonds is possible (and carried out by the Waipukurau grower), and would be a possible mitigation in locations with low slope suitability.

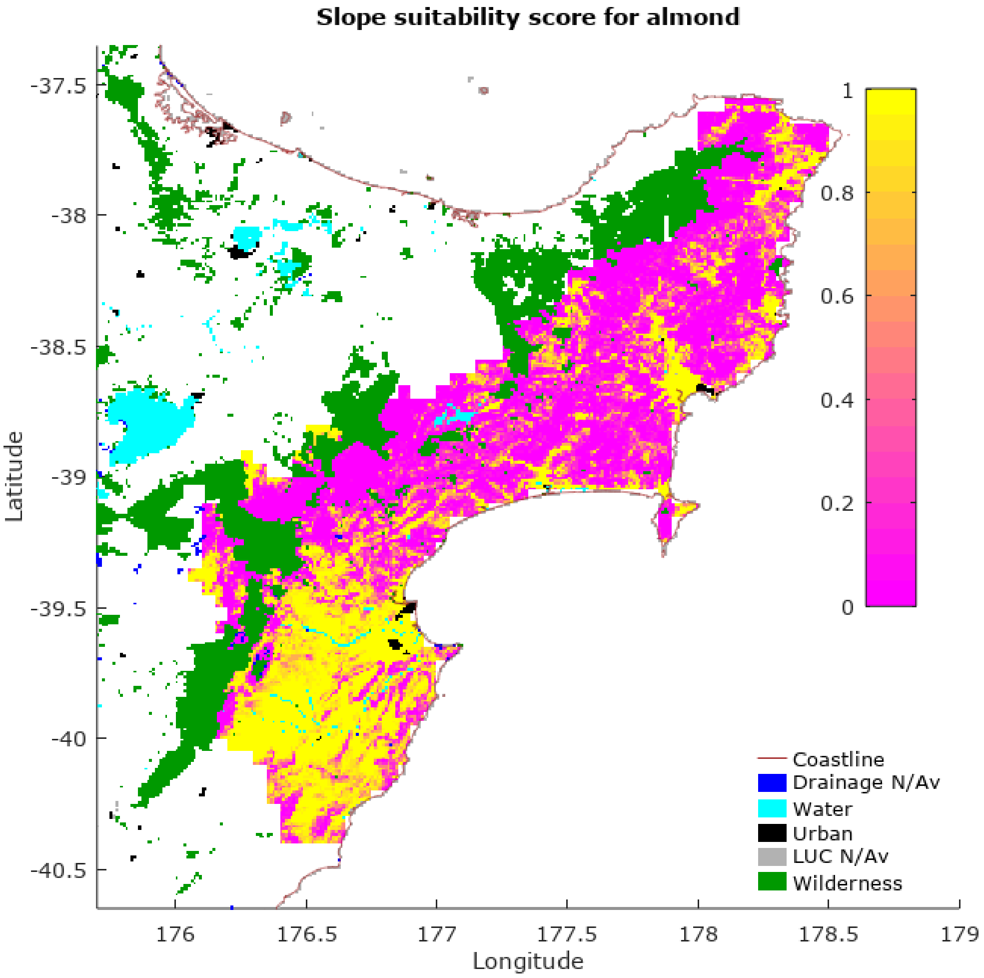

Figure 13. Slope suitability scores for locations across the Hawke's Bay and Gisborne regions indicating the suitability of slopes for almond, in particular with consideration of machine harvesting.

3.1.11 Drainage

Drainage suitability was generally high for most locations in Gisborne, although large parts of the Poverty Bay Flats and surrounding areas were found to have drainage of low suitability for almonds (Figure 14). Much of Hawke's Bay north of the Napier region was found to have high drainage suitability, with some areas of poor drainage located in some coastal and peri-coastal areas, and from Napier South to Waipukurau, the suitability maps shows a mosaic of high- and low-suitability areas (Figure 14).

It might still be possible to grow almonds in locations with low drainage suitability, but this would require extra costs and effort to improve soil drainage, for example by mounding, subsurface ploughing, or installing drainage systems.

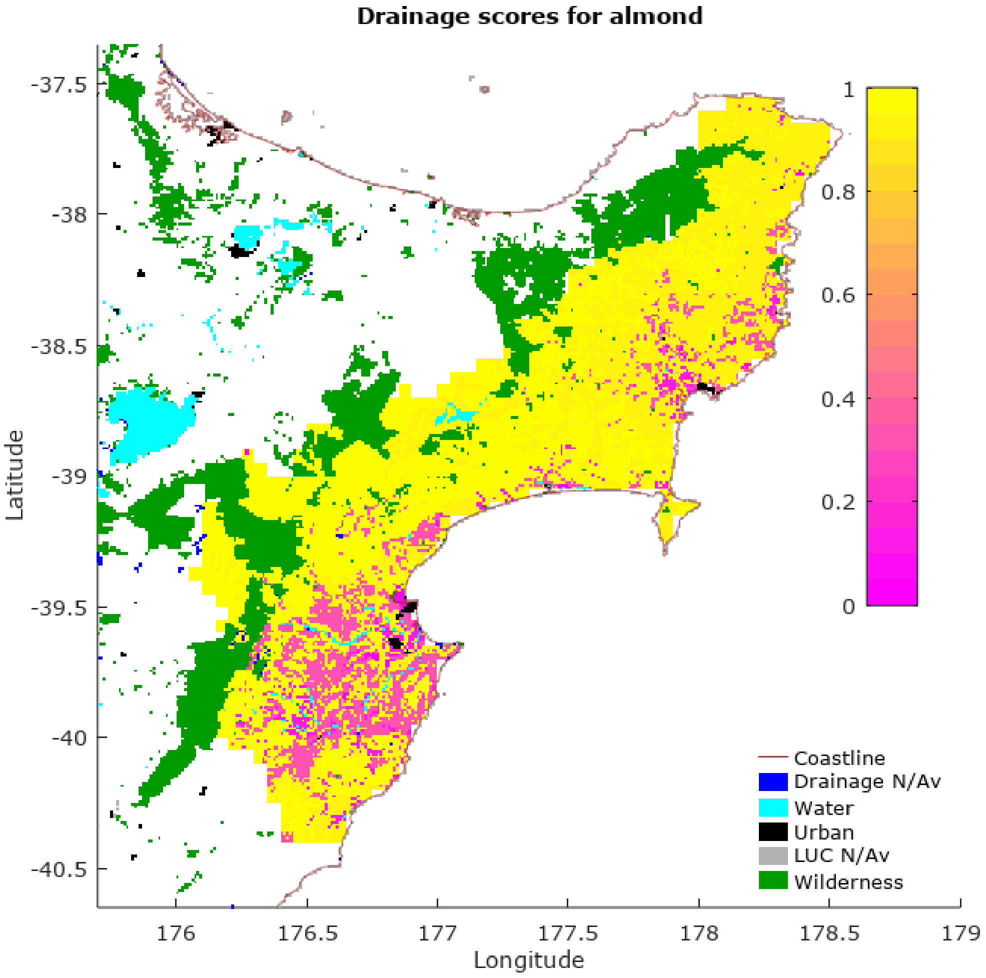

Figure 14. Drainage suitability scores for locations across the Hawke's Bay and Gisborne regions for growing almond.

3.1.12 Land use capability class

LUC classifications provide a generic assessment of land suitability for different uses, and thus there is some overlap between LUC class descriptors and slope, PRD and drainage information. However, LUC class also contains extra information regarding the soil properties and thus provides a useful suitability criterion. We found that most areas of the Hawke's Bay and Gisborne regions scored lowly in LUC suitability score, with notable exceptions being in and around the Poverty Bay Flats, the Heretaunga Plains, and around Waipukurau and the Takapau Plains (Figure 15).

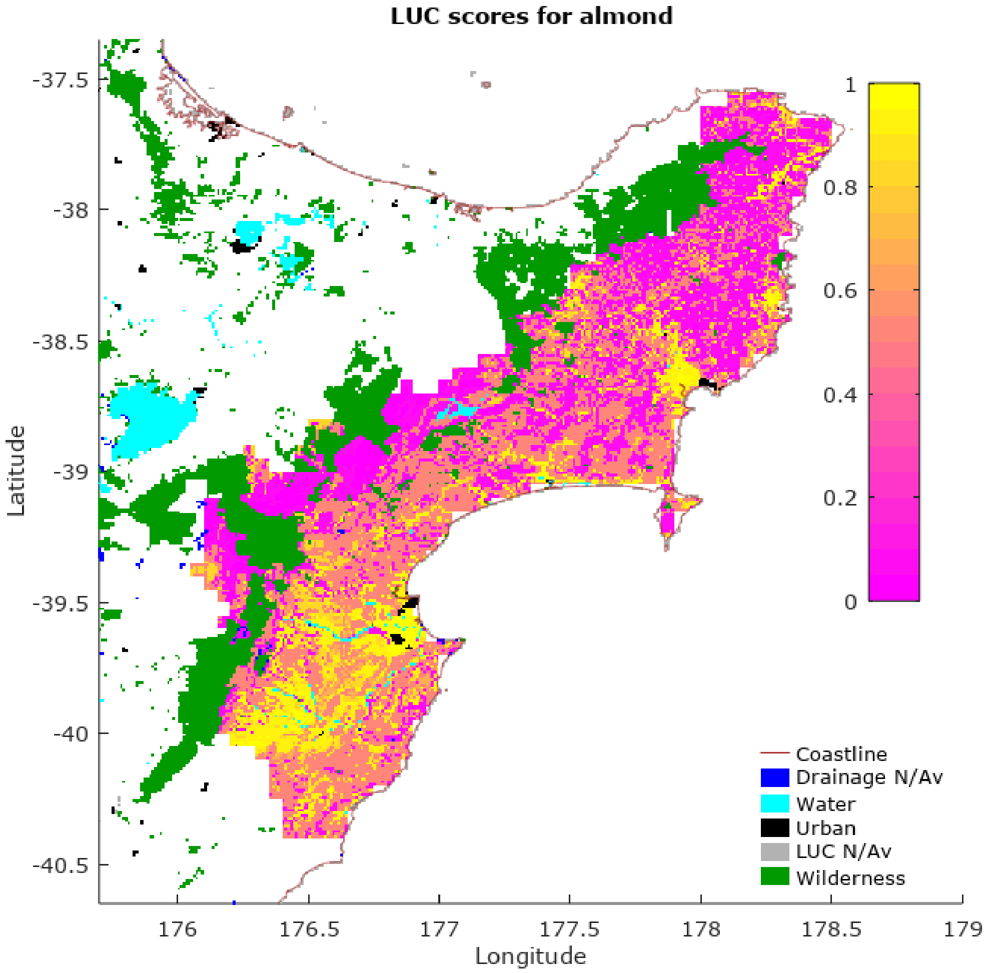

Figure 15. Land use capability (LUC) class suitability scores for locations across the Hawke's Bay and Gisborne for growing almond.

3.1.13 Cultivation suitability

The cultivation suitability score combines the climate suitability score with the land-related suitability scores using weighted geometric averaging. The weight for the climate suitability score was 9.5, which is the sum of the weights for the individual climate-related suitability scores used when calculating it (Section 3.1.8). A weight of 3 was used for slope suitability, a weight of 2 for drainage suitability and weights of 1 for PRD suitability and LUC suitability. Slope suitability was given the highest weight since it would be harder to mitigate if a commercial grower required harvesting machinery.

The cultivation suitability map shows a diverse suitability landscape across both the Hawke's Bay and Gisborne regions, with some locations in the Heretaunga Plains, especially around Hastings and Havelock North, having the highest cultivation suitability scores. A number of locations in Central Hawke's Bay have slightly lower cultivation suitability scores, and although these locations are likely to be subject to more limitations or extra mitigation costs, these could be potential sites for successful almond orchards. A number of locations around Poverty Bay and inland of the Flats are identified as potential areas for almonds, but also likely to experience limitations to production or require extra establishment and on-going costs, compared with highly suitable locations.

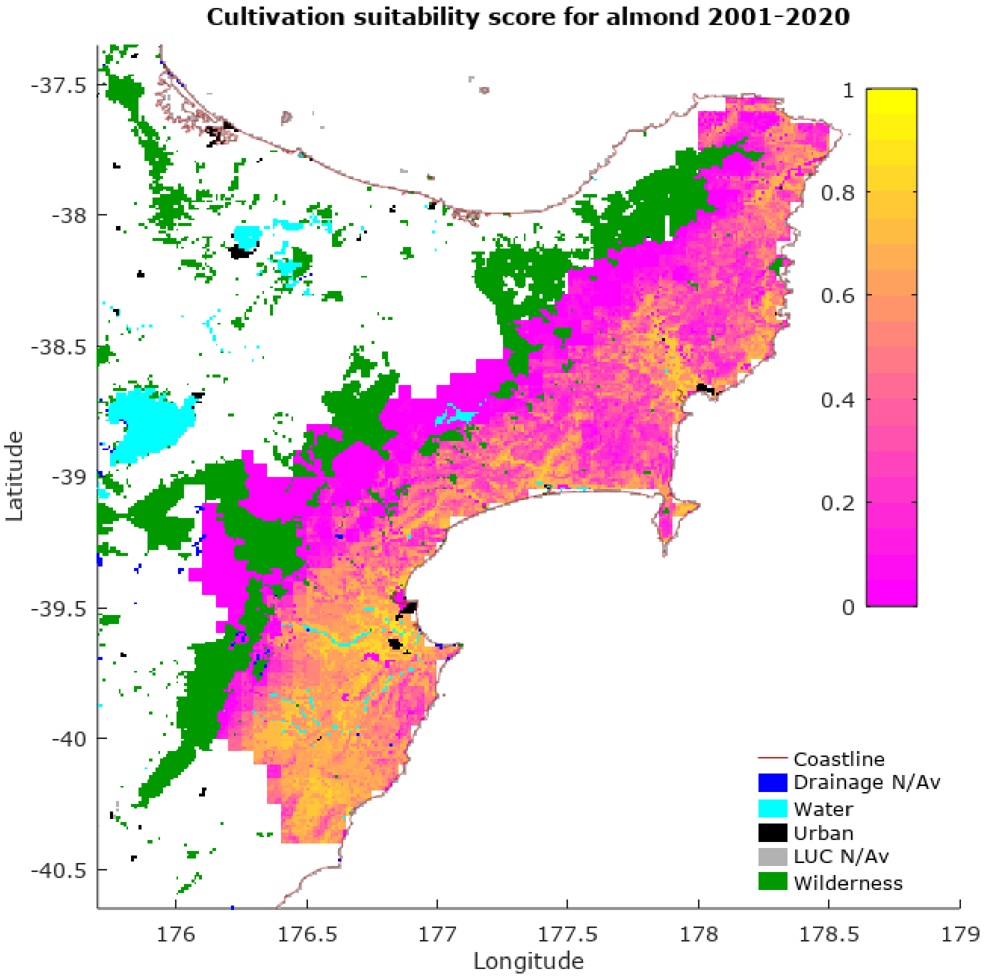

Figure 16. Cultivation suitability scores showing overall suitability for locations across the Hawke's Bay and Gisborne for growing almond by providing weighted average of individual climate-related and soil-related suitability scores.

3.2 Projecting climate change impacts on suitability

Within each RCP, the simulation datasets from the six different GCMs provide six alternative versions of future weather patterns. The approach is to use each of the six datasets to perform suitability calculations, and then to take the mean as the projected future suitability for the RCP. The standard deviation of the six alternative suitability calculations is often used to indicate the uncertainty in the mean projection.

The VCSN-based suitability maps show suitability of the current climate for almonds. However potential climate change impacts on suitability should be estimated by comparing suitability scores calculated from climate model projection data for a future period with suitability scores calculated from climate model data for the hindcast (RCP Past) period. We calculated projected suitability scores for the future periods 2031–2050 and 2051–2070 using the SLM RCP datasets, and to estimate climate change impacts, calculated suitability scores for the period 1981–2000 using the SLM RCP Past datasets. The projected changes are useful for indicating the direction of change for different locations, and the relative magnitudes of change between locations.

Projected suitability for individual criteria and combined criteria were mapped for the two future periods for both RCP 8.5 and 6.0, and are presented in Appendix 2 (page 61), along with maps of the standard deviations of suitability score projections and of change in suitability with respect to the 1981–2000 hindcast period (page 61).

RPC 8.5, which is consistent with unabated GHG emissions, is likely the closest to the current emissions trajectory, and we discuss the projection results in this section. For brevity, we present only maps for overall cultivation suitability and maps for projected change in climate suitability.

3.2.1 Climate change impact under RCP 8.5

Cultivation suitability 2031 to 2050 period

The projected cultivation suitability map for 2031 to 2050 under RCP 8.5 (left panel of Figure 17) is similar to the cultivation suitability map for the 2001–2020 (Figure 16), which represents current suitability. The projected change in climate suitability (right panel of Figure 17) shows the trend in climate suitability under RCP 8.5 and indicates a generally positive impact on overall climate suitability.

Note that projected changes for cultivation suitability will have smaller magnitudes than projected changes for climate suitability. This is because when climate suitability and land suitability scores are combined by geometric averaging, the climate contribution is diluted. Note also that the change in projection is calculated for a time difference of 50 years, while the time difference between the contemporary and future periods is 30 years. Thus projected changes should be interpreted as only indicators of the direction of change.

Examining the maps for projected changes in individual suitability which are presented in Appendix 2, there were a very few locations of historically high chill-force suitability that had significant decreases in chill-force suitability. This can be linked directly to a decrease in CU accumulations. However, there were generally only very small decreases in chill-force suitability in areas that historically were very high, and these areas remained of high suitability. Small decreases in CU can be compensated for by increased GDH accumulation. There were large improvements in some areas of historically low chill-force suitability that substantially improved their scores. These areas were historically too cold to accumulate sufficient GDH for timely flowering, and under the climate projection, improved their GDH accumulation while still maintaining adequate chill.

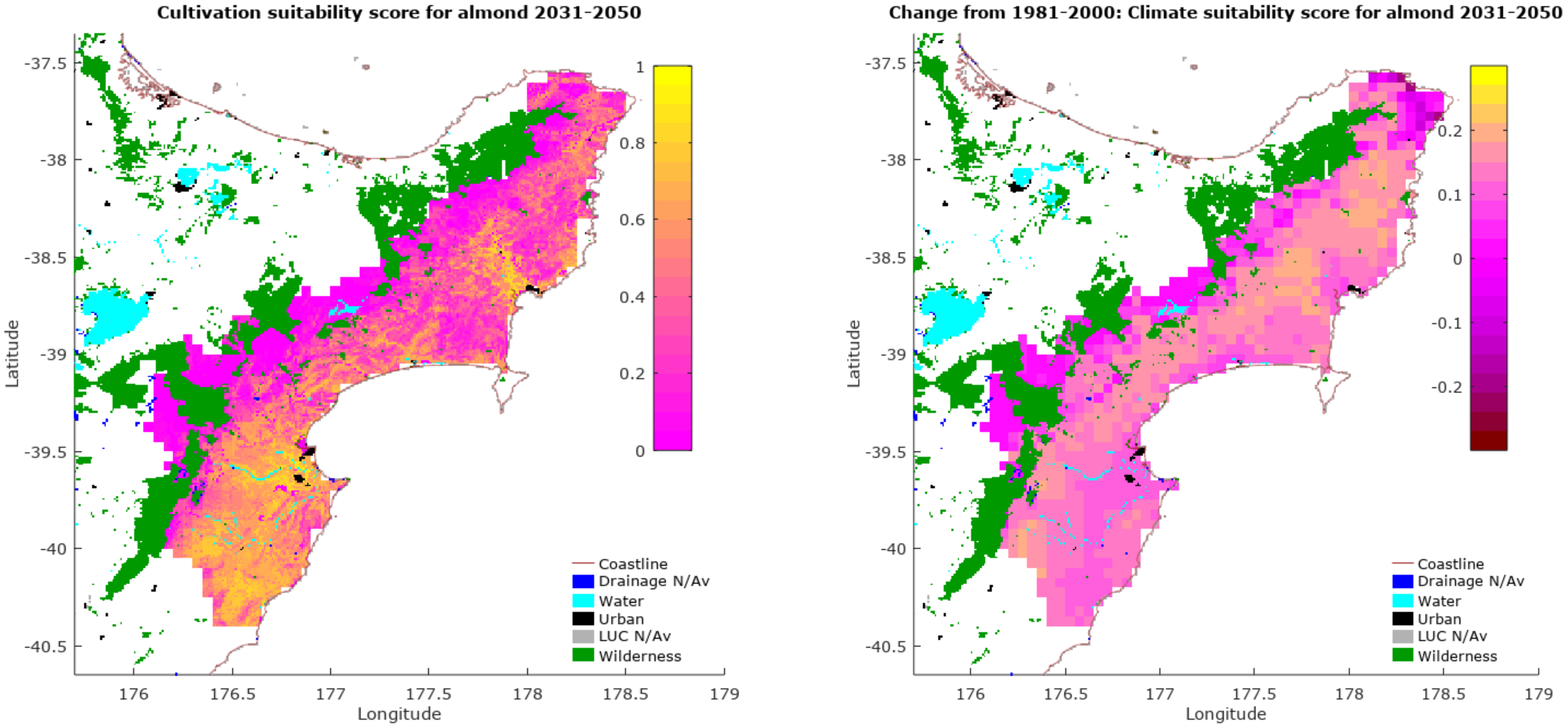

Figure 17. Projected cultivation suitability scores for 2031–2050 under RCP 8.5 (left) showing overall suitability of locations across the Hawke's Bay and Gisborne regions for growing almond, and projected change in cultivation suitability scores for 2031–2050 compared with 1981–2000 under RCP 8.5 (right) showing the direction of suitability change.

There was generally little change in GDH suitability for areas with historically high suitability since these already had sufficient heat accumulation, and larger increases in some locations that historically had low GDH that closely matched increases in the areas of historically low chill-forcing suitability (Appendix 2). This correlation is not unexpected since GDH accumulation in the model was contingent on adequate CU being accumulated.

There was little projected change in harvest rain suitability, except for big deceases in suitability for some areas that, for the contemporary period, were calculated as having high suitability because they were too cold to produce a crop (Appendix 2). These areas had warmed sufficiently under the climate projection to produce a crop in some year, and subsequently rain at harvest would become an issue. Pollination suitability was generally projected to increase, especially in areas of historically higher suitability, and frost suitability was also projected to increase in most locations, with other locations tending to have only small declines (Appendix 2). Declines in frost suitability can occur when warmer climates bring forward flowering into a frost risk period.

Projected changes to the generic disease risk suitability score were minor, as were projected changes to the annual rainfall suitability score (See Appendix 2). With respect to the latter, although annual rainfall was not projected to change significantly for Hawke's Bay or Gisborne, the rainfall patterns may well do, but the rainfall model is not sensitive to this.

Cultivation suitability 2051 to 2070 period

The projected cultivation suitability map for 2031 to 2050 under RCP 8.5 (left panel of Figure 18) is similar to the cultivation suitability map for the 2001–2020 (Figure 16) but indicates slightly higher cultivation suitability in Central Hawke's Bay and also parts of the Heretaunga Plains, with little suitability change indicated for around the Poverty Bay area. The projected change in climate suitability (right panel of Figure 18) shows the trend in climate suitability under RCP 8.5 and indicates a generally positive impact on overall climate suitability with suitability changes having up to twice the magnitude compared with the projected changes to 2031–2050 period. The largest changes were decreases in suitability around the East Cape area, in the order of 0.4.

A slight decline in suitability in many historically high chill-force locations was projected, with a continued improvement of colder locations with historically insufficient GDH accumulation for forcing (See Appendix 2). Projections indicate little change in GDH suitability for areas with historically high suitability and larger increases in some locations with historically low GDH accumulation, following the projected changes discussed above for the 2031–2050 period (See Appendix 2).

For most areas, very slight to small increases in harvest rain suitability were projected, but large decreases in suitability were projected for some locations. These latter locations included the same locations that were projected to have big decreases in harvest rain suitability by 2031–2050, but the projected declines are much larger (See Appendix 2). These locations which were historically too cold to produce a crop and thus were calculated as having low harvest rain risk, have continued to warm and fruit successfully in more years, and thus have more years in which rain at harvest is a risk.

Frost risk suitability was projected to increase in almost all locations across the two regions, with very high frost suitability scores for most areas other than in some higher altitude locations. Pollination suitability was projected to improve across the two regions, with bigger suitability increases in lower-elevation locations, resulting in a much improved pollination suitability map for 2051–2070 than for the contemporary period. As was the case for 2031–2050, projected changes to the generic disease risk suitability and annual rain suitability scores were minor (Appendix 2).

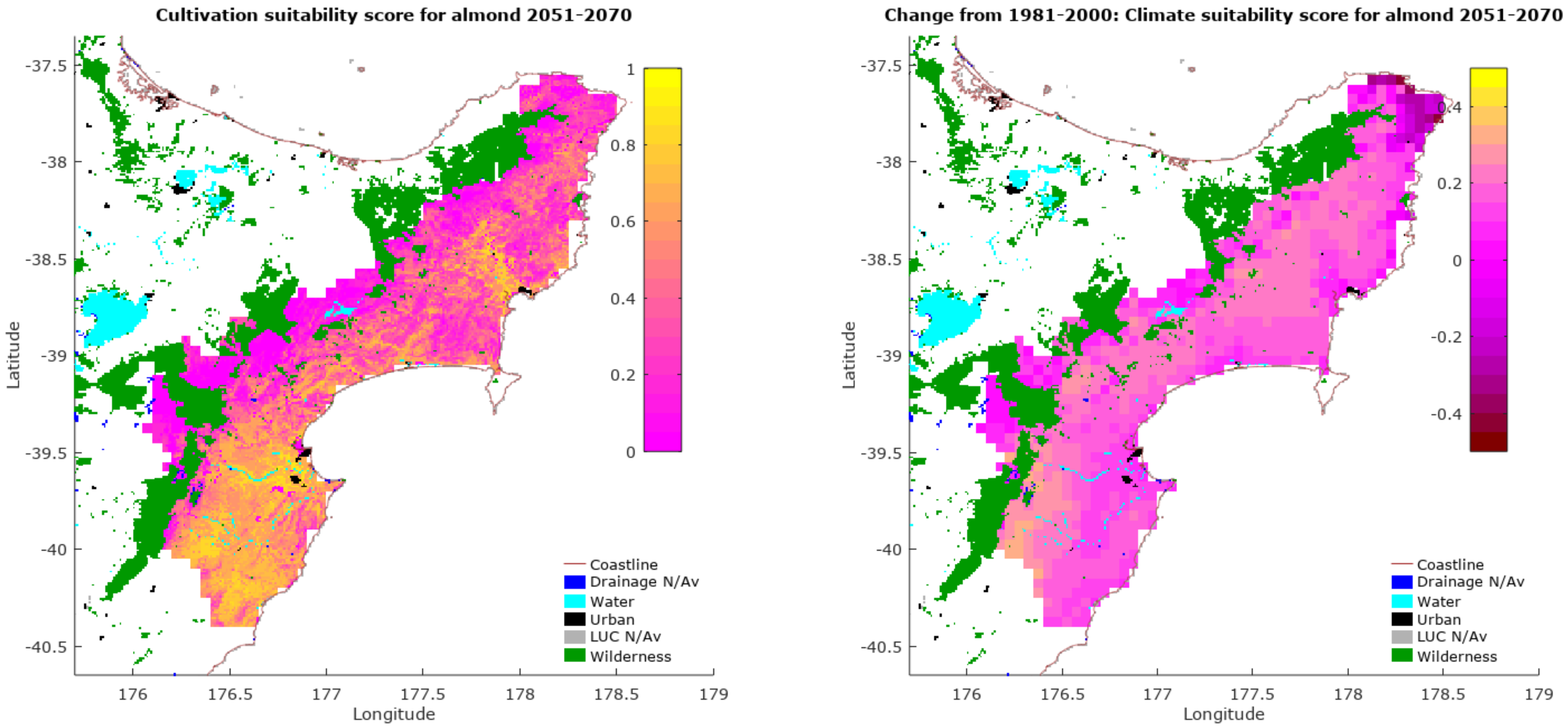

Figure 18. Projected cultivation suitability scores for 2051–2070 under RCP 8.5 (left) showing overall suitability of locations across the Hawke's Bay and Gisborne for growing almond, and projected change in cultivation suitability scores for 2051–2070 compared with 1981–2000 under RCP 8.5 (right) showing the direction of suitability change.

The trends in the projected changes in suitability scores under RCP 6.0 are similar in direction to those under RPC 8.5, but the magnitudes of projected change are smaller – i.e. the rate of change over time is slower. Graphs showing projected means, standard deviations of projected mean, and projected change under RCP 6.0 are presented in Appendix 2.

3.3 Life cycle assessment

3.3.1 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) translates emissions and resource extractions into a set of environmental impact scores using characterisation factors (ISO 2006a, 2006b). In this study, the LCIA method ReCiPe 2016 (Huijbregts et al. 2017) and the most recent GWP100 metrics (IPCC 2014) were applied to calculate the potential carbon footprint of harvested almonds, reported here as kg of carbon dioxide equivalents per kg of raw almonds (kg CO_2-eq/kg). Results have been aggregated into groups to make them easier to interoperate. For example, glyphosate, pesticide, and fertiliser production includes the emissions associated with the production of the product, transport and shipping. Similarly machinery operations represent all the emissions associated with machinery activities within the orchard.

Based on the inputs to the orchard system outlined above, Results indicate that there is potential carbon footprint of 1.83 kg CO_2-eq/kg of almonds associated with the life cycle of almond production to the farm gate. Overall, irrigation has the greatest contribution to the system (1.24 CO_2-eq/kg) accounting for 68% of the associated footprint; this is followed by machinery operations (0.23 CO_2-eq/kg) and fertiliser applications (0.17 CO_2-eq/kg). Table 1 and Figure 19 and Figure 20 provide a summary of the results based on the orchard activities.

Table 1. Potential carbon footprint associated with almond production.

Activity/input	**kg CO_2-eq/kg**
Glyphosate Production	0.02
Pesticide Production	0.06
Urea Production	0.06
KCl Production	0.05
Machinery Operation	0.23
Fertiliser Applications	0.17
Irrigation	1.24
Total	1.83

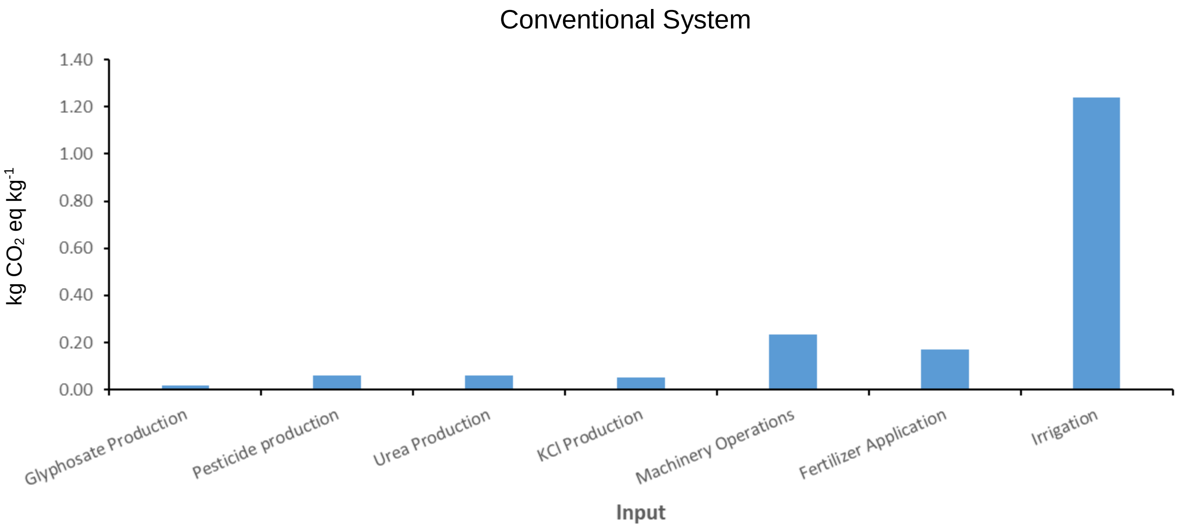

Figure 19. Potential emissions from each input of the conventional system.

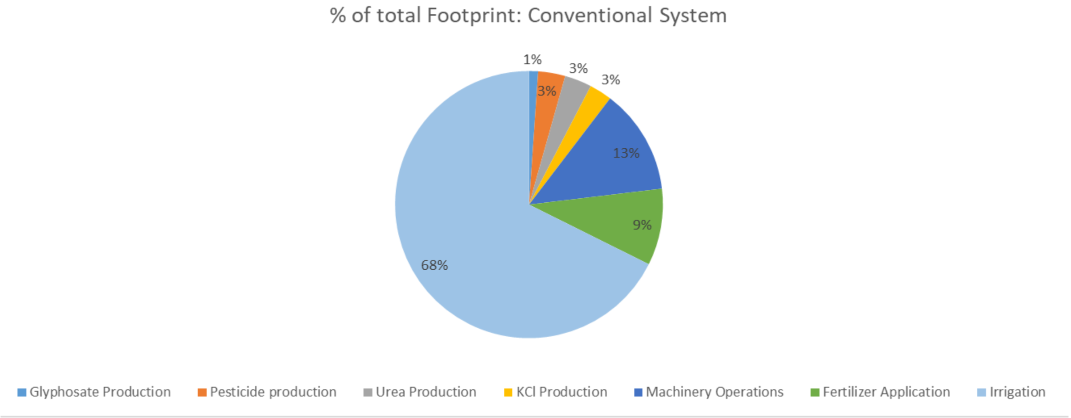

Figure 20. Percentage contribution of each input of the conventional system to the total potential carbon footprint.

3.3.2 Sensitivity Analysis

From the LCIA, irrigation was identified as a major hotspot within the almond life cycle accounting for 68% of the overall potential footprint. Here, adjustments were made to the total amount of irrigation to assess what influence this may have on the overall results. The essence of the adjusted LCA model, and its inputs, was kept the same as per the conventional system with only the total volume of irrigation adjusted. As there are no current New Zealand specific data relating to irrigation inputs and yield response of almonds, adjustments to the amount of irrigation applied where based on work by Moldero et al. (2021) and used only as a guide. The total inputs to irrigation were taken as a percentage of the total used in the conventional scenario (i.e. 12 ML). Adjustments were as follows: 65% and 30% of total irrigation and zero irrigation. Table 2 and Figure 21, Figure 22, Figure 24, Figure 23, Figure 25, Figure 26 summarise the results of the adjusted inputs.

Table 2. Adjusted carbon footprint based on reduced irrigation inputs.

% of irrigation from conventional input	Total kg CO_2-eq/kg	Total kg CO_2-eq/kg contributed from Irrigation	% reduction of total kg CO_2-eq
100	1.83	1.24	0
65	1.40	0.81	23
30	0.96	0.37	48
0	0.59	0	68

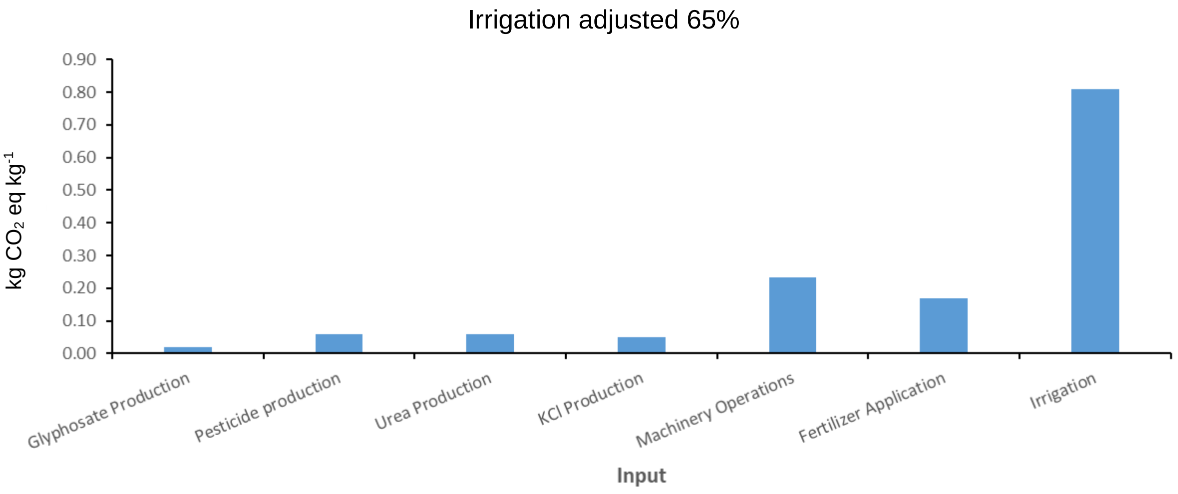

Figure 21. Potential emissions associated with each input and assuming 65% of total irrigation from conventional system.

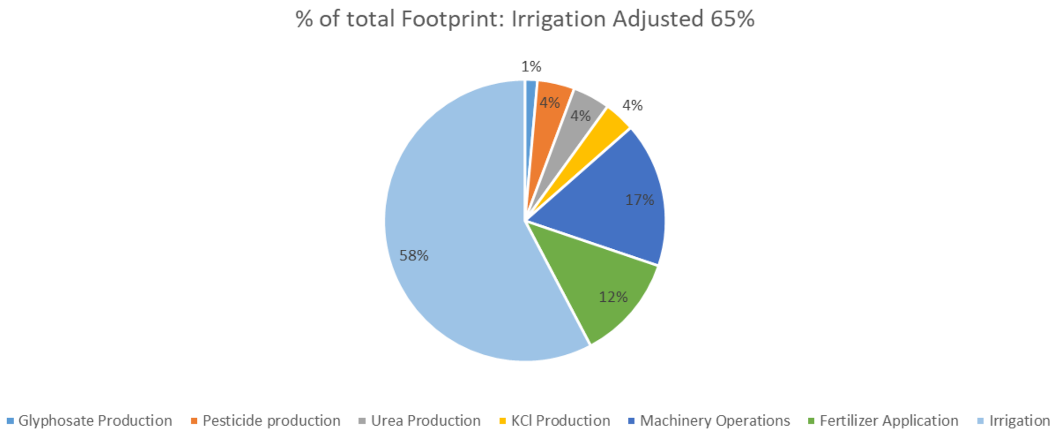

Figure 22. Percentage contribution of each input to the total potential carbon footprint, assuming 65% of total irrigation.

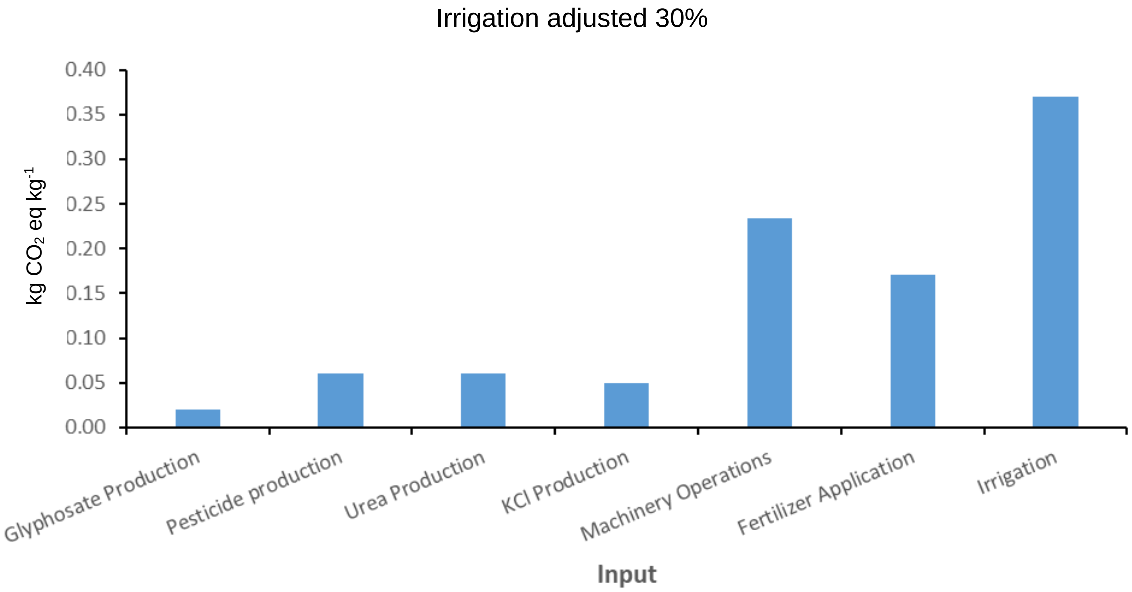

Figure 23. Percentage breakdown of carbon footprint associated with each input and assuming 30% of total irrigation of conventional system.

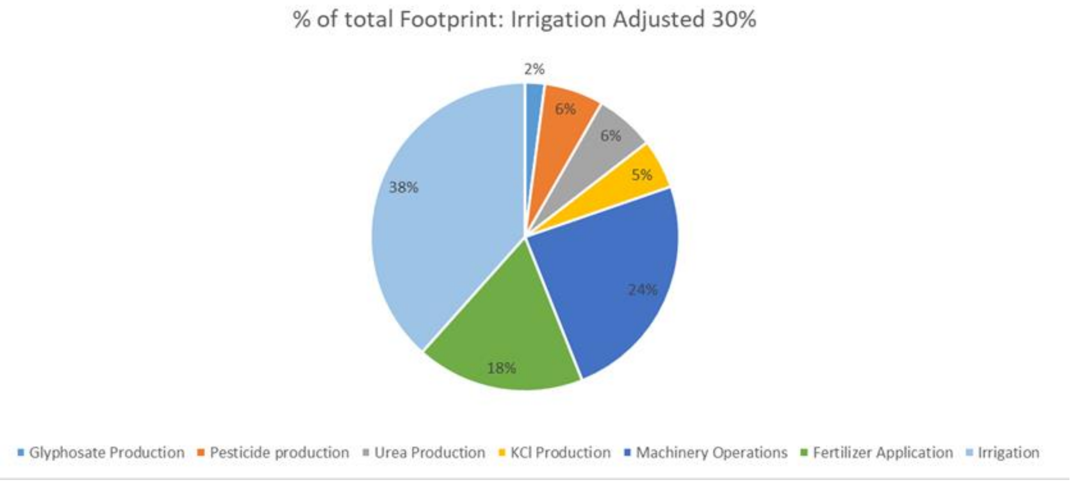

Figure 24. Potential emissions associated with each input and assuming 30% of total irrigation from conventional system.

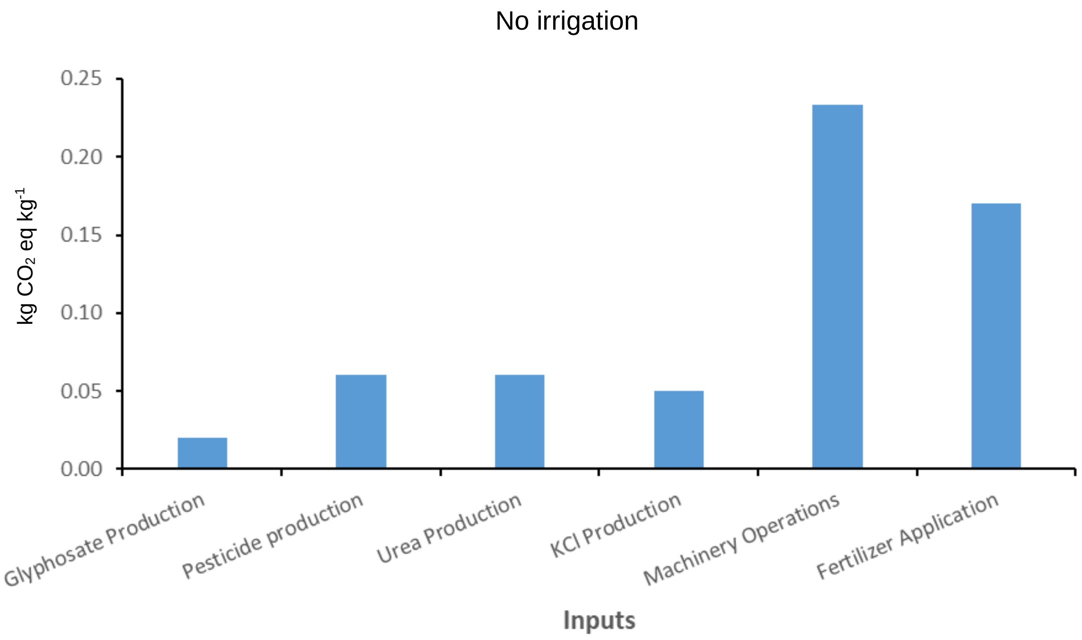

Figure 25. Potential emissions associated with each input and assuming no irrigation.

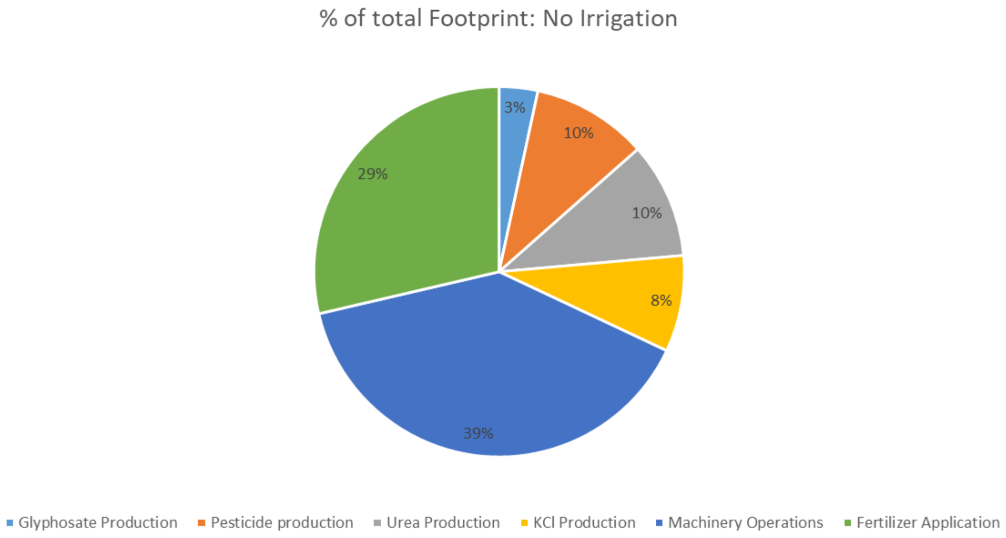

Figure 26. Percentage breakdown of carbon footprint associated with each input and assuming no irrigation.

4 Discussion and conclusion

4.1 Suitability modelling

Suitability models

The continuous suitability models provides a more flexible assessment than commonly used binary (suitable/unsuitable) models or categorical models (e.g. poor vs fair vs good vs very good) that require the stipulation of cut-off values for indicator variables. The use of cut-offs can result in artificial distinctions of two similar locations, or class two dissimilar sites into one category. Continuous suitability modelling not only allows optimal locations to be identified and ranked on merit, it also allows the study of gradual shifts in suitability under climate change, which cannot be done when one is dealing with categories. Continuous suitability modelling is useful also when appropriate data on crop or cultivar requirements are sparse or unavailable.

Many of the climate-related risks to almonds are dependent on the phenological stage of the tree, such as frost risk, rain at harvest or poor pollination weather. Thus modelling phenological stages over time was a key component of the suitability modelling, allowing the severity of a risk to be gauged on the basis of the probability of the tree being at a phenological stage vulnerable to that risk.

Going into the project, the phenology component of the PFR suitability model had an initial parameterisation that was theoretical, being based on published data from overseas studies that were not aligned with New Zealand climates or with the cultivars grown here. There was a lack of New Zealand almond phenology data with which to test our phenology model, but it was evident that the requirements for heat and chill accumulation published for almonds are largely not relevant for the New Zealand situation.

Our re-parameterisation of the phenology model was based on incomplete data from two sites taken over one or two years, and thus cannot be considered robust. This should be borne in mind when considering results, although the behaviour of the phenology model appeared sensible.

The weighted geometric averaging of continuous suitability scores for individual criteria to get overall soil, climate and cultivation suitability scores provides a means to aggregate considerations of multiple requirements and criteria in a way that reflects their relative importance (as reflected by their weighting). The selection of weights is subjective, and can vary among growers. For example, we gave the slope the highest weighting on the grounds that highly sloped land is less conducive to machine harvesting, and cannot be readily mitigated if a prospective grower intended to use machine harvesting. However a small-scale grower who is happy to harvest manually may consider that slope suitability should have a lower weight.

Suitability of locations for growing almonds

The suitability study was aimed at identifying suitable locations for growing almonds in the Poverty Bay area as well as the Hawke's Bay region, and thus we included Gisborne in our study. Our suitability models identified no locations with very high cultivation suitability scores (i.e. close to 1). Such locations would allow cultivation of almonds with few or no limitations from the climate, soil properties or the terrain.

However, a number of locations with suitability scores with "moderate" values in the order of 0.6 to 0.8, with some locations in the Heretaunga Plains in the vicinity of Hastings were identified as the most suitable. These locations of moderate cultivation suitability were found to be distributed across many areas of the Hawke's Bay region, with a large density in the Central Hawke's Bay District, and in some parts of the Gisborne region, including Poverty Bay – in the Flats and surrounding area.

Such locations would allow the successful cultivation of almonds, albeit with limitations that could result in decreased yields or require additional costs to mitigate. For reference, the Waipukurau and Te Puke orchards had calculated cultivation suitability scores of 0.69 and 0.62 respectively, climate suitability scores of 0.61 and 0.73 respectively, and soil suitability scores of 0.81 and 0.53 respectively. Due diligence is recommended before establishing large-scale establishment of almond orchards in these locations.

Annual rain suitability

The annual rainfall suitability score reflected the beneficial effect of rain towards maintaining crop evapotranspiration, as opposed to its damaging effect at harvest. Annual rainfall was not included in the calculation of overall cultivation suitability but intended to be used separately as a guide on irrigation requirements.

Projected impacts under climate change

The projected impact of climate change under RCP 8.5 was a slight improvement in cultivation suitability, due to such factors as decreased frost and disease risks, and increased GDH accumulation. The trend in improvement continued from the 2031–2050 period through to the 2051–2070 period. Projected changes in suitability scores under RCP 6.0 were qualitatively similar to those under RCP 8.5, but occurring at a slower pace.

An important difference between this study and previous climate change studies is on the issue of winter chill and flowering. For example, Vetharaniam et al. (2021) found that increased temperatures under RCP8.5 could lead to a lack of winter chill and lack of flowering. In that study, the chill models were either based on mean winter temperature or purely accumulation of chill. In this study, we have used a chill-force model in which chill accumulation is required for buds to reach ecodormancy and then heat accumulation is required to force buds to the flowering stage. In the chill-force model, decreased chill can be partially compensated for by increased GDH, and this would essentially mitigate increasing temperatures, but only up to a point.

4.2 Life cycle analysis

The main objective of this study was to evaluate the potential carbon footprint associated with growing almonds in Hawke Bay and to highlight hotspots within the almond production system. Using inputs previously outlined, a typical almond system under conventional management has a potential footprint of 1.83 kg CO_2-eq/kg associated with almond production. Previous studies which have also assessed the environmental impact associated with almonds, indicated a potential carbon footprint of 1.92 kg CO_2-eq/kg of almonds (Volpe et al. 2015) while work by Marvinney et al. (2014) Kendall et al. (2015) found a potential carbon footprint of 1.76 kg CO_2-eq/kg and 1.6 kg CO_2-eq/kg, respectively. In this study, irrigation has been highlighted as the greatest potential hotspot within the life cycle, accounting for 68% of the total associated footprint and an area within the production system which may provide opportunity for environmental improvement. This was followed by machinery operations (13%) and fertiliser applications (9%). Orchard operations and nutrient management were also highlighted as large contributors to the overall potential emissions associated with almond production in California. This was attributed to the energy-intensive process associated with fertiliser manufacture and the large quantities applied during the growing season, and also the energy required for operations such as irrigation and harvesting (Kendall et al. 2015)

Sensitivity analysis revealed that by applying 65% less irrigation than the conventional system, the potential footprint was reduced by 23%, while applying only 30% of the total irrigation or no irrigation at all resulted in a potential footprint reduction of 48% and 68%, respectively. Noting that as the overall impact contributed by irrigation decreased, the relative proportion of other inputs, in terms of their overall impact, gradually increased, although their overall magnitude remained the same. While irrigation has been identified as a system hotspot, data used here are based on intensive almond production systems in California (Duncan et al. 2019) and not related to site-specific information here in New Zealand. Furthermore, the total energy demand to operate a specific irrigation system was not known and the database used to provide the irrigation inputs in GaBi professional were used only as a proxy and may not be representative of a typical orchard operation.

Water availability can be a limiting factor in crop production and can potentially have a negative correlation with total kernel total yield (Moldero et al. 2021). Improving the environmental performance may not be as simple as reducing irrigation inputs without first considering other influences to the system. It is recommended that any decisions regarding irrigation requirements should first be considered with other site-specific data such as evapotranspiration rates, soil characteristics, local climate and planting density. Under the reduced irrigation scenarios, emissions associated with nutrient management and machinery operations contributed to a larger overall percentage to the total footprint.

Operation of machinery during the growing season and harvesting can be an energy-intensive process, and harvesting in particular is also associated with other negative environmental impacts in the form of pollution via air-borne particulate matter (Faulkner 2013). While reducing the reliance of machinery, especially during harvest, may be considered as a potential mitigation strategy for reducing environmental footprints, this may affect the overall efficiency of crop recovery, harvesting time, and result in increased costs required for manual labour (Pascuzzi & Santoro 2017). Based on the data available, we cannot say with confidence what the energy requirements and emissions would be for each mechanisation process, but assume that the total contribution from machinery operation will still remain significant to the overall potential footprint.

Emissions associated with fertilisers will vary over space and time, and will also be dependent on other factors such as, the type of fertiliser applied, soil and climate, and the emission factors used (Oertel et al. 2016; Wu et al. 2021). For example, if the New Zealand specific soil emission factor for leaching was used (0.07) it would result in 0.14 kg CO2-eq/kg potential emissions from fertiliser in contrast to 0.17 kg CO2-eq/kg using the emission factor from the IPCC (0.3). This adjustment would bring the total emissions from 1.83 kg CO2-eq/kg to 1.80 kg CO2-eq/kg. If we assumed that the same amount of fertiliser was applied (i.e. 165kg) as calcium ammonium nitrate (CAN) which has an N content of 27%, then the overall emissions associated with fertilisers would be reduced further to 0.08 kg CO2-eq/kg. But, as per the recommendations for irrigation, it is advised that fertiliser inputs be considered with other site-specific information as nutrient requirements will be crop dependent.

In the context of this study, there have been a number of assumptions and approximations made due to the lack of data availability. To help improve the robustness of the LCA model and provide greater confidence in the results, there are a number of recommendations for future assessments:

- A focus on accurate data collection relating to orchard inputs and management practices, and perhaps over a longer time scale. Irrigation, nutrient management, and machinery operations have already been identified as areas that may have the greatest potential impact, but more extensive data will allow more detailed analysis and interpretation. This may reveal hotspots in other areas of the life cycle or reduced impacts from those areas already identified.
- More in-depth sensitivity analysis will allow us to determine how multiple scenarios will influence the results, especially if the limitations of the orchard system are known.
- Looking beyond the farm gate and extending the system boundary to include processing, packaging, distribution etc. may also significantly alter the results. For example Milà i Canals et al. (2007) noted that one of the biggest contributing factors in the apple production life cycle can be related to shipping and transport. This was also true for the kiwifruit supply chain where shipping was one of the greatest impact stages (Mithraratne et al. 2010).
- Considering the utilisation of harvest by-products, i.e. husks and hulls, for use in other process such as feed supplement or for power generation, this could help reduce the overall impact by reducing inputs from other stages. Kendall et al. (2015) found that by using almond by-products, i.e. shell and husks, for the generation of power or as supplementary feed, the overall potential carbon footprint of almond production was reduced from 1.6 to 0.9 kg CO_2-eq/kg.

LCA studies should be used as a tool to make more informed decisions regarding environmental performance. The interpretation of LCA results should be considered alongside other information and environmental metrics, keeping the goal, scope, and functional unit in mind. Where data are unavailable, assumptions about model inputs must be made. This may lead to uncertainties regarding the reliability of the LCA model (Björklund 2002; Bicalho et al. 2017). Furthermore, LCAs do not provide an absolute value in terms of the total environmental impact associated with

LCA Conclusion

Life cycle assessment has been used to evaluate the potential environmental footprint associated with growing almonds in Hawke's Bay and to highlight system hotspots within almond production to the farm gate. Results from this initial assessment found a potential footprint of 1.83 kg CO_2-eq/kg associated with almond production. There is potential to reduce the overall environmental impact of the system but to really understand and determine where they can be made, future assessments should consider accurate data collection of inputs and management practices to provide more confidence in the overall results. Any input changes that are considered should be done so in respect to other inputs to the system and what effects they may have on yield and crop quality. As is the case when considering environmental improvements, there is often a trade-off between one area and another.

5 Acknowledgments

We thank NIWA for providing us access to the VCSN climate database for use in this project. We thank Graham Farnell, Tony Kuklinski and Tessa Leitch for sharing experiences with growing almonds and providing data and other information, and Grant Thorp for helpful discussions.

Funding was provided by Central Hawke's Bay District Council, Hastings District Council, Hawke's Bay Regional Council, Wairoa District Council, and Picot Productions and Tony Kuklinski.

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Appendix 1. LCA model inputs and data

Pesticide production data

a) Data relating to production and transport taken from Müller et al. (2011); b) RoW refers to "rest of world" database in GaBi Professional and is based on global average for production; c) product was assumed to be formulated in Europe and shipped to New Zealand via Australia.

Pesticide (a, b, c, d)	**Active ingredient**	**Function**
Roundup® (a)	Glyphosate	Herbicide
Goal 2XL® (b, c)	Oxyfluorfen	Herbicide
Matrix® SG (b, c)	Rimsulfuron	Herbicide
Vanguard® WG (b, c)	Cyprodinil	Fungicide
Pristine® (b, c)	Pyraclostobin	Fungicide
Bravo-Weatherstik® (b, c)	Chlorothalonil	Fungicide
Abamectin® 0.15 EC (b, c)	Abamectin	Insecticide
Intrepid 2F® (b, c)	methoxyfenozide	Insecticide
Clinch® 9 (b, c)	Abamectin	Insecticide

Pesticide transport data.

Location, transport and distances considered for pesticide production (excluding glyphosate).

Location	**Transport**	**Distance (km)**
Leverkusen – Hamburg	Rail	346
Hamburg – Brisbane	Ship	12224
Brisbane Port to Factory	Truck	25
Brisbane – Sydney	Ship	952
Sydney – Auckland	Ship	2359
Auckland – Napier	Truck	414

Fertiliser production data

Reference to fertiliser database used for fertiliser production.

Fertiliser	**LCI data base**
Potassium Chloride (KCL)	EU-28: Potassium Chloride (GaBi Professional)
Urea (46%)	EU-28: Urea (46%) (GaBi Professional)

Fertiliser transport data

Location, transport and distances considered for fertiliser production.

Product	Location	Transport	Distance (km)
KCl	Hamburg – Napier	Ship	13550
Urea (46%)	Kapuni (Taranaki) – Napier	Truck	372

Orchard inputs

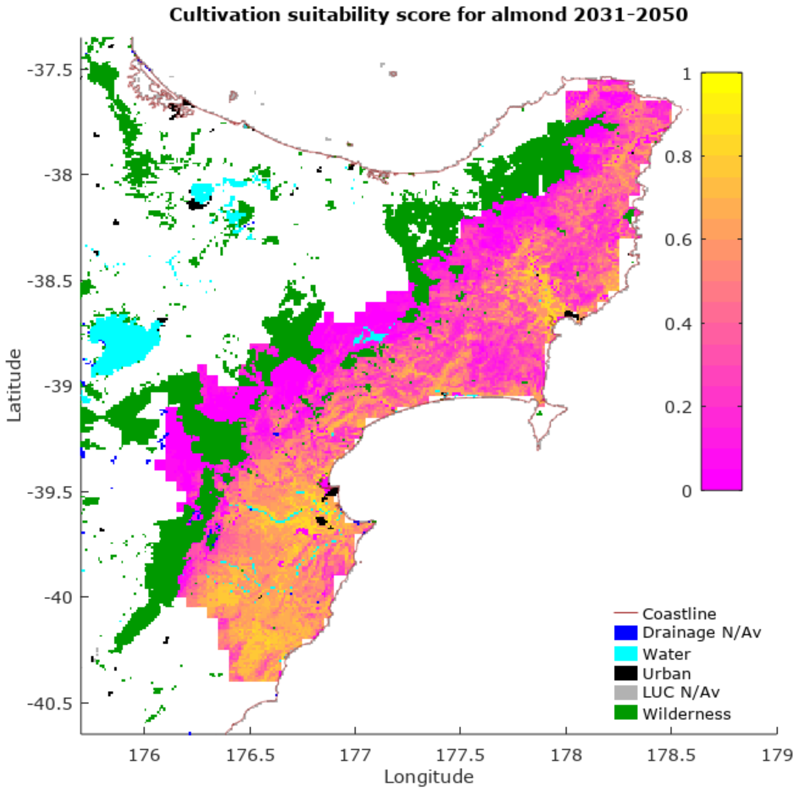
Orchard inputs used for LCA model; a) information taken from (Duncan et al. 2019); b) data base used to model irrigation inputs (CH irrigation); c) database used for gas inputs (AU Natural gas Mix); d) database used for diesel inputs (AU diesel mix at refinery).

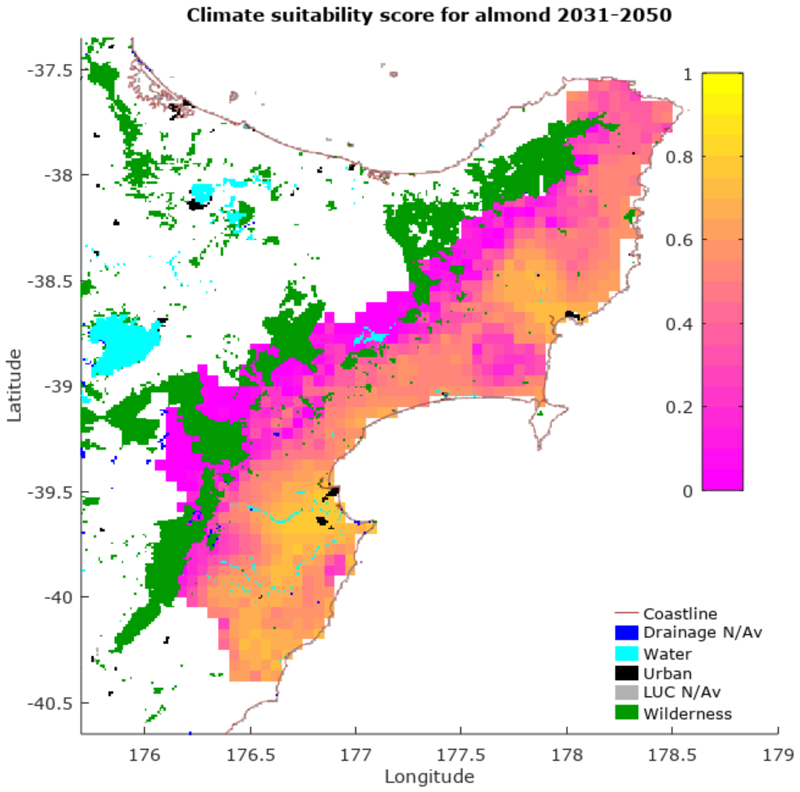
Orchard Operation (a, b, c, d)	Input	Amount	Unit
Spraying (a)	Roundup®	3.45	L/ha
Spraying (a)	Goal®	1.11	L/ha
Spraying (a)	Matrix SG®	0.27	kg/ha
Spraying (a)	Vanguard WG®	0.34	kg/ha
Spraying (a)	Pristine®	0.58	L/ha
Spraying (a)	Bravo Weatherstik®	3.5	L/ha
Spraying (a)	Abamectin®	0.36	L/ha
Spraying (a)	Intrepid 2F®	3.36	kg/ha
Spraying (a)	Clinch®	0.55	kg/ha
Fertiliser (a)	Urea	165	kg/ha
Fertiliser (a)	KCL	392	kg/ha
Irrigation (a, b)	water	12	ML/ha
Gas for Machinery (a, c)	Natural Gas	25	L/ha
Diesel for Machinery (a, d)	Diesel	166	L/ha

Appendix 2. Climate projection maps

RCP 8.5 2031 to 2050

Climate suitability projections




Climate suitability score for almond 2031-2050
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-38
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-39
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Latitude
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177
177.5
178
178.5
179
Longitude
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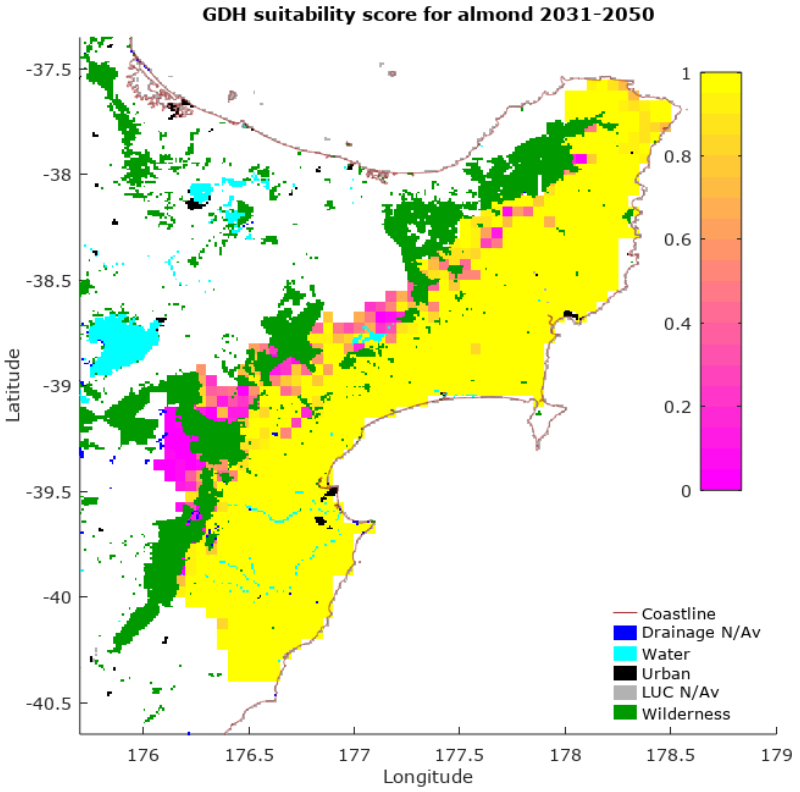
0.4
0.2
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GDH suitability score for almond 2031-2050
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Latitude
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177.5
178
178.5
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Longitude
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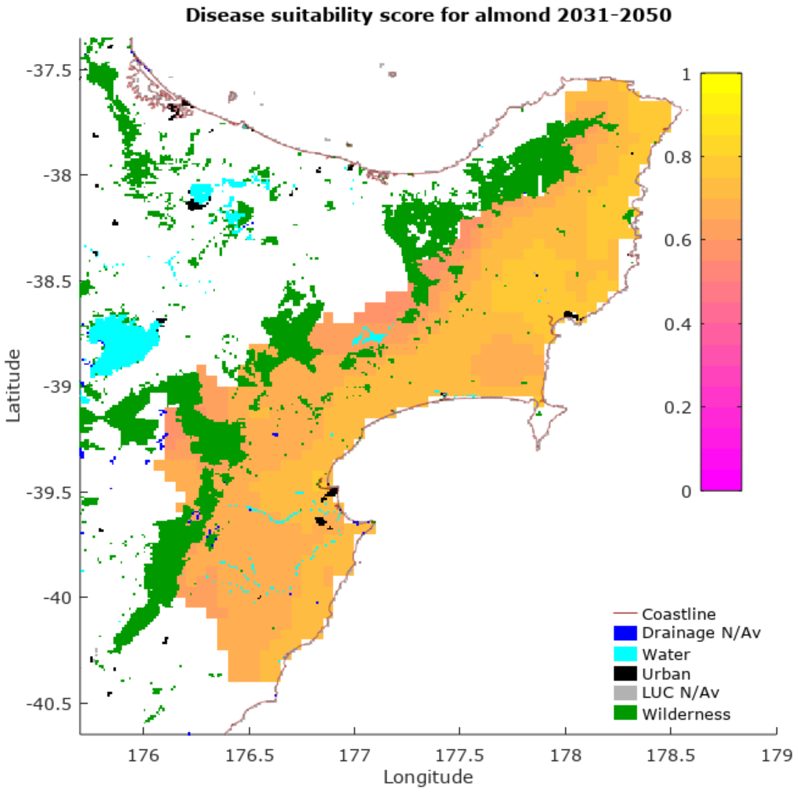
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Disease suitability score for almond 2031-2050
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Longitude
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177
177.5
178
178.5
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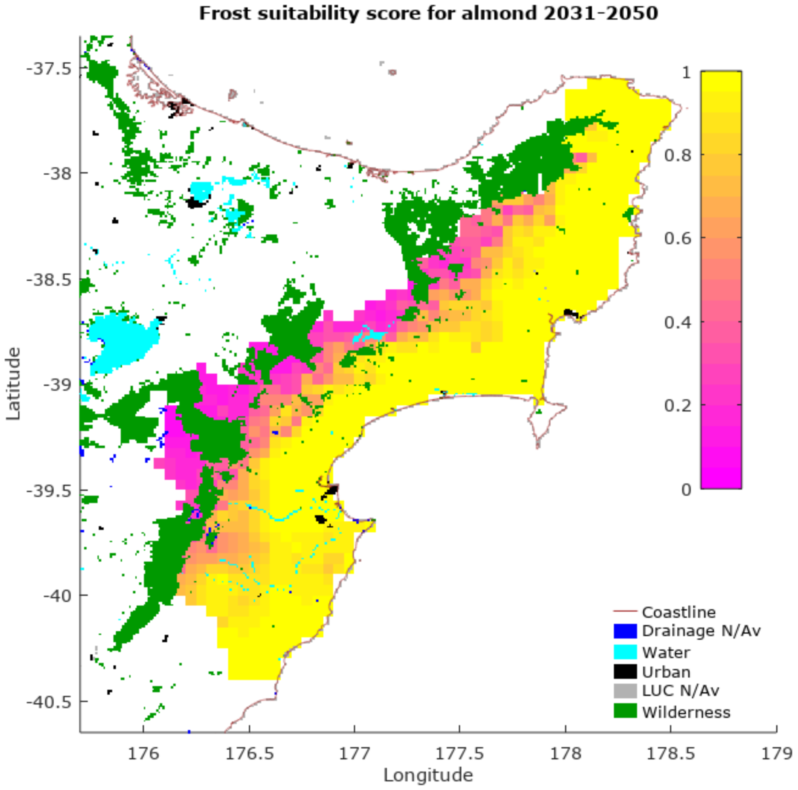
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Frost suitability score for almond 2031-2050
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Longitude
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177
177.5
178
178.5
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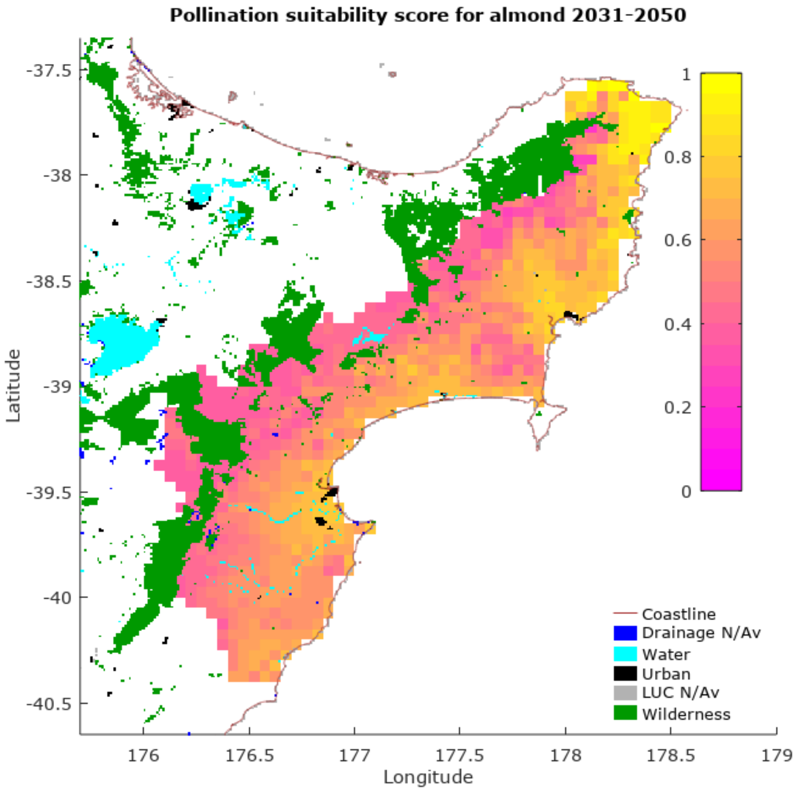
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Pollination suitability score for almond 2031-2050
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Latitude
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177.5
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178.5
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Longitude
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Coastline
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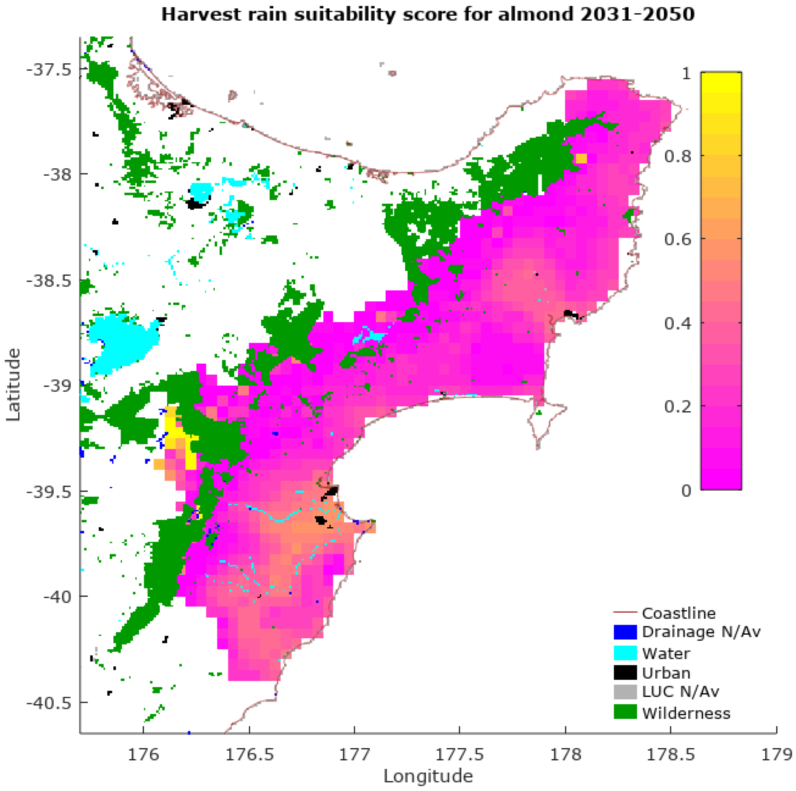
Water
Urban
LUC N/Av
Wilderness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177.5
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178.5
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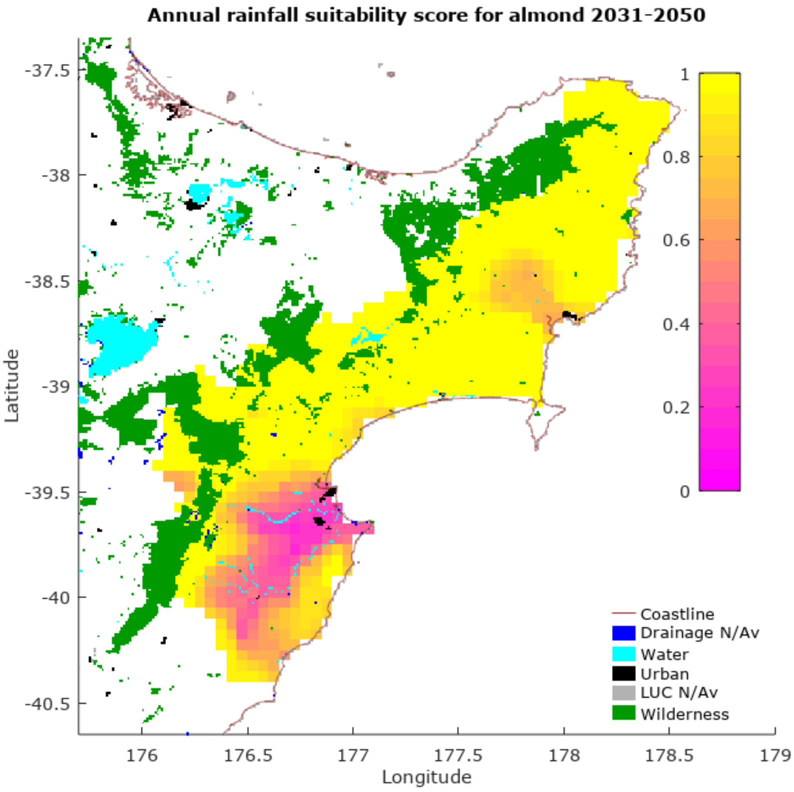
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Annual rainfall suitability score for almond 2031-2050
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Longitude
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177
177.5
178
178.5
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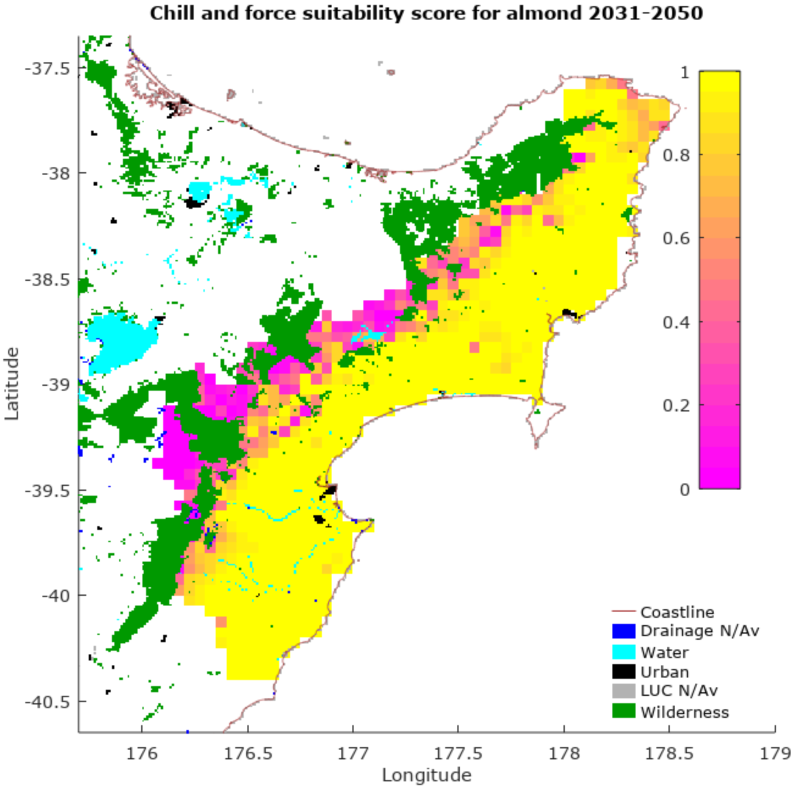
0.2
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Chill and force suitability score for almond 2031-2050
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Longitude
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177.5
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178.5
179
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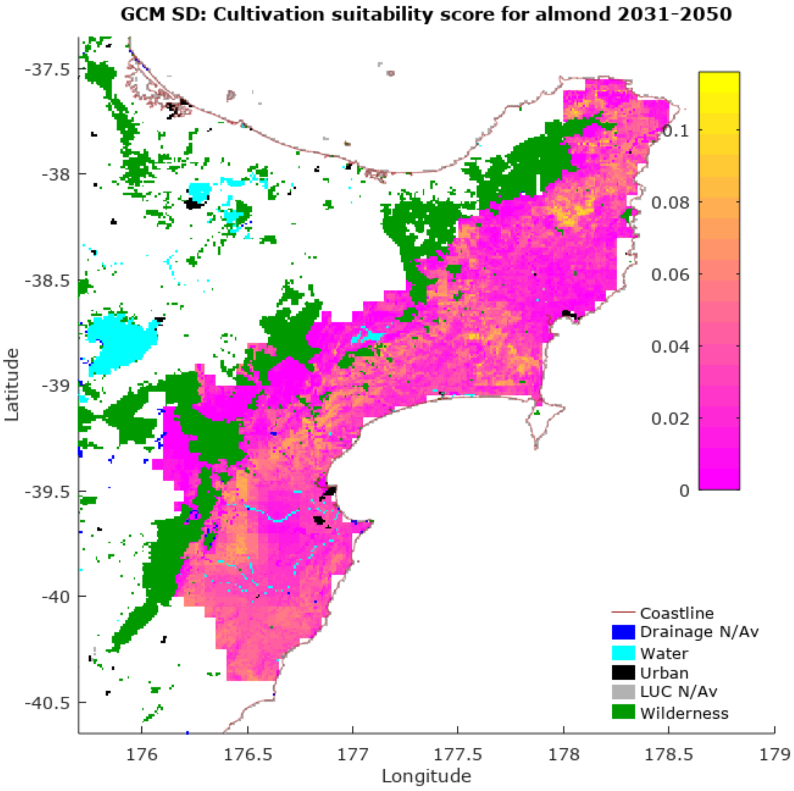
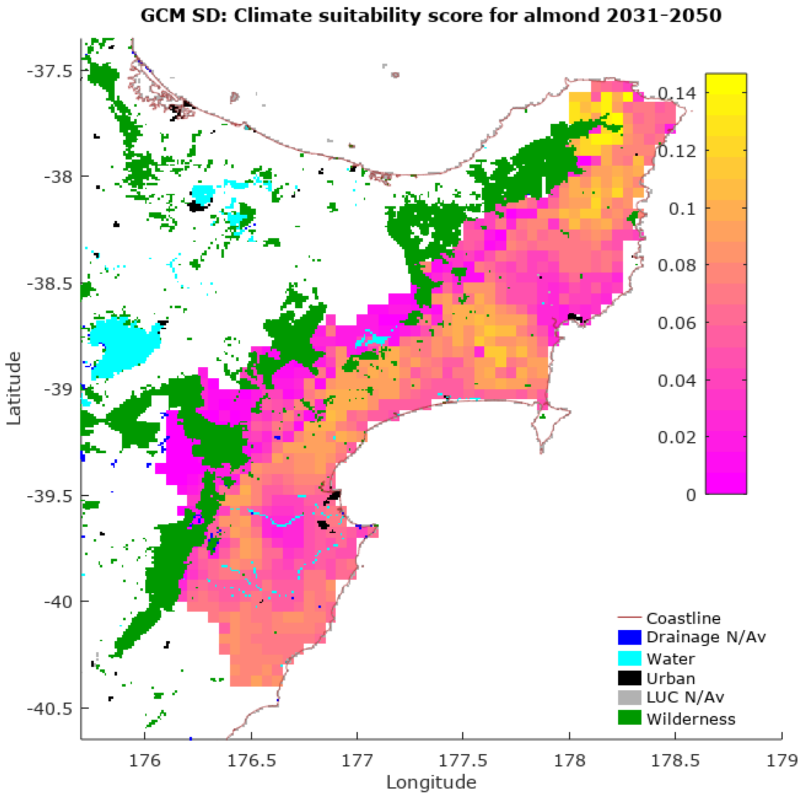
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

Standard deviation (SD) of projections




GCM SD: Climate suitability score for almond 2031-2050
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Longitude
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177
177.5
178
178.5
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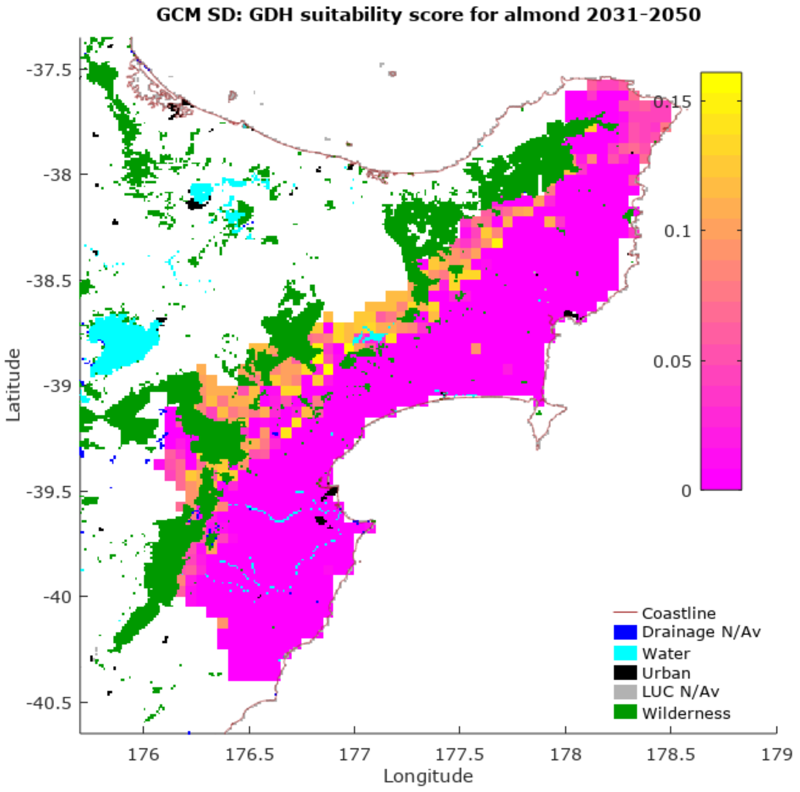
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: GDH suitability score for almond 2031-2050
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-40.5
Longitude
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176.5
177
177.5
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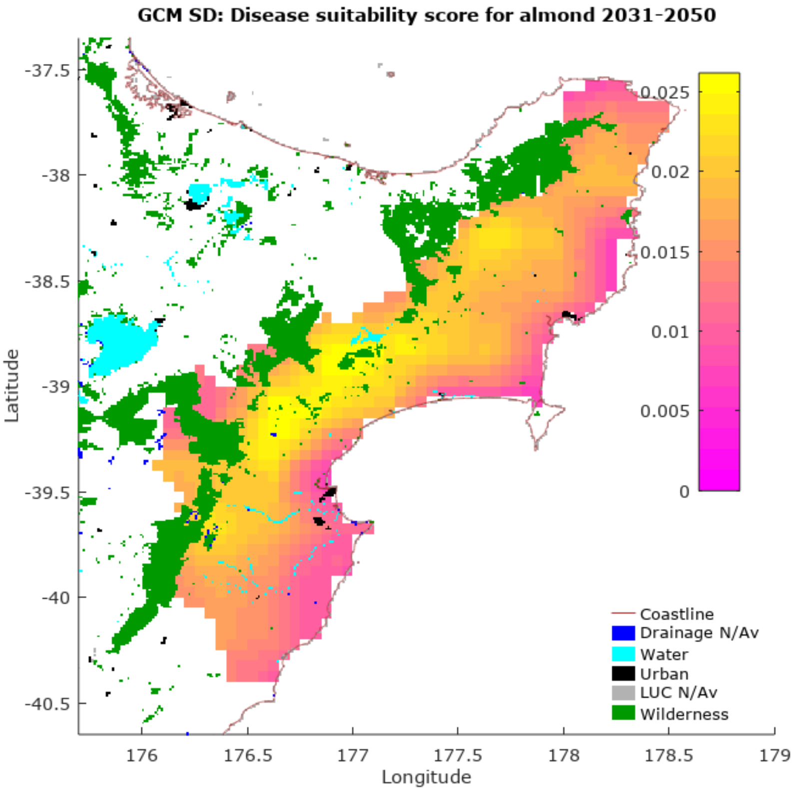
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Disease suitability score for almond 2031-2050
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-40.5
Latitude
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177
177.5
178
178.5
179
Longitude
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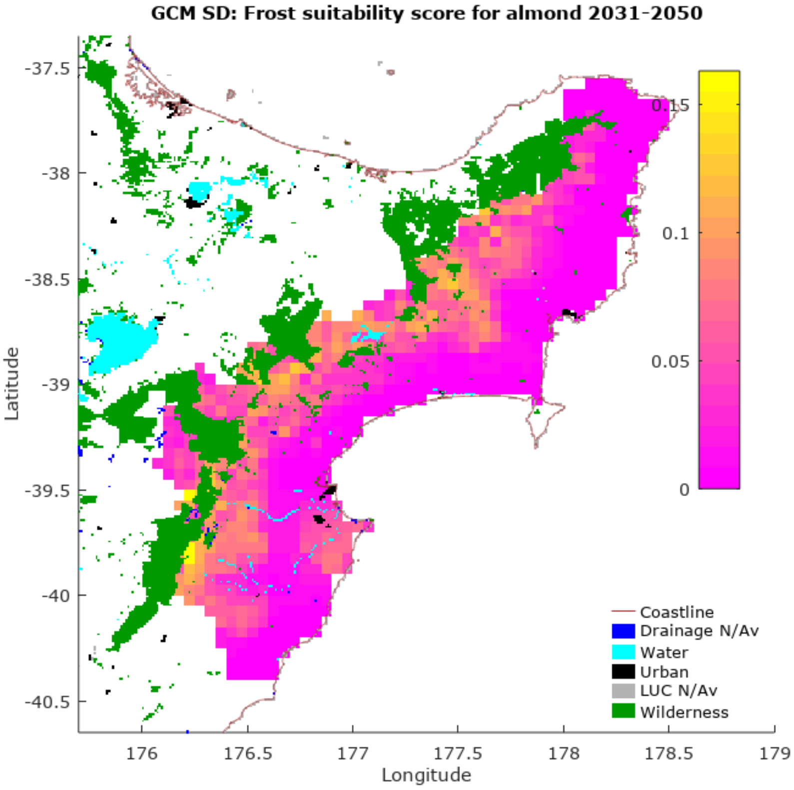
Water
Urban
LUC N/Av
Wilderness


GCM SD: Frost suitability score for almond 2031-2050
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177
177.5
178
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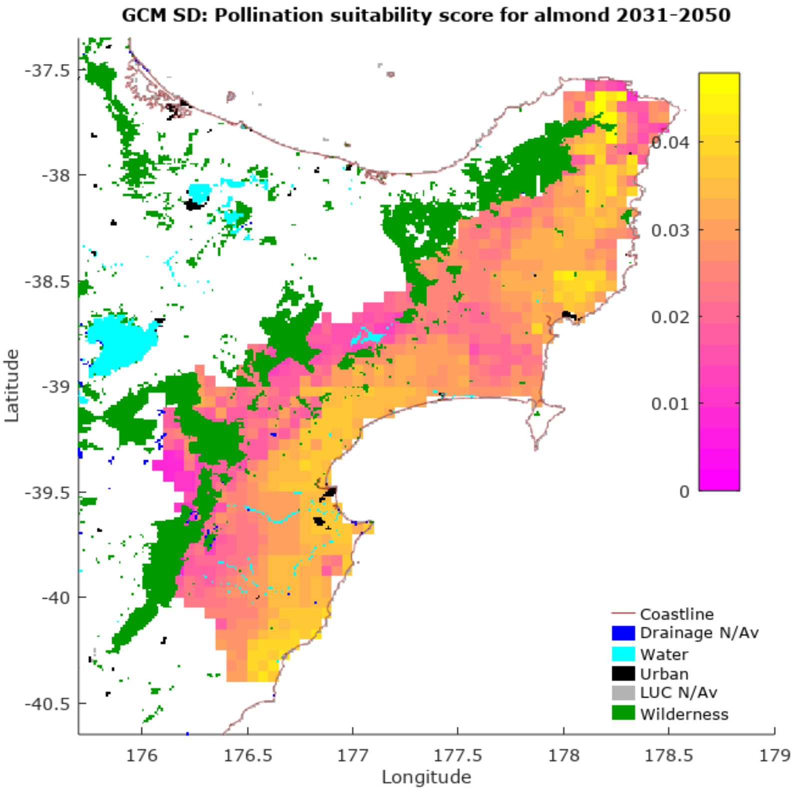
Water
Urban
LUC N/Av
Wilderness


GCM SD: Pollination suitability score for almond 2031-2050
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Longitude
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176.5
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178
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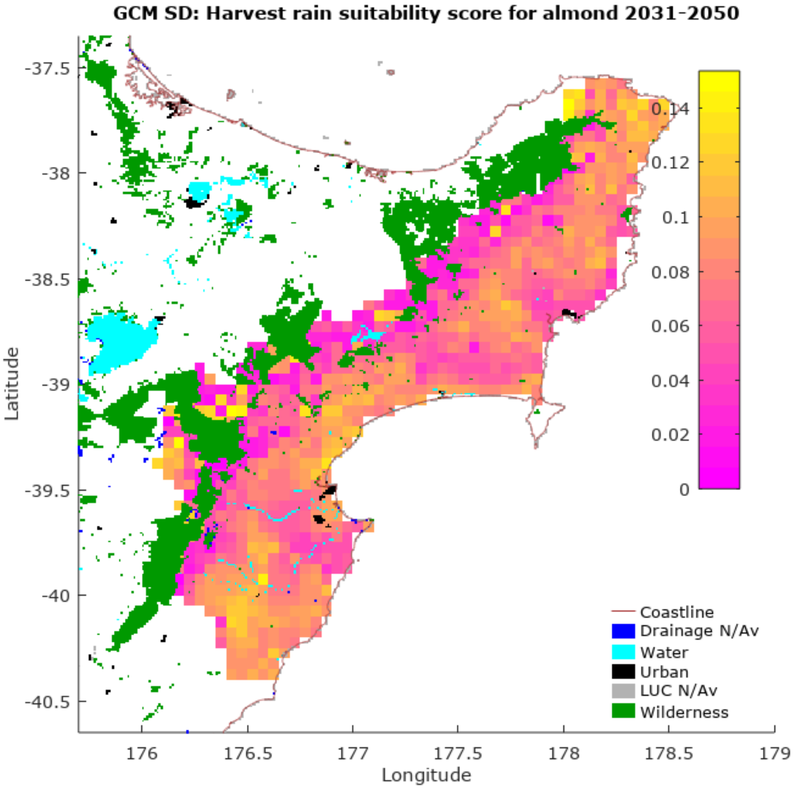
Water
Urban
LUC N/Av
Wilderness


GCM SD: Harvest rain suitability score for almond 2031-2050
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Longitude
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176.5
177
177.5
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179
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Coastline
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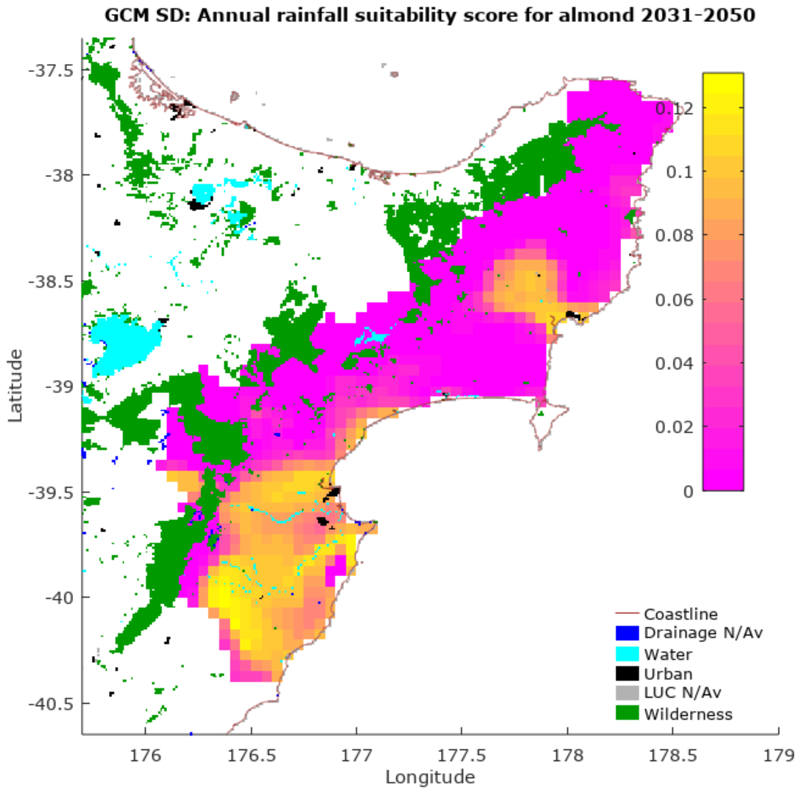
Water
Urban
LUC N/Av
Wilderness


GCM SD: Annual rainfall suitability score for almond 2031-2050
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Longitude
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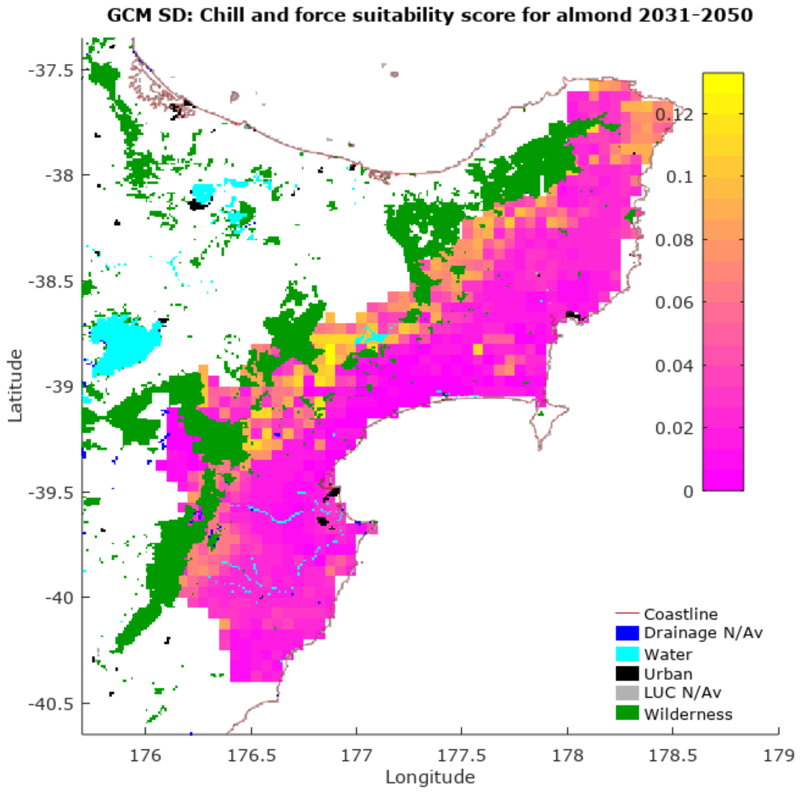
Water
Urban
LUC N/Av
Wilderness


GCM SD: Chill and force suitability score for almond 2031-2050
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177
177.5
178
178.5
179
Longitude
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0.08
0.06
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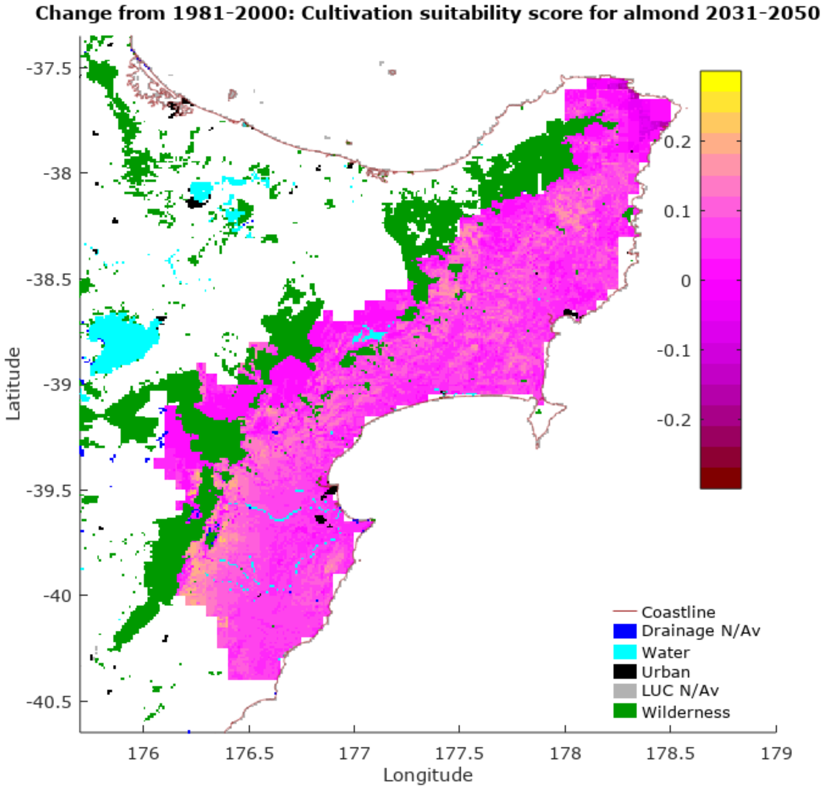
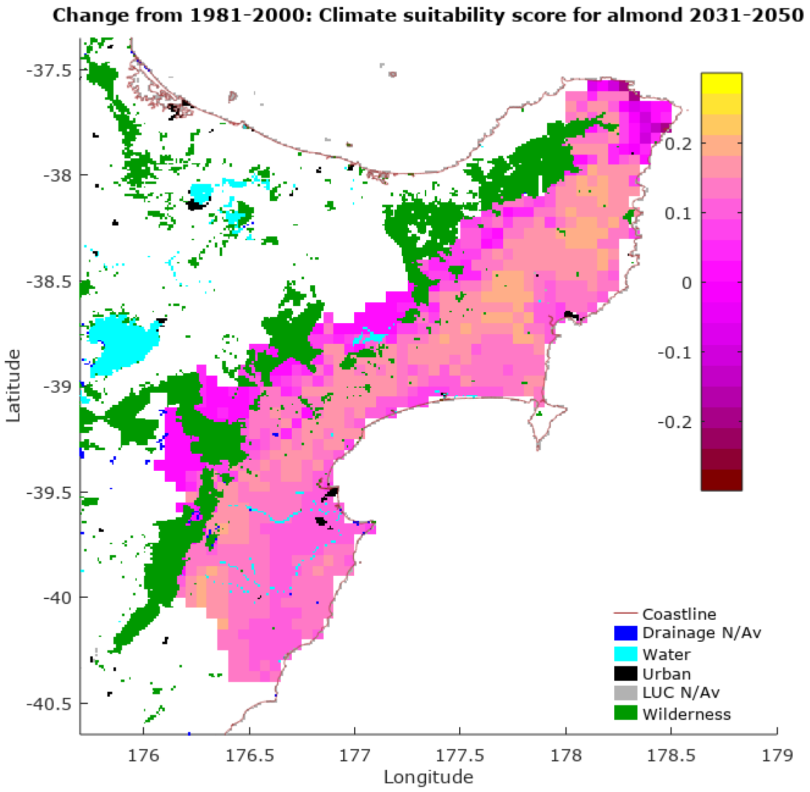
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

Projected change from 1981–2000 (RCP Past period)




Change from 1981-2000: Climate suitability score for almond 2031-2050
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178.5
179
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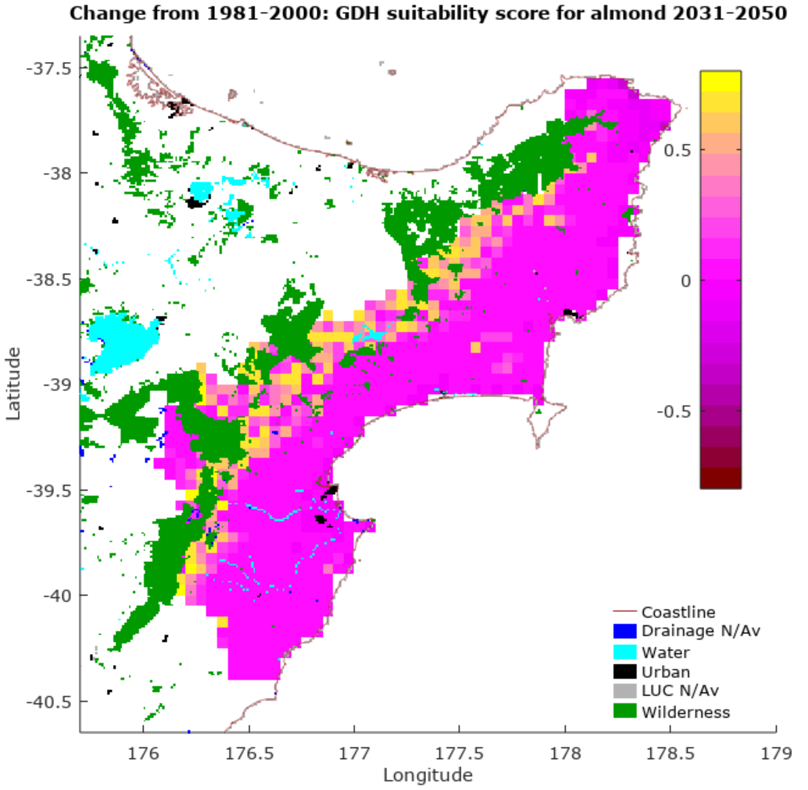
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness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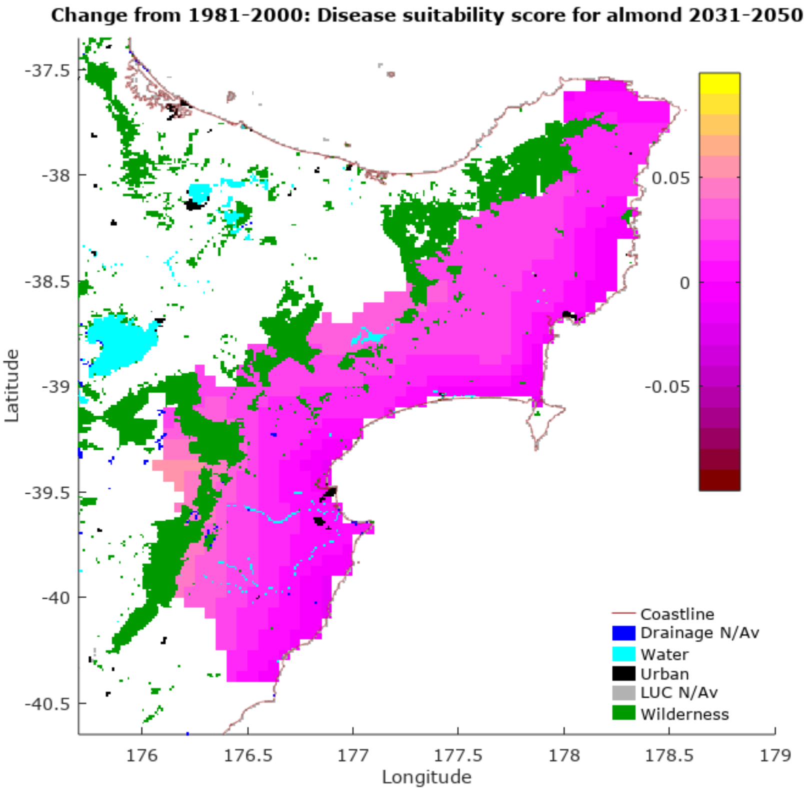
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Disease suitability score for almond 2031-2050
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Longitude
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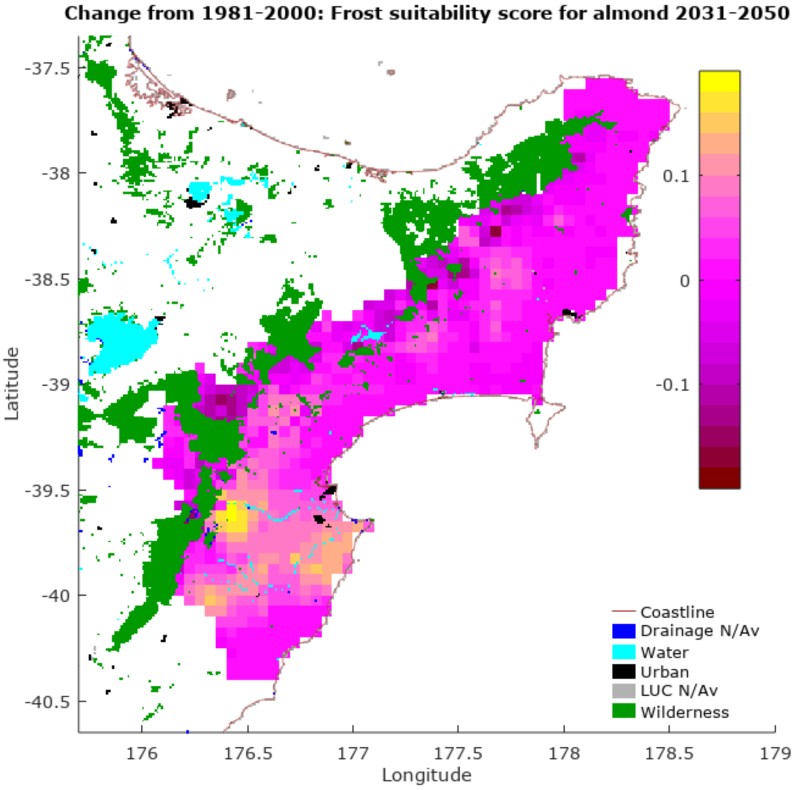
Water
Urban
LUC N/Av
Wilderness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Longitude
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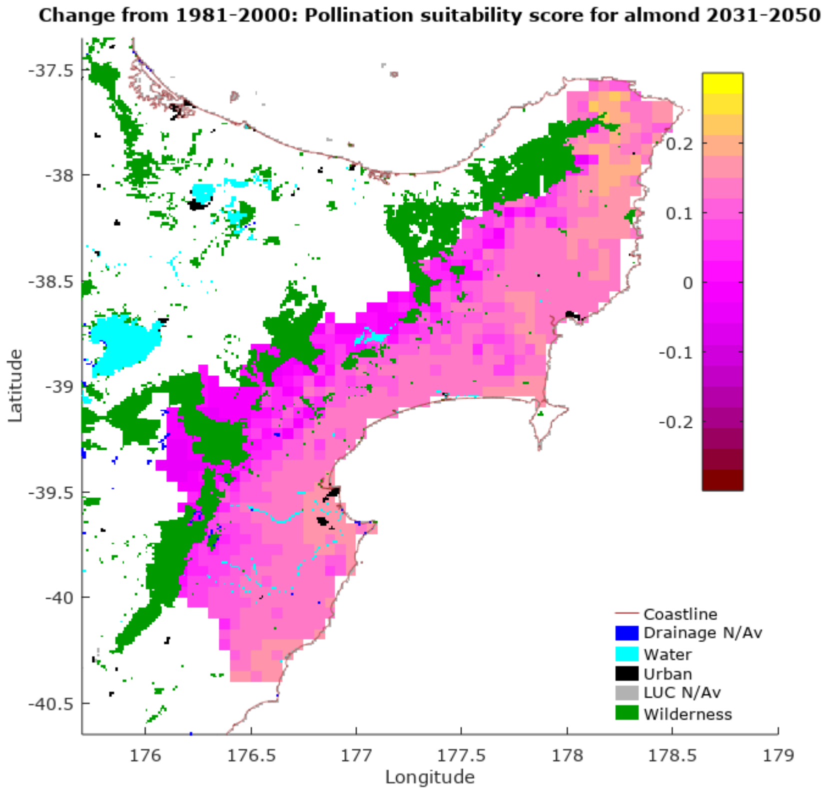
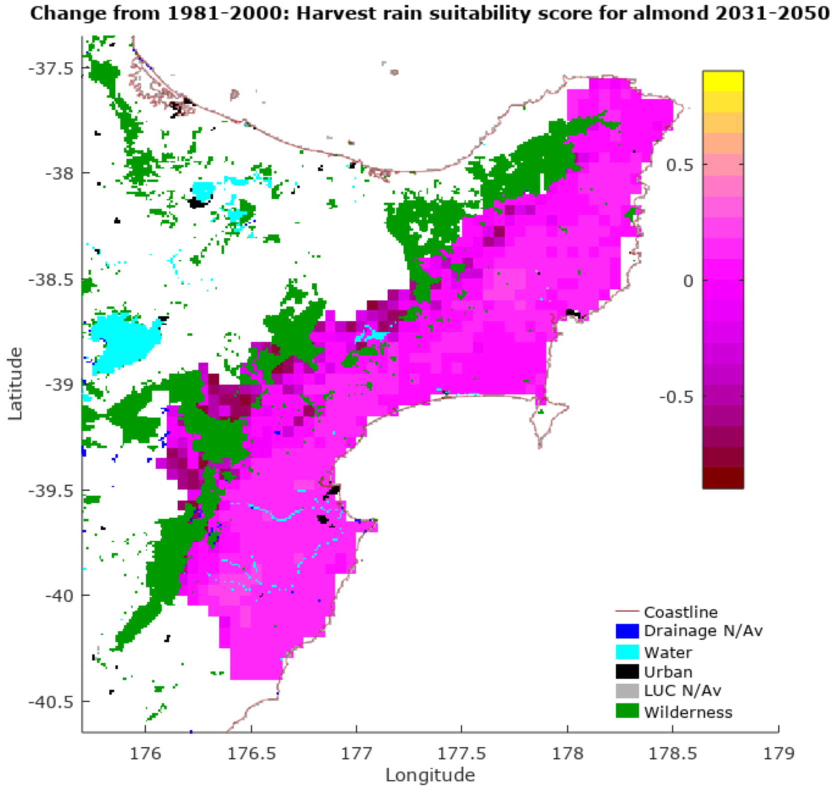
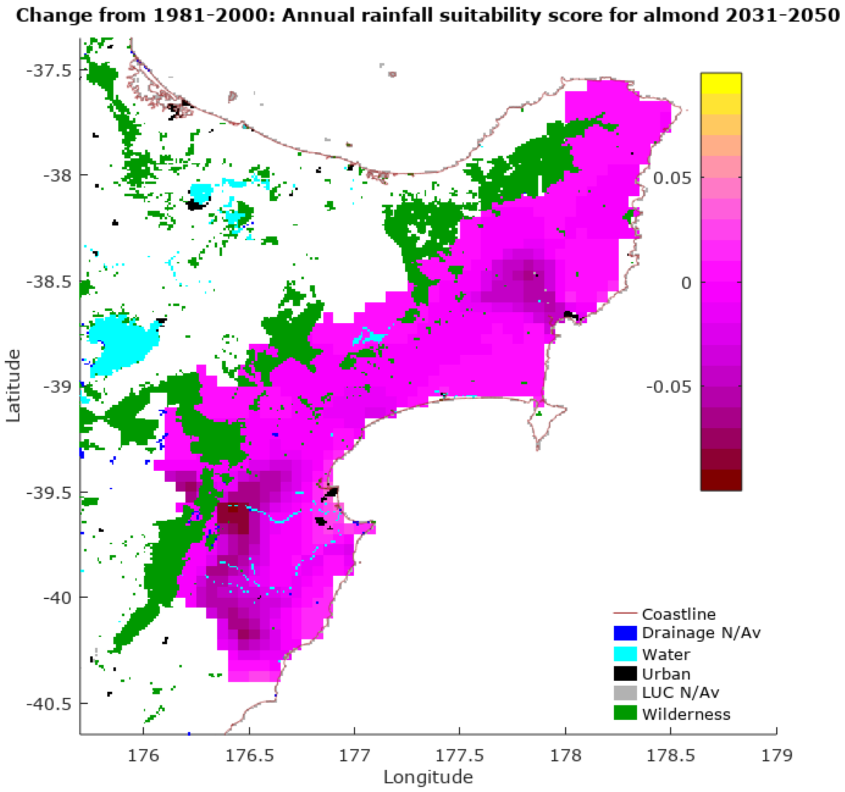
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness



Change from 1981-2000: Pollination suitability score for almond 2031-2050



Change from 1981-2000: Harvest rain suitability score for almond 2031-2050


Change from 1981-2000: Annual rainfall suitability score for almond 2031-2050
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Longitude
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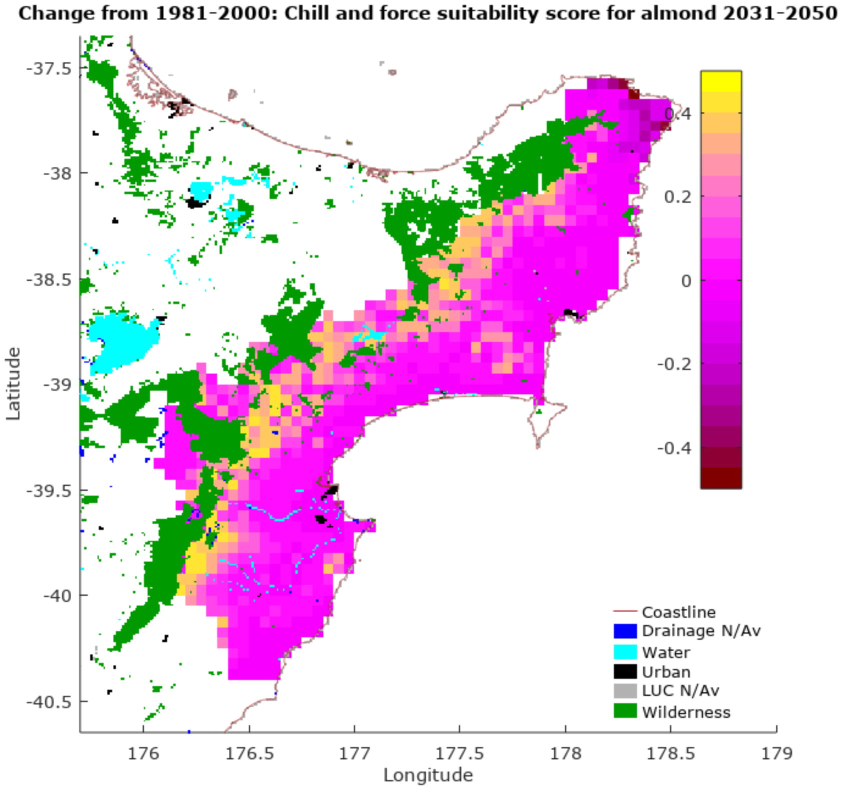
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Chill and force suitability score for almond 2031-2050
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Longitude
176
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177
177.5
178
178.5
179
0.4
0.2
0
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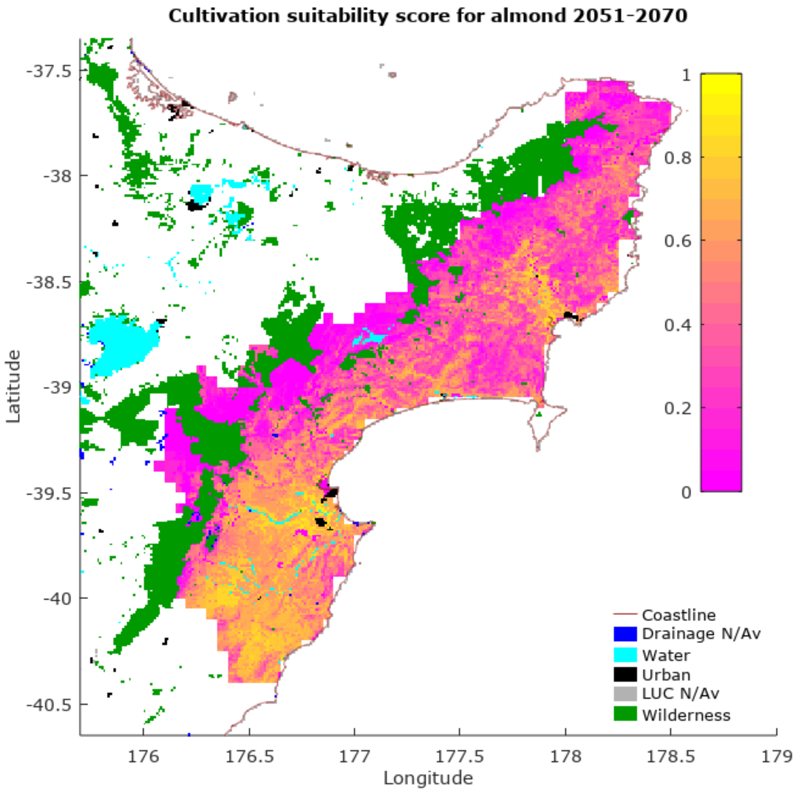
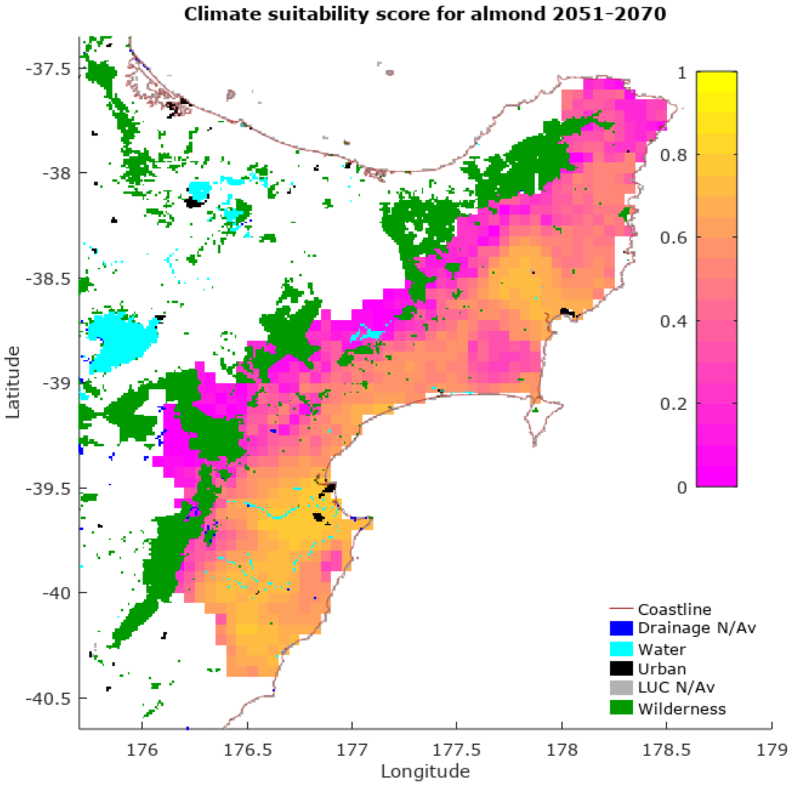
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

RCP 8.5 2051 to 2070

Climate suitability projections

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Longitude
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176.5
177
177.5
178
178.5
179
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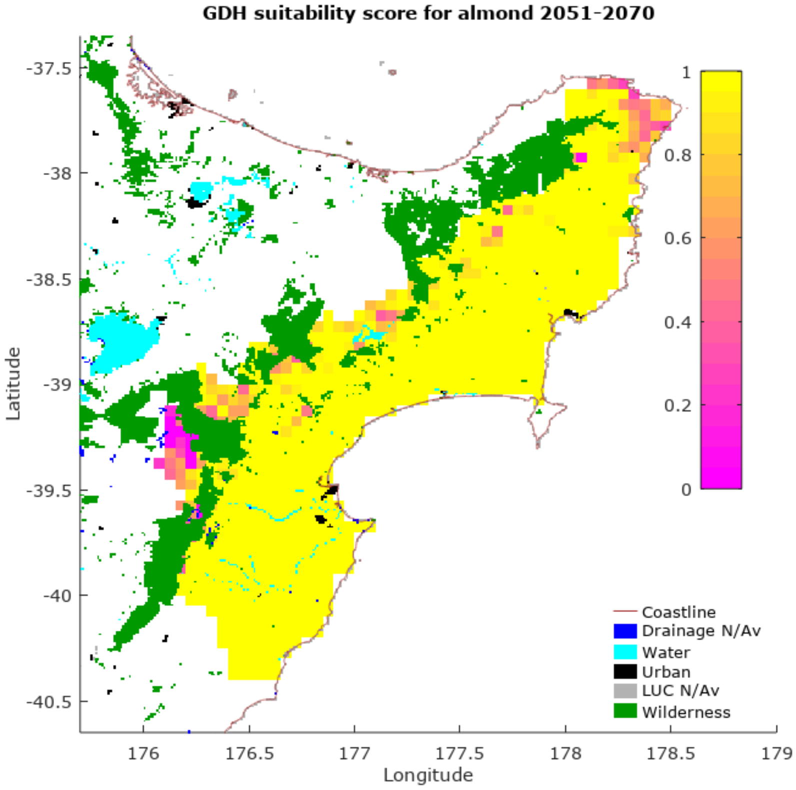
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GDH suitability score for almond 2051-2070
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Longitude
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-40
-40.5
176
176.5
177
177.5
178
178.5
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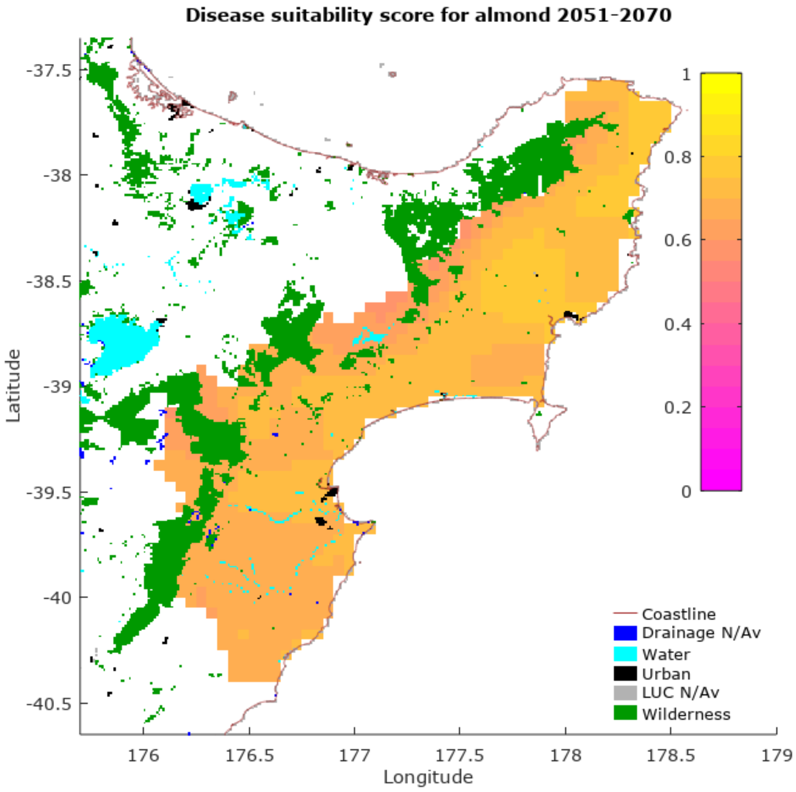
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Disease suitability score for almond 2051-2070
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Longitude
176
176.5
177
177.5
178
178.5
179
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0.8
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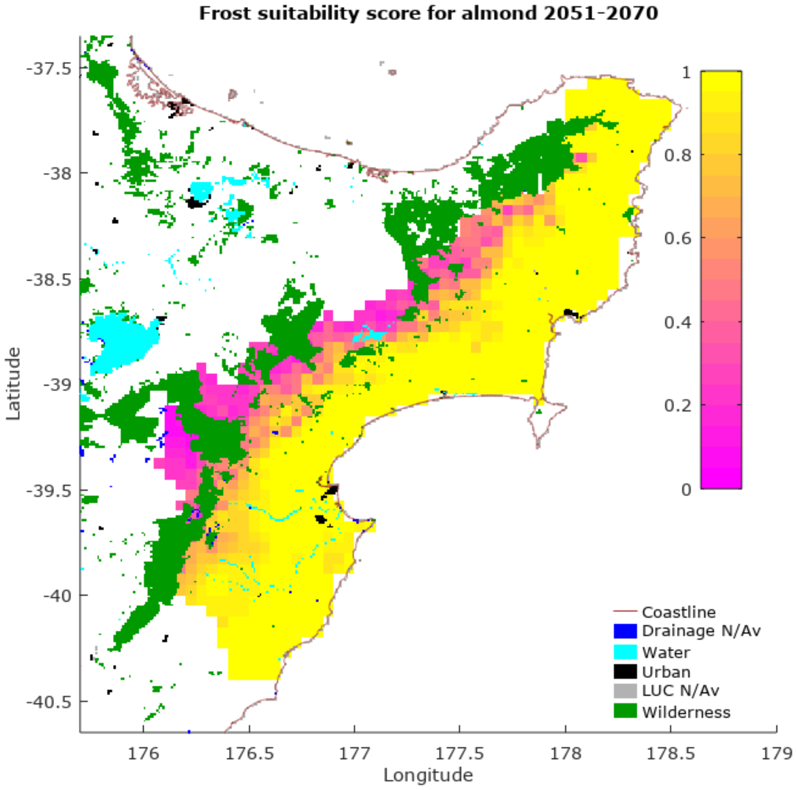
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Frost suitability score for almond 2051-2070
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Longitude
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Coastline
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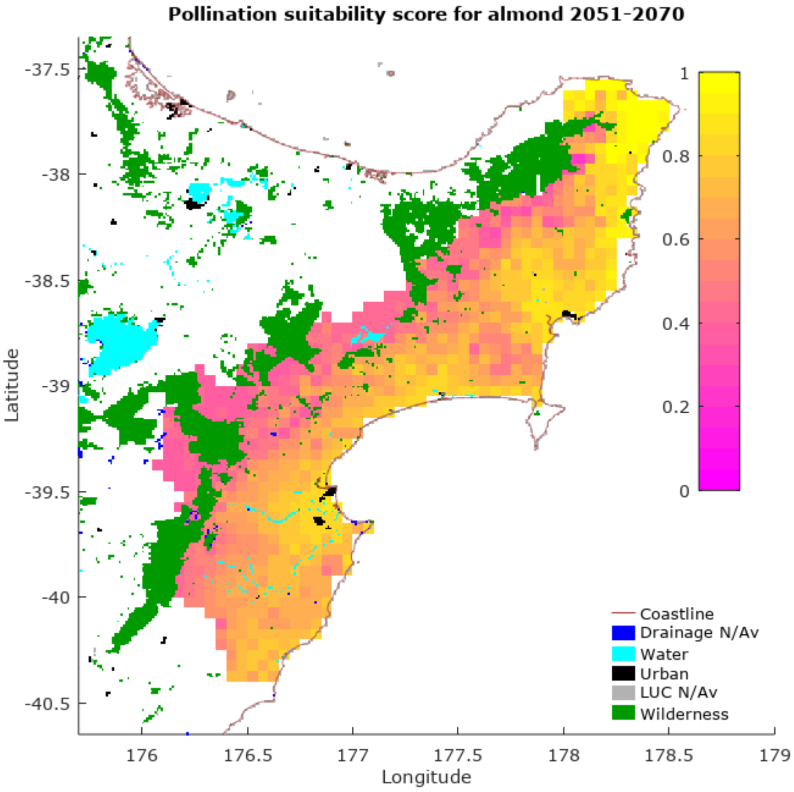
Water
Urban
LUC N/Av
Wilderness


Pollination suitability score for almond 2051-2070
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Longitude
176
176.5
177
177.5
178
178.5
179
1
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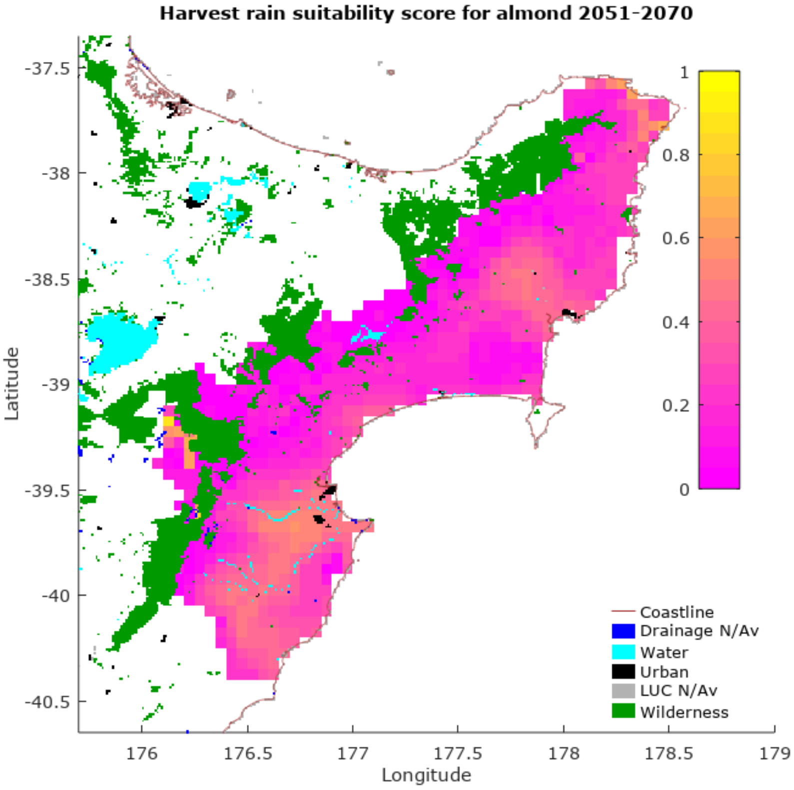
0.6
0.4
0.2
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Harvest rain suitability score for almond 2051-2070
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-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
1
0.8
0.6
0.4
0.2
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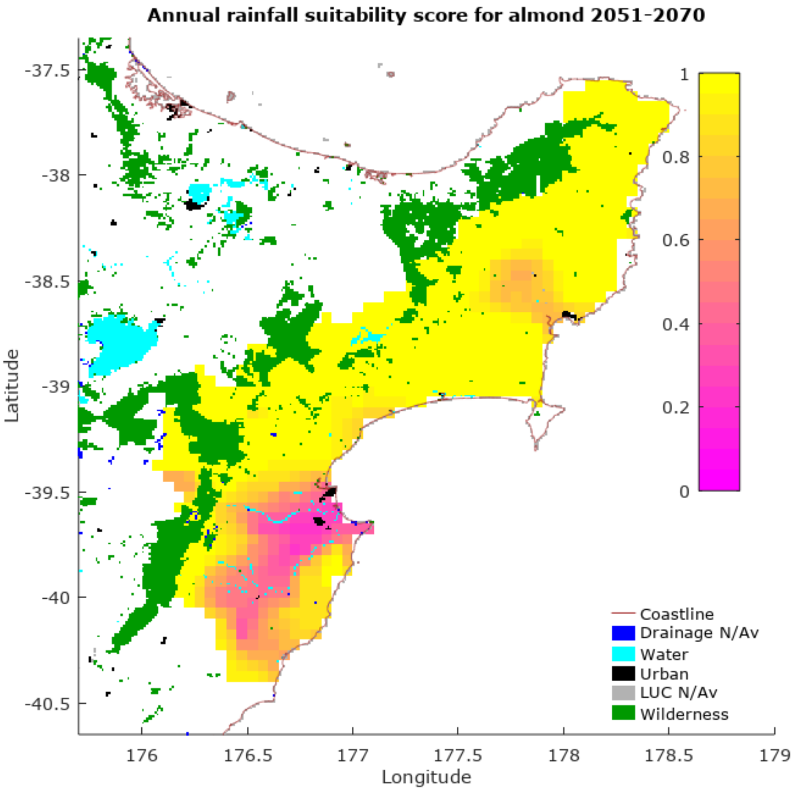
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Annual rainfall suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
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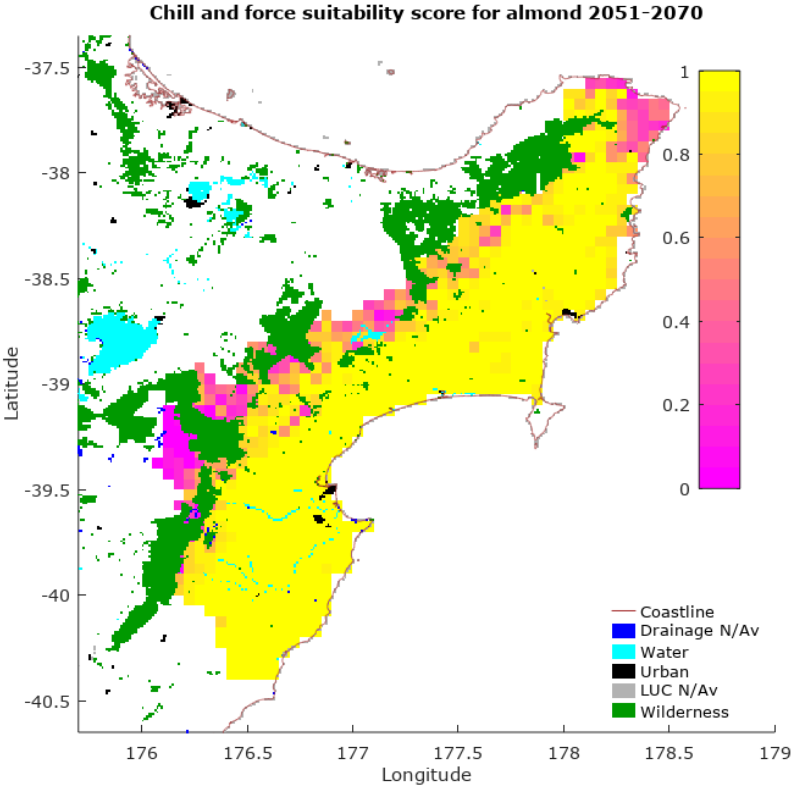
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Chill and force suitability score for almond 2051-2070
Latitude
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-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
1
0.8
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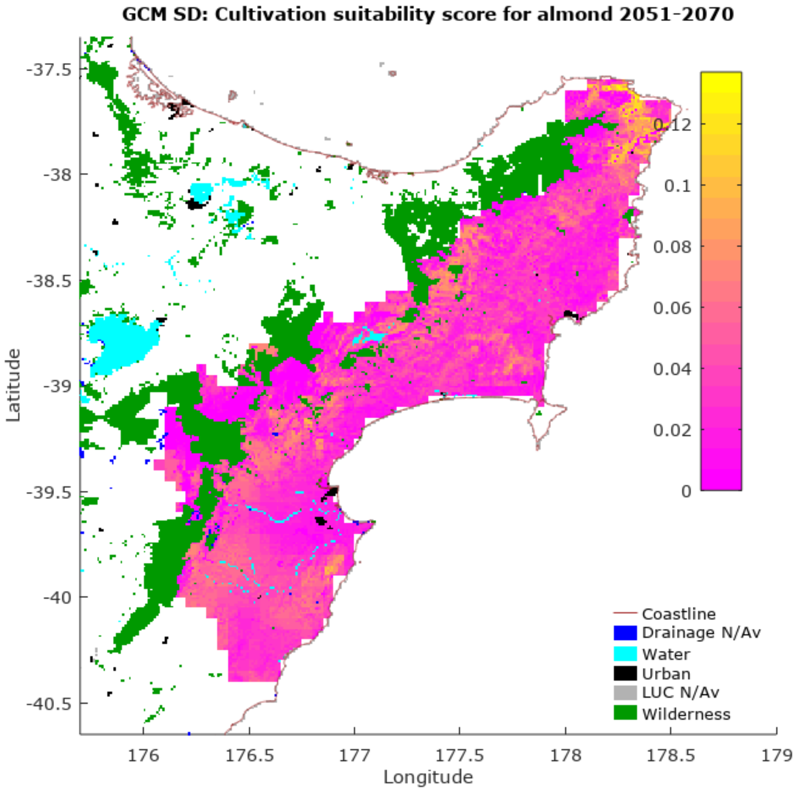
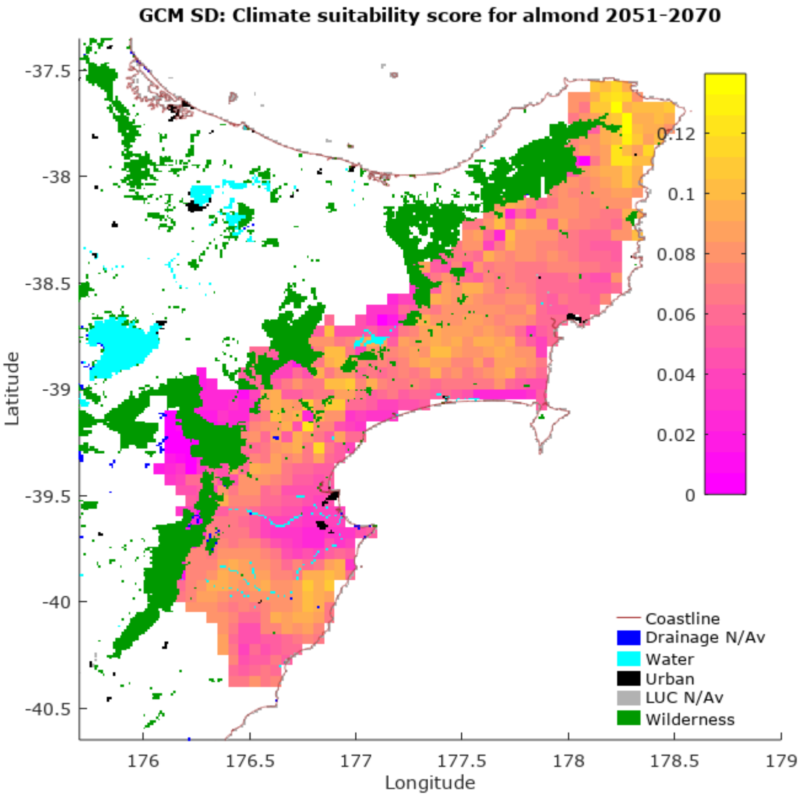
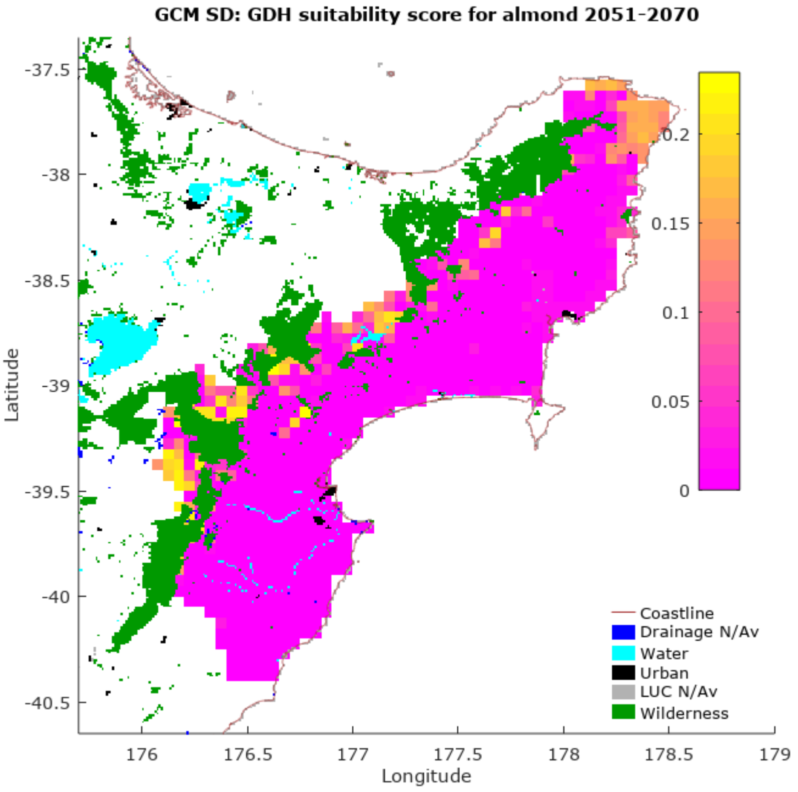
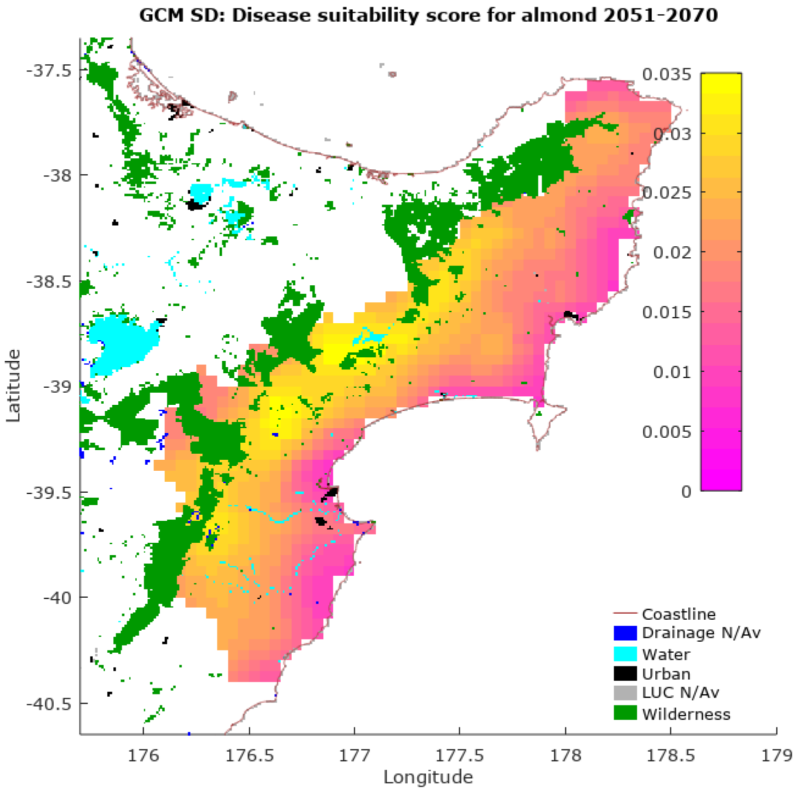
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

Standard deviation (SD) of projections




GCM SD: Climate suitability score for almond 2051-2070


GCM SD: GDH suitability score for almond 2051-2070


GCM SD: Disease suitability score for almond 2051-2070
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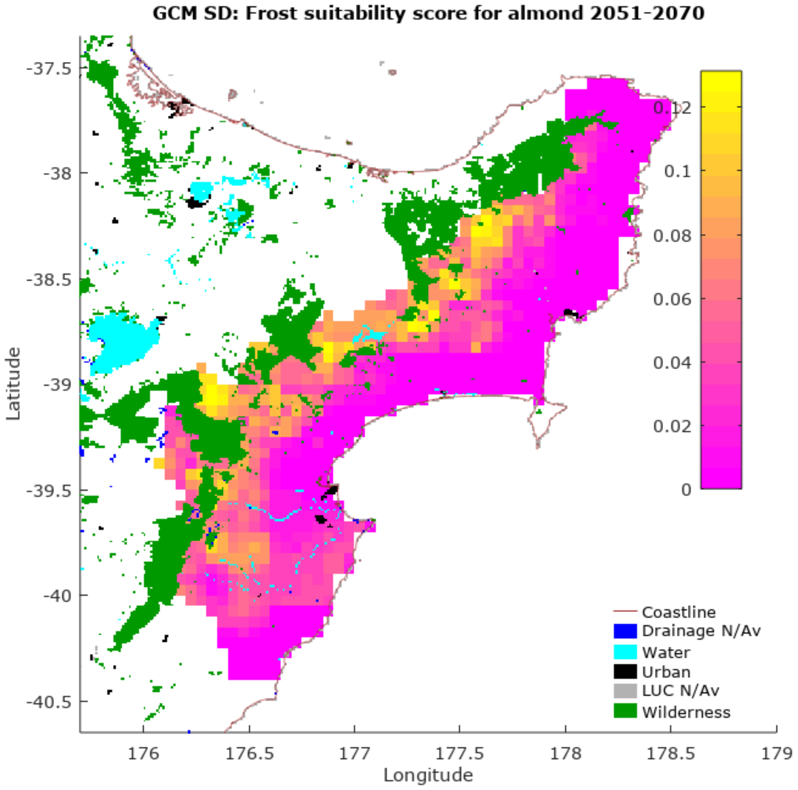
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Frost suitability score for almond 2051-2070
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-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.12
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0.04
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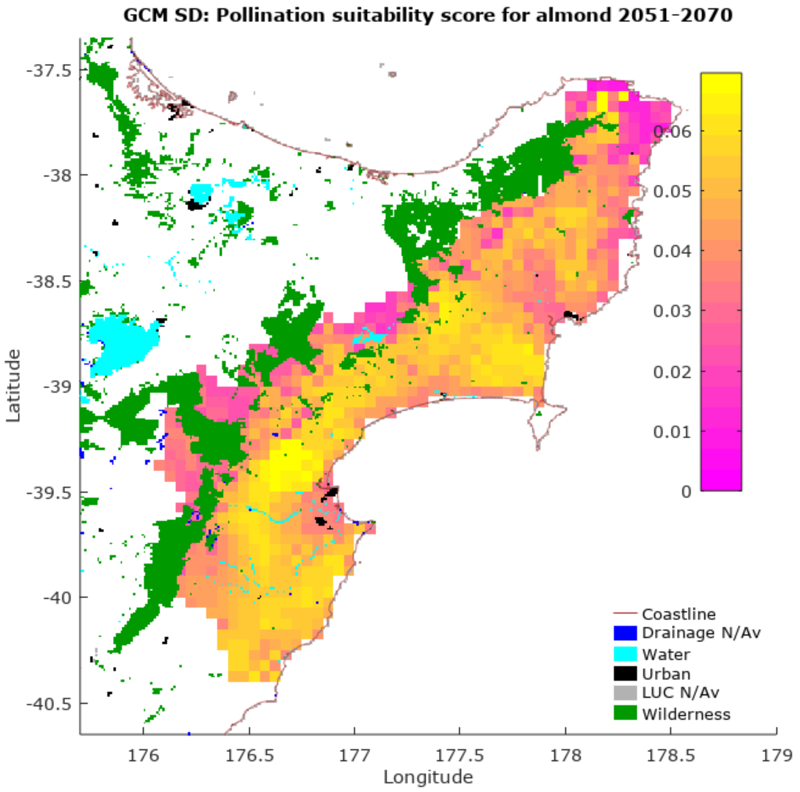
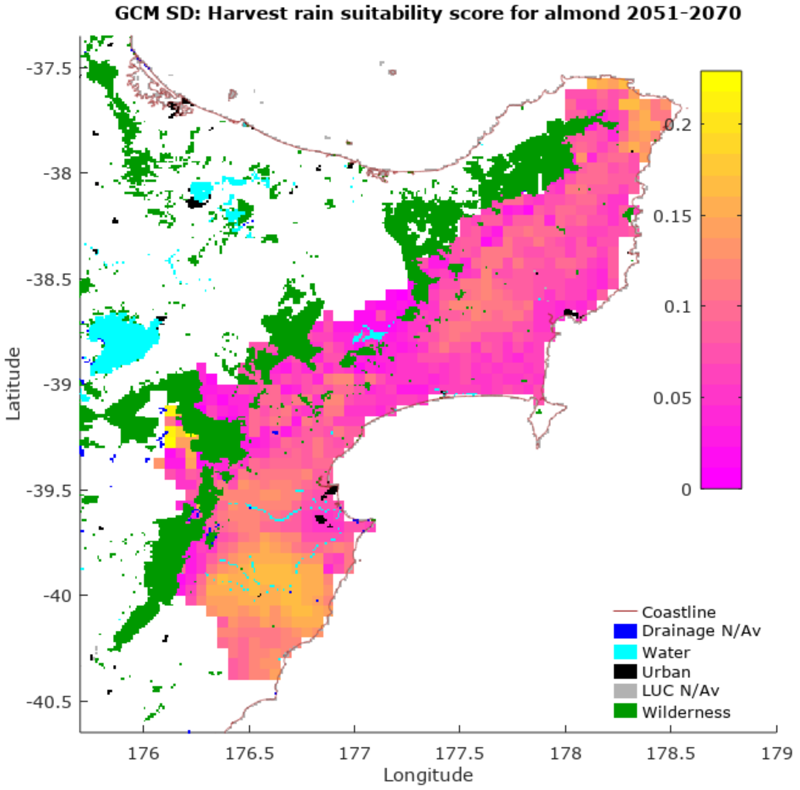
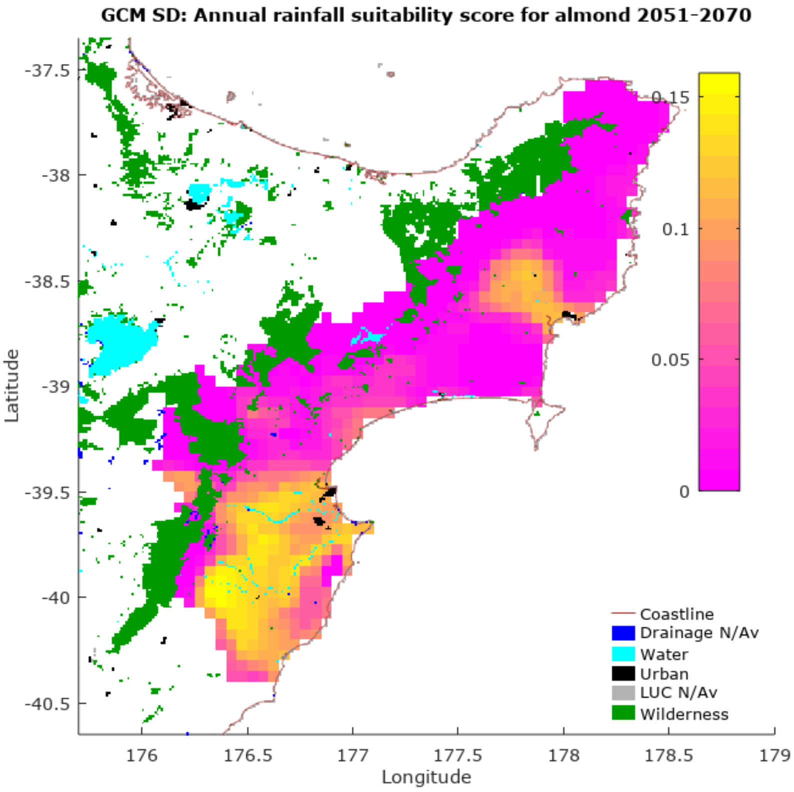
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Pollination suitability score for almond 2051-2070


GCM SD: Harvest rain suitability score for almond 2051-2070


GCM SD: Annual rainfall suitability score for almond 2051-2070
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-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
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179
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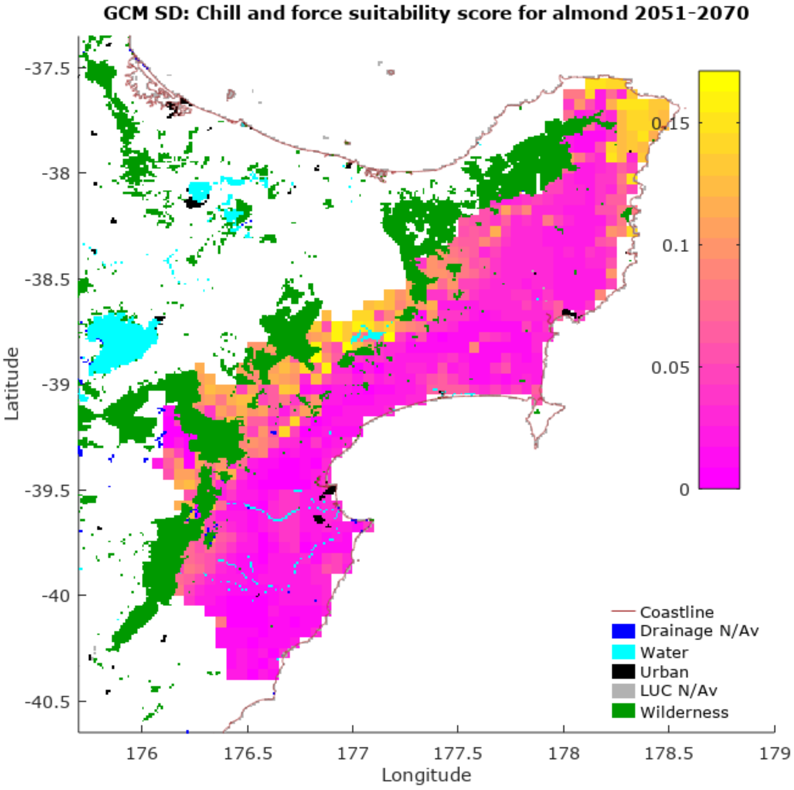
0.1
0.05
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Chill and force suitability score for almond 2051-2070
Latitude
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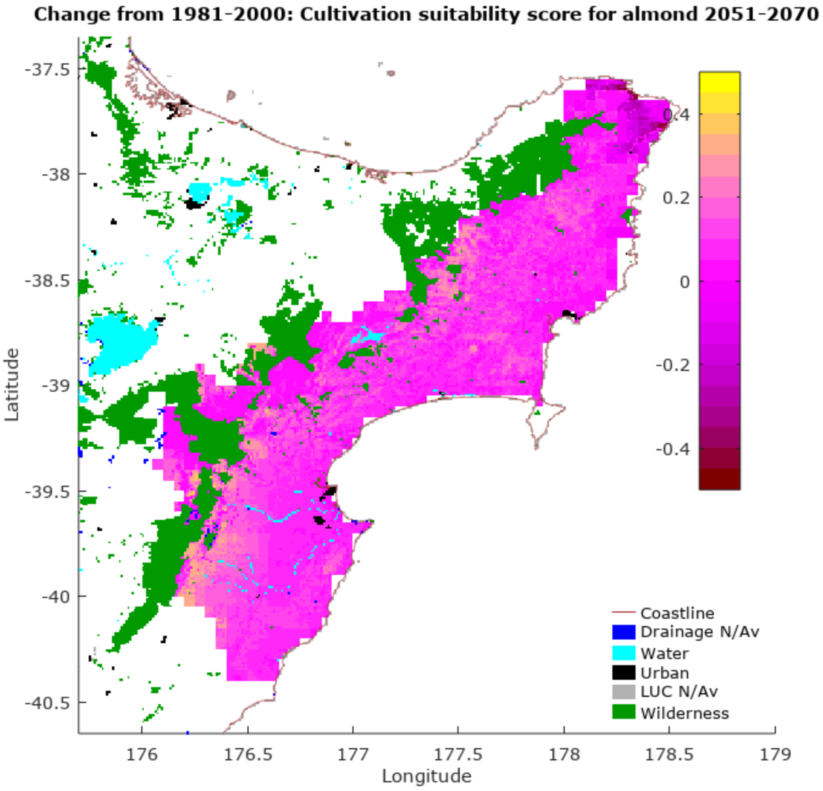
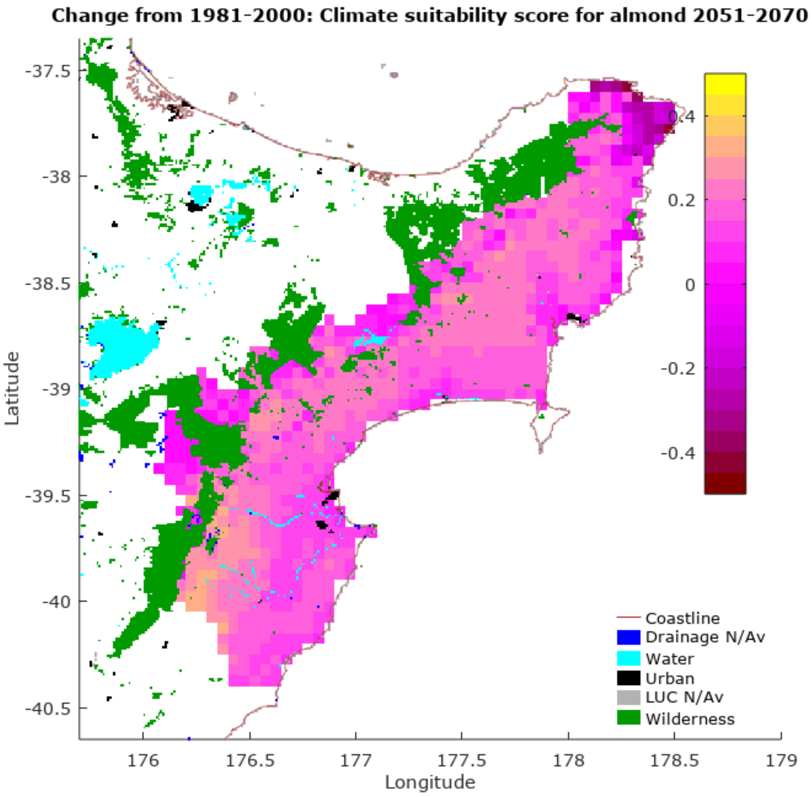
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.15
0.1
0.05
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

Projected change from 1981–2000 (RCP Past period)




Change from 1981-2000: Climate suitability score for almond 2051-2070
-37.5
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-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
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0.2
0
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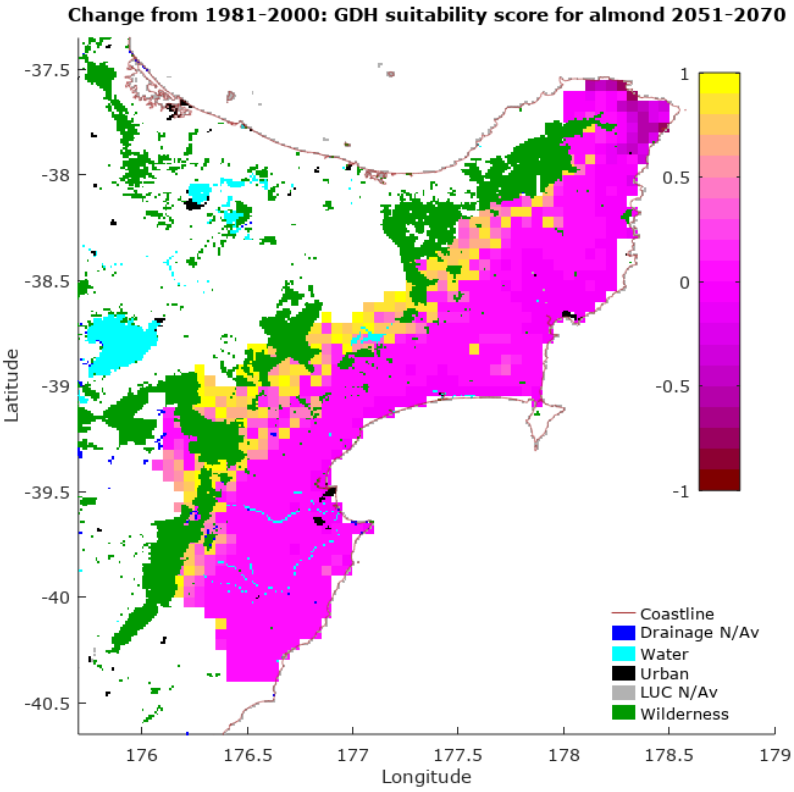
-0.4
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: GDH suitability score for almond 2051-2070
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-40
-40.5
Latitude
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176.5
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177.5
178
178.5
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Longitude
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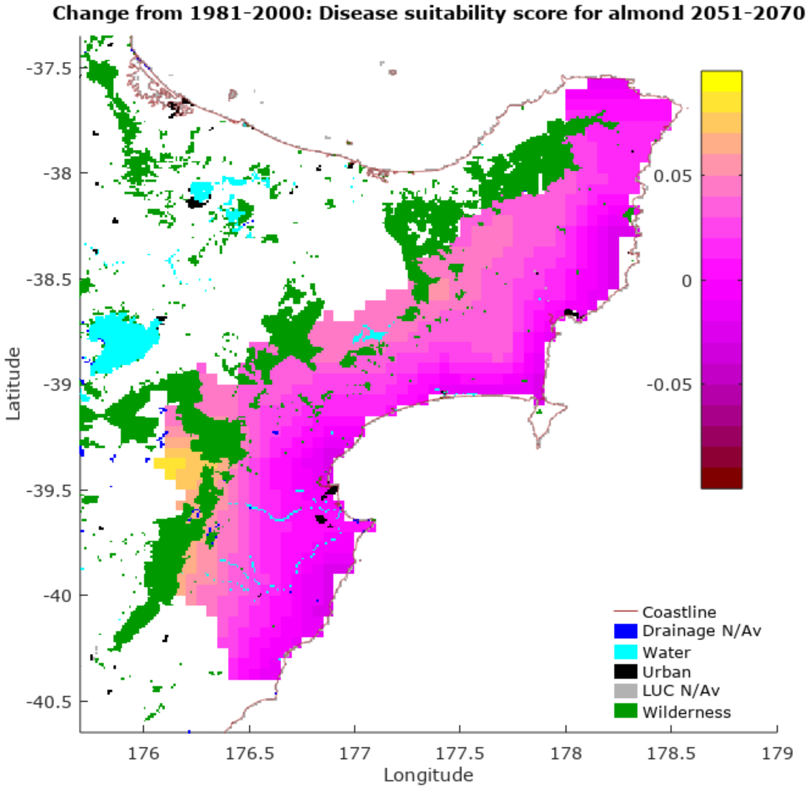
-1
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Disease suitability score for almond 2051-2070
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Longitude
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-38.5
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-39.5
-40
-40.5
176
176.5
177
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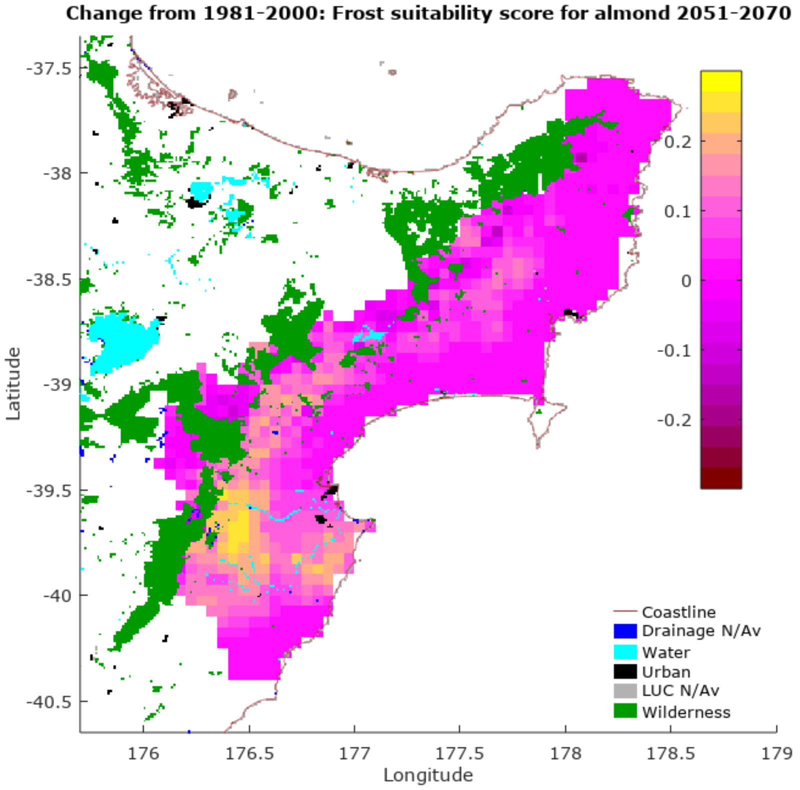
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Frost suitability score for almond 2051-2070
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Longitude
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-38.5
-39
-39.5
-40
-40.5
176
176.5
177
177.5
178
178.5
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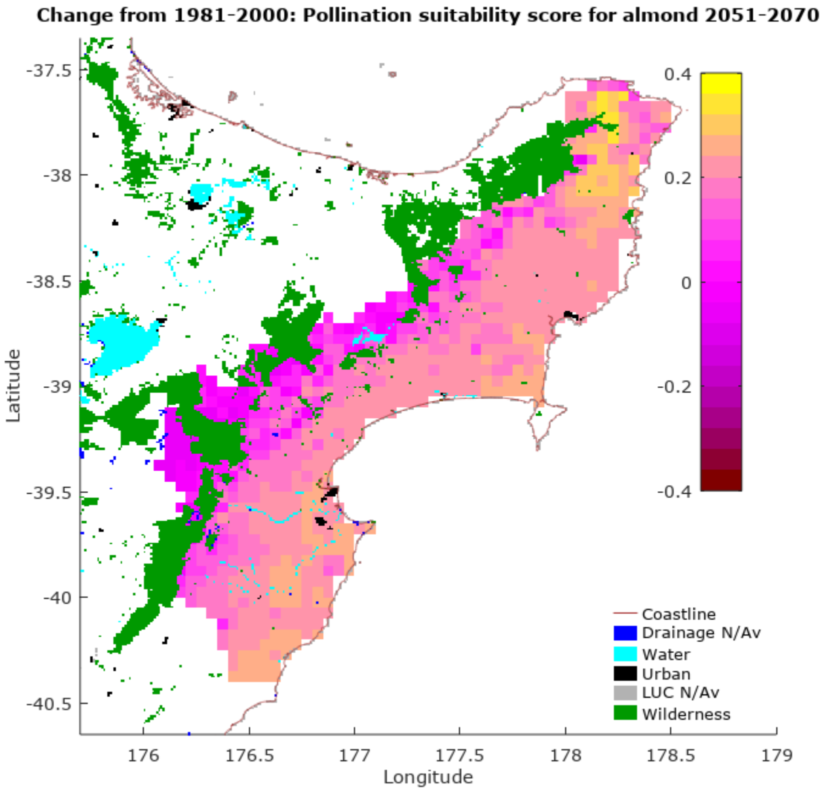
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Pollination suitability score for almond 2051-2070
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-38.5
-39
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-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
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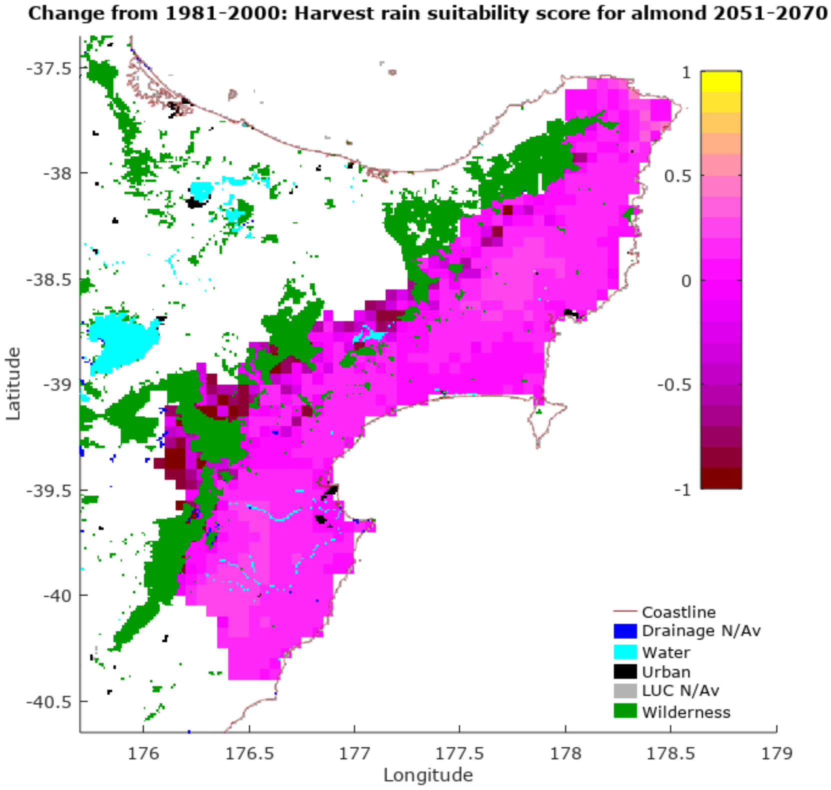
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Harvest rain suitability score for almond 2051-2070
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-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
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Longitude
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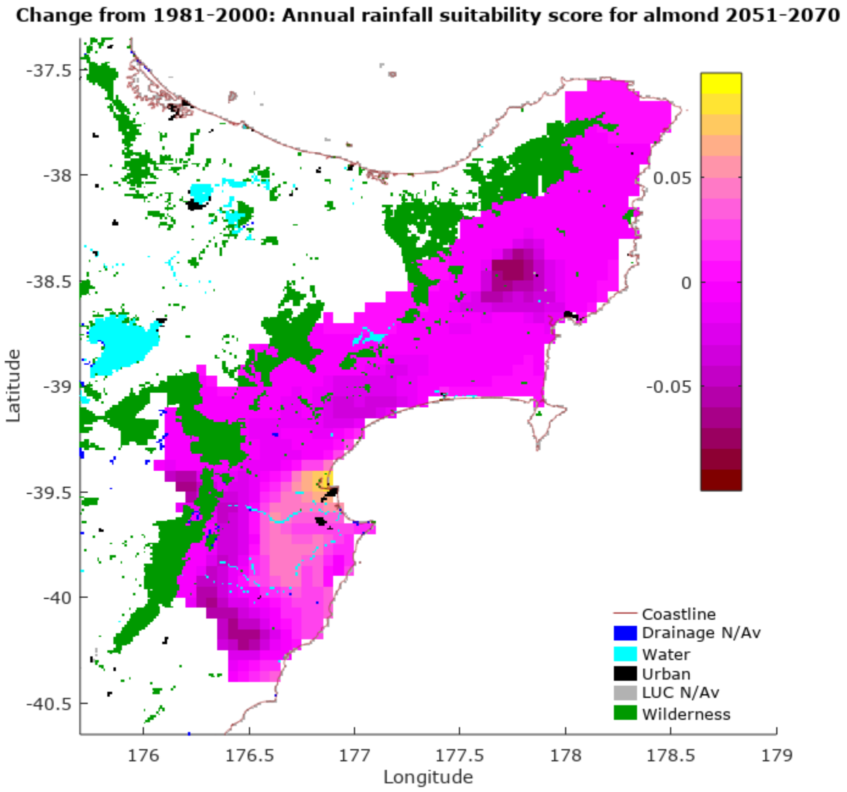
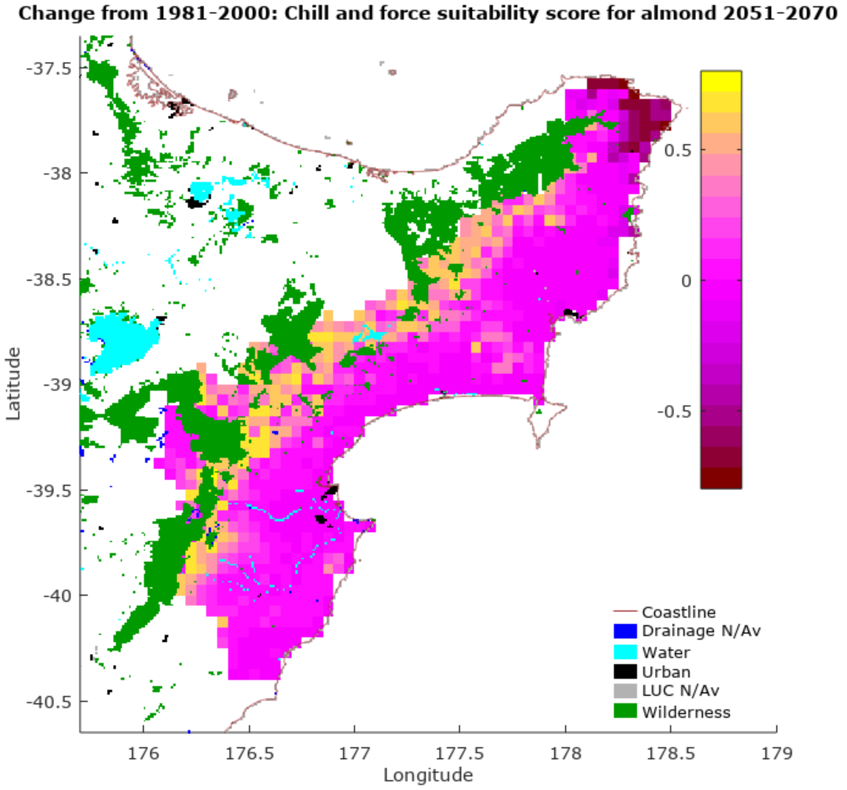
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness



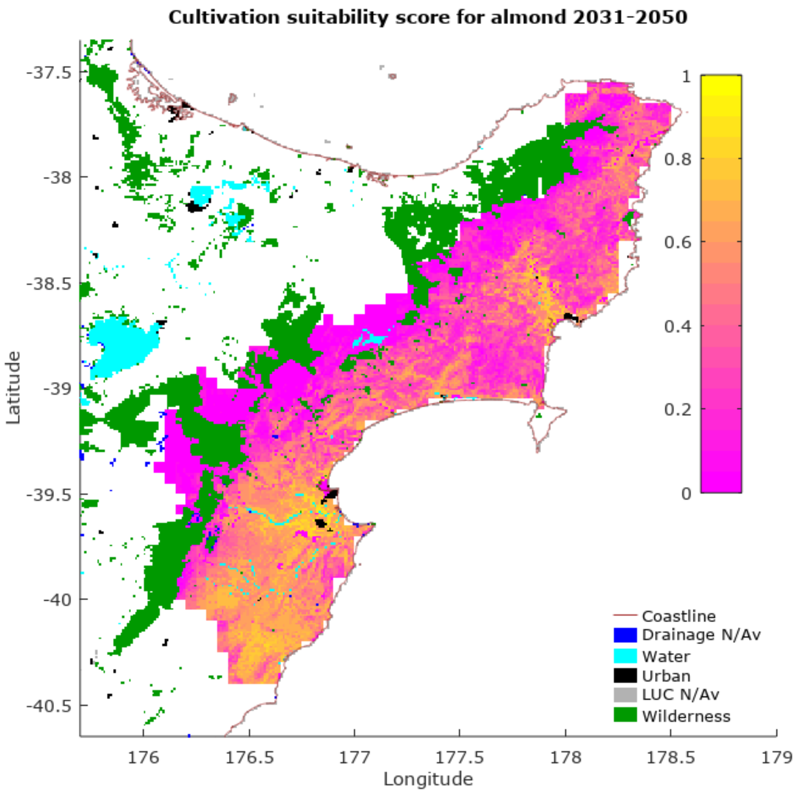
Change from 1981-2000: Annual rainfall suitability score for almond 2051-2070

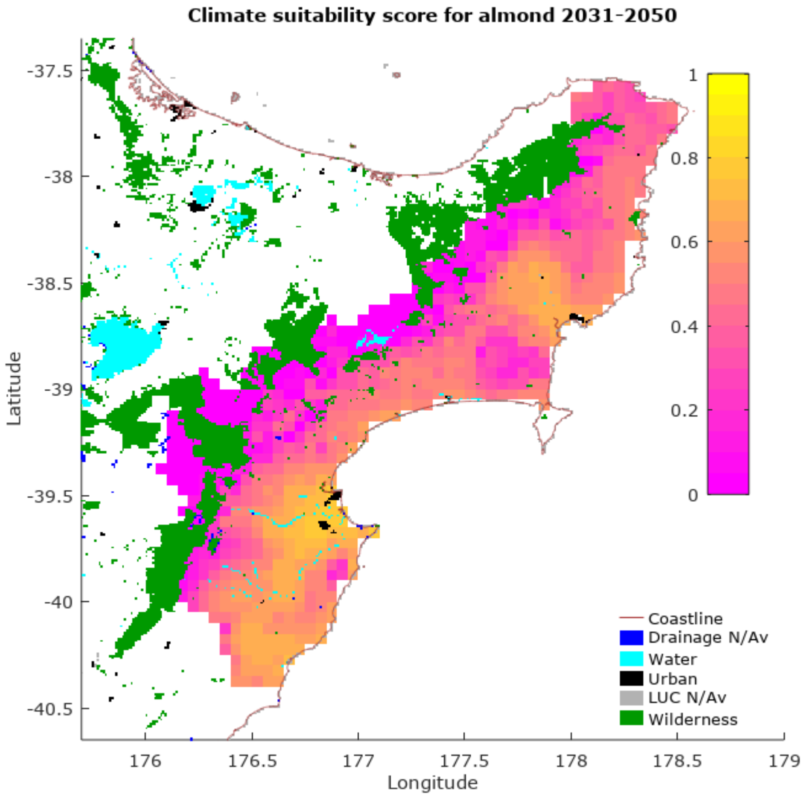


Change from 1981-2000: Chill and force suitability score for almond 2051-2070

RCP 6.0 2031 to 2050

Climate suitability projections




Climate suitability score for almond 2031-2050
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Longitude
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-38.5
-39
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-40
-40.5
176
176.5
177
177.5
178
178.5
179
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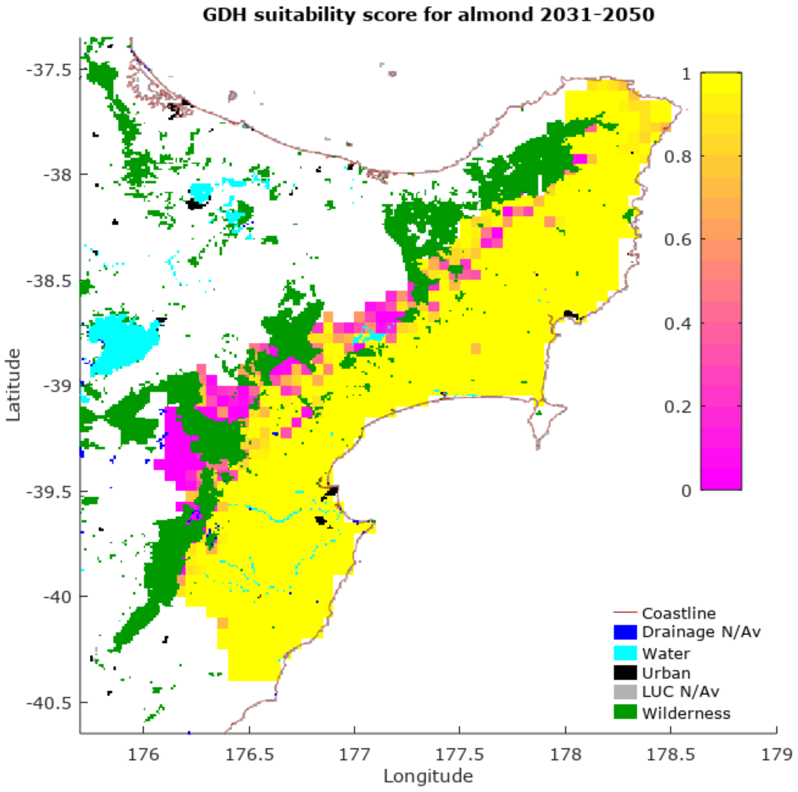
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GDH suitability score for almond 2031-2050
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Longitude
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-39
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-40
-40.5
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176.5
177
177.5
178
178.5
179
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0.4
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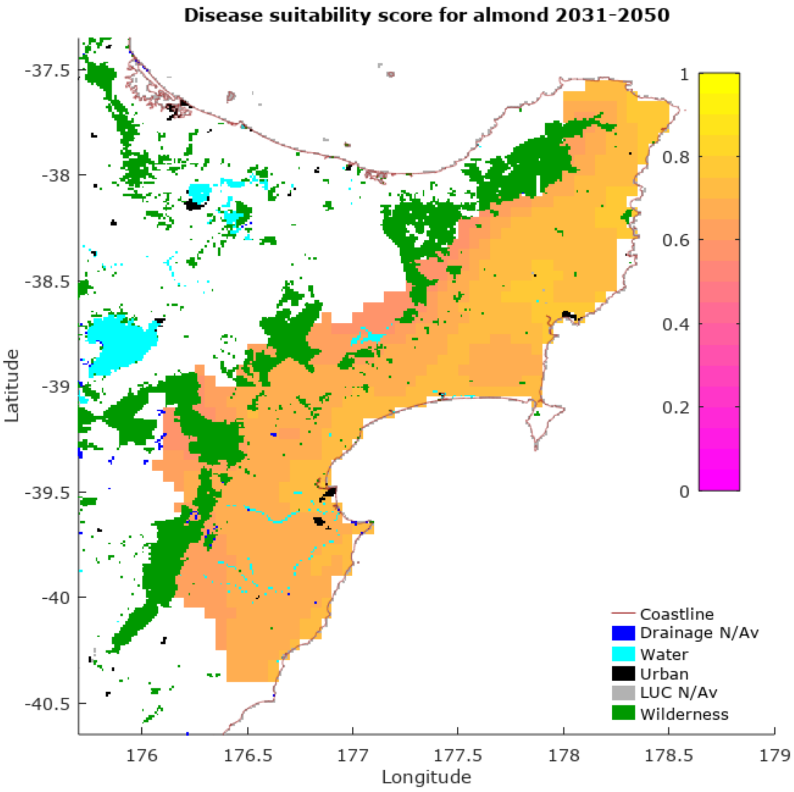
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Disease suitability score for almond 2031-2050
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-39.5
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-40.5
Longitude
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176.5
177
177.5
178
178.5
179
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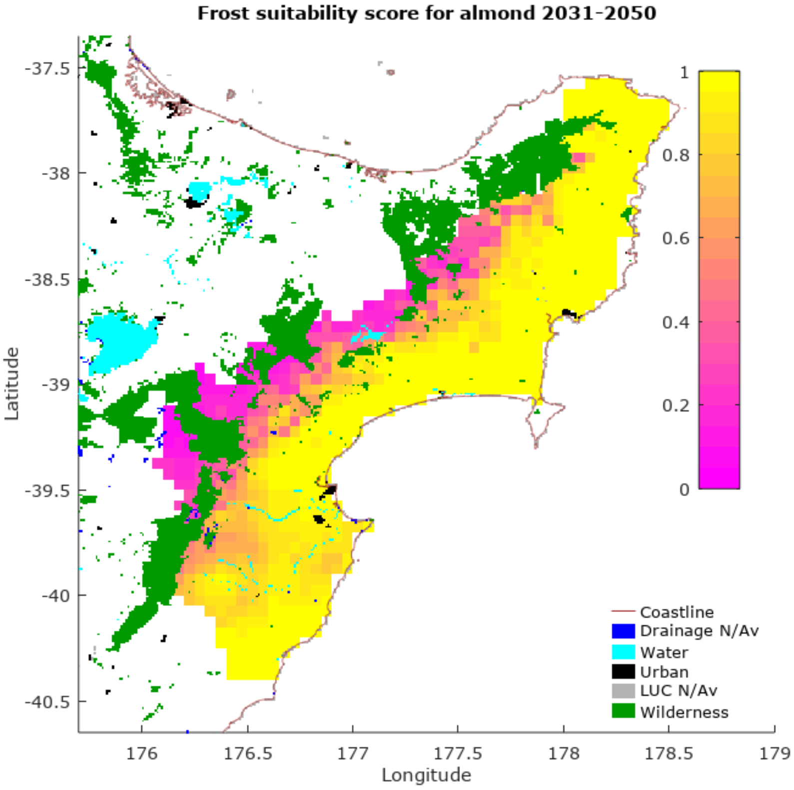
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Frost suitability score for almond 2031-2050
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-39.5
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-40.5
Longitude
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176.5
177
177.5
178
178.5
179
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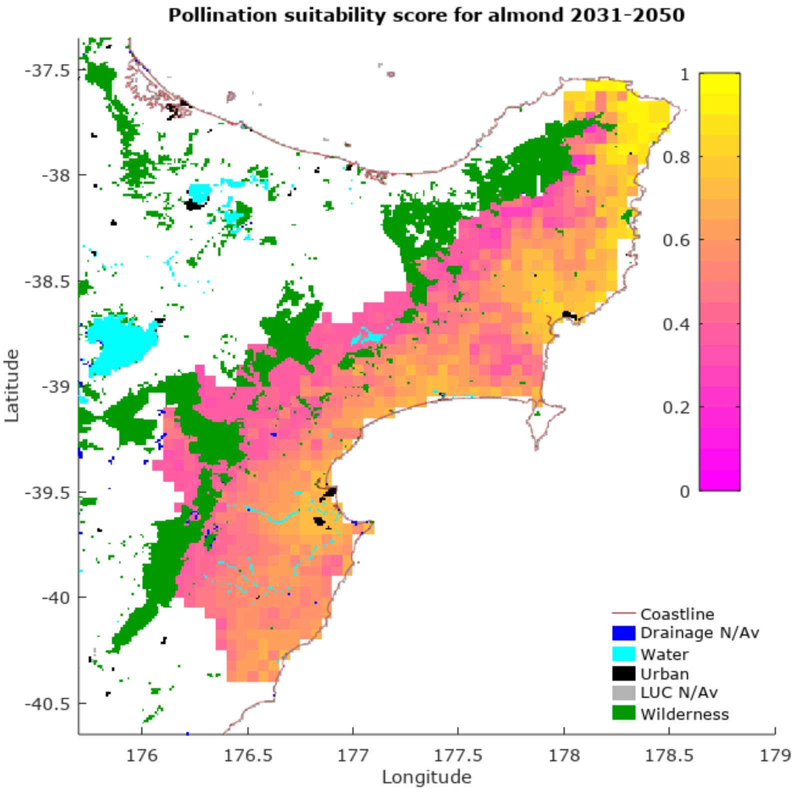
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Pollination suitability score for almond 2031-2050
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-40.5
Longitude
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176.5
177
177.5
178
178.5
179
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0.4
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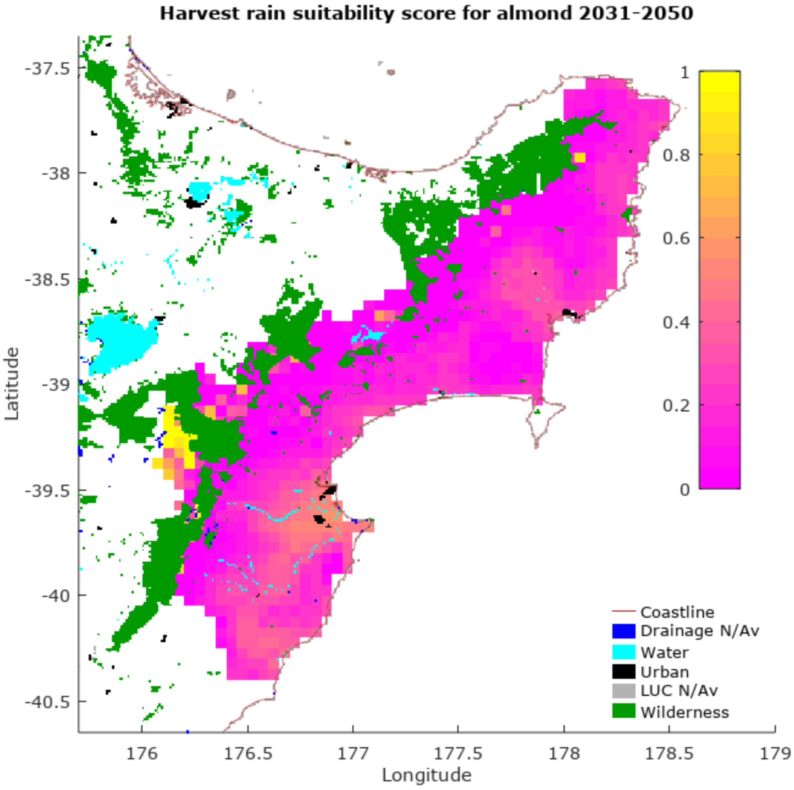
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Harvest rain suitability score for almond 2031-2050
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-40.5
Longitude
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176.5
177
177.5
178
178.5
179
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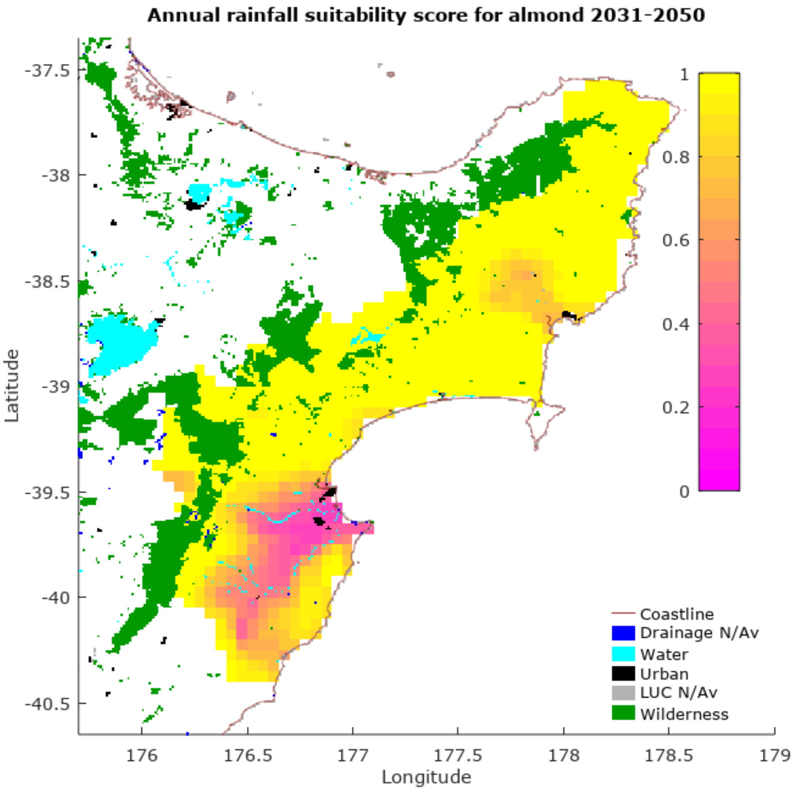
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Annual rainfall suitability score for almond 2031-2050
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Latitude
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176.5
177
177.5
178
178.5
179
Longitude
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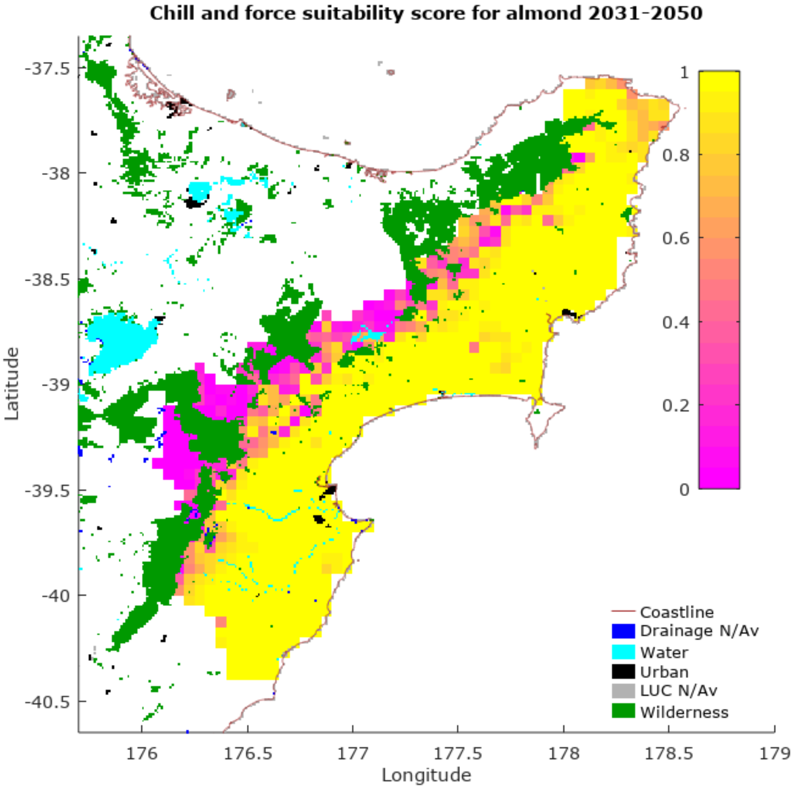
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Chill and force suitability score for almond 2031-2050
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Latitude
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176.5
177
177.5
178
178.5
179
Longitude
1
0.8
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0.4
0.2
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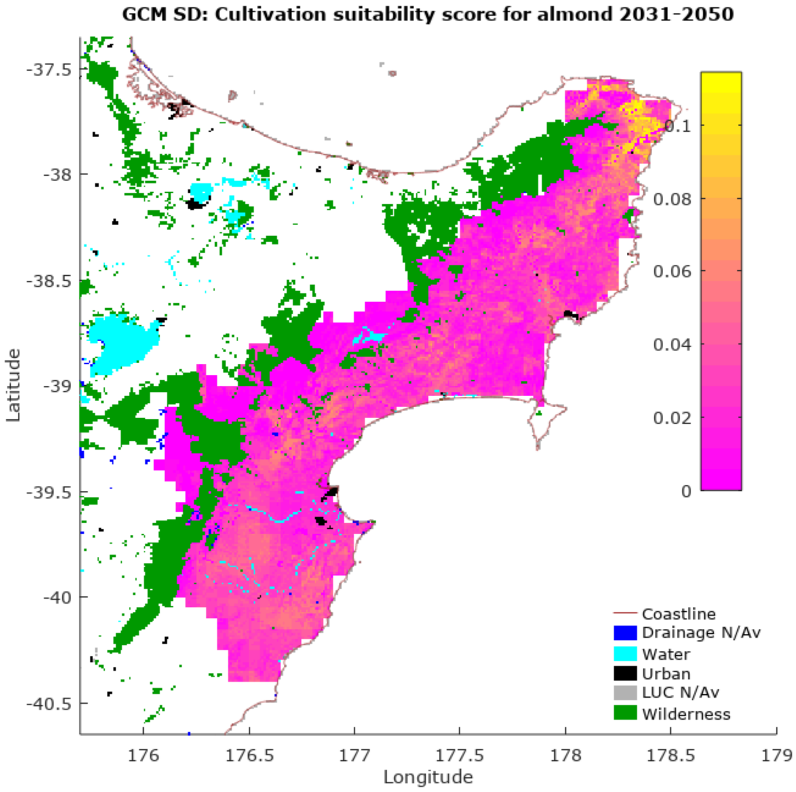
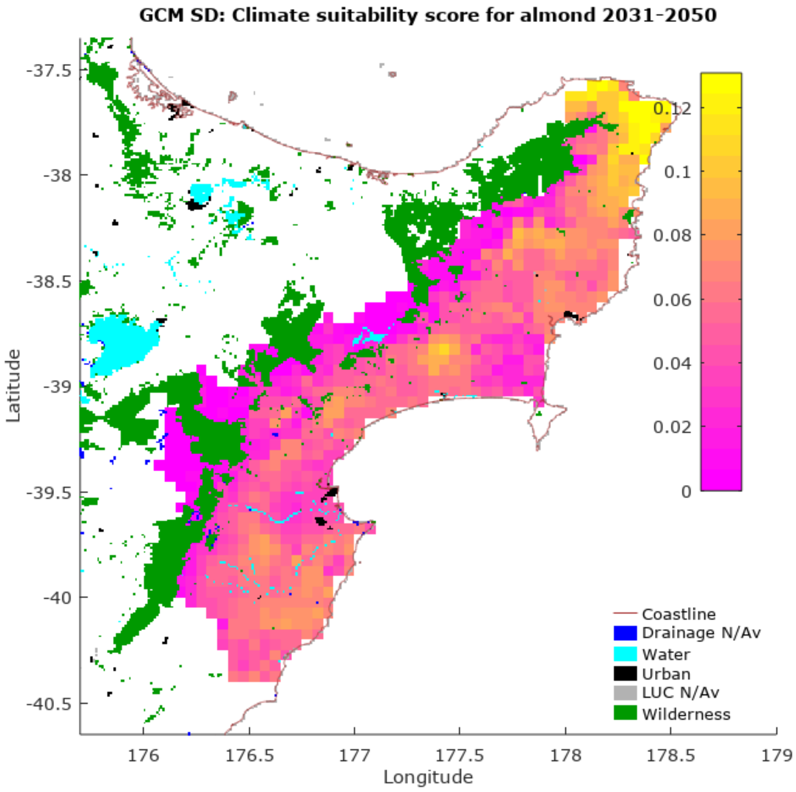
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

Standard deviation (SD) of projections




GCM SD: Climate suitability score for almond 2031-2050
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-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
0.12
0.1
0.08
0.06
0.04
0.02
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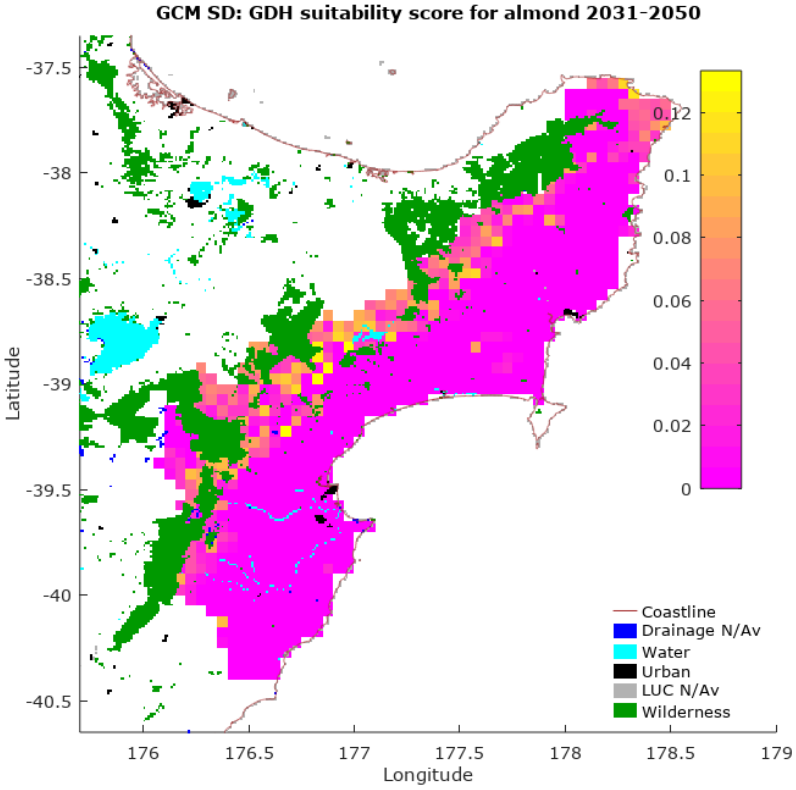
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: GDH suitability score for almond 2031-2050
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-40.5
Latitude
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176.5
177
177.5
178
178.5
179
Longitude
0.12
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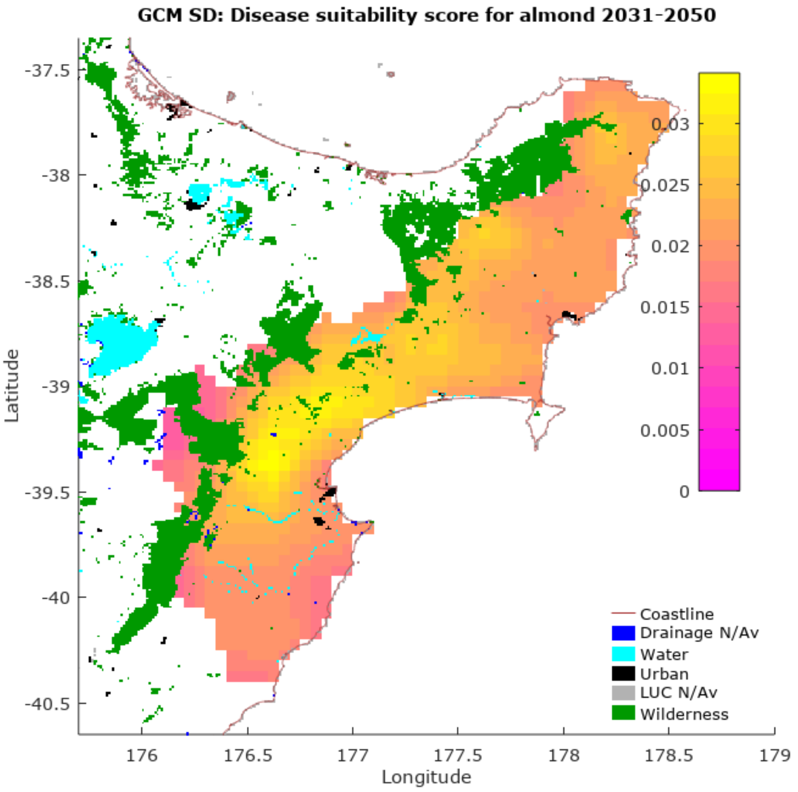
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Disease suitability score for almond 2031-2050
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-40.5
Longitude
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176.5
177
177.5
178
178.5
179
0.03
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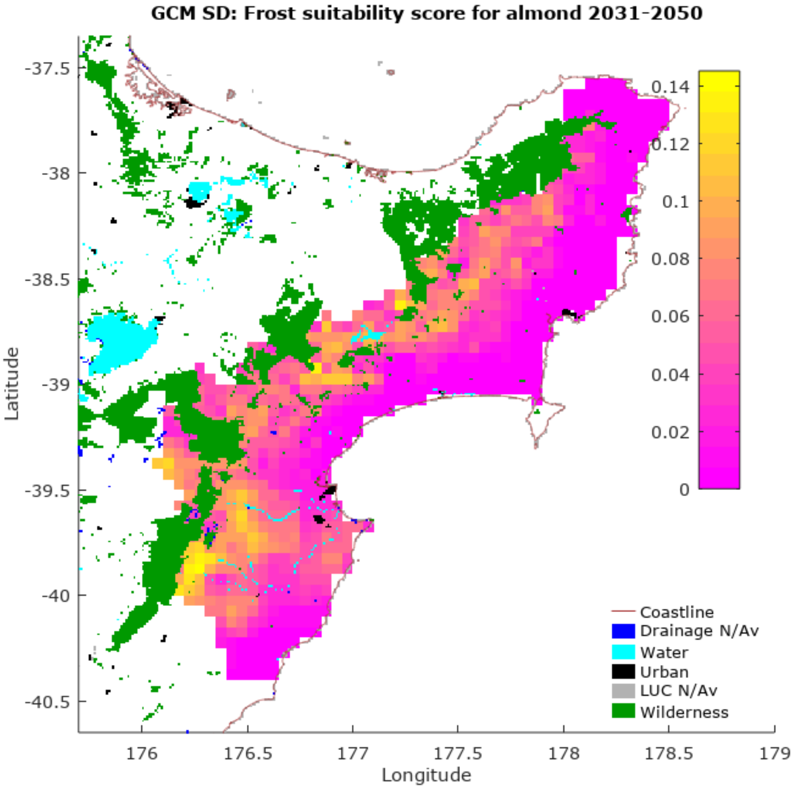
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Frost suitability score for almond 2031-2050
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-39
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-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.14
0.12
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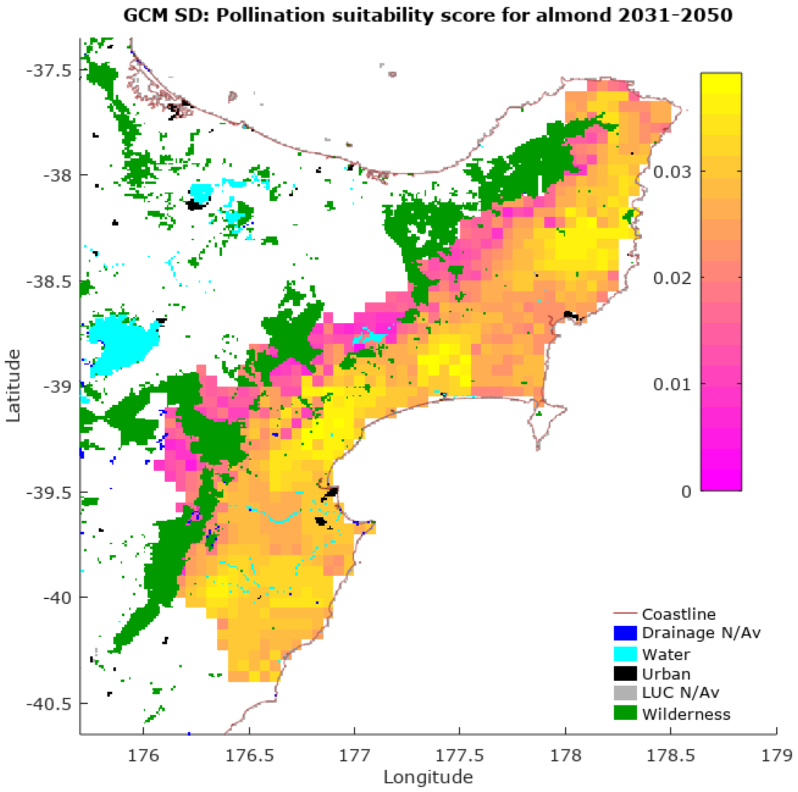
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Pollination suitability score for almond 2031-2050
Latitude
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-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
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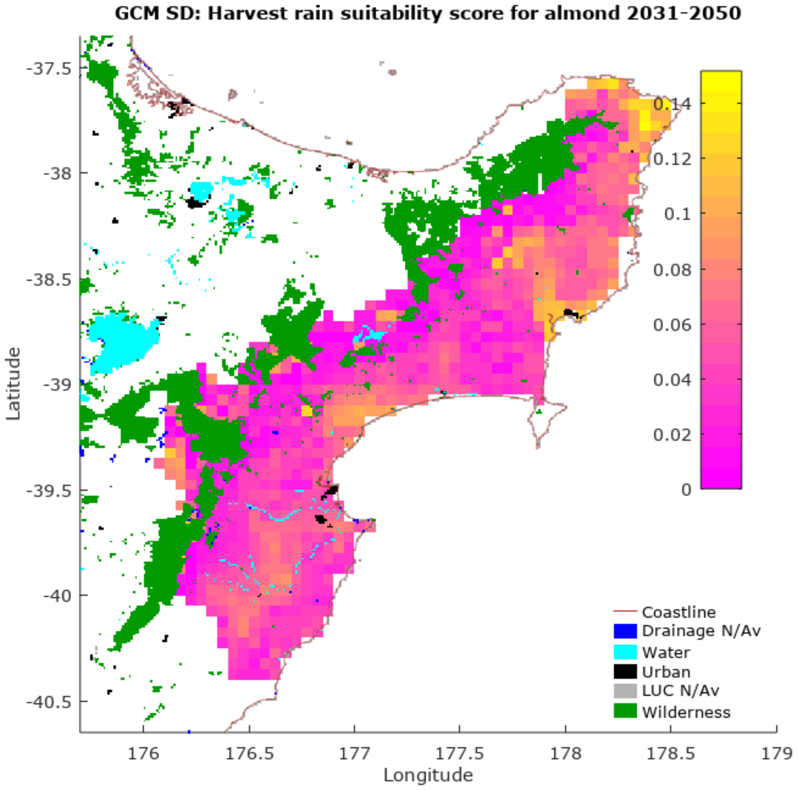
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Harvest rain suitability score for almond 2031-2050
Latitude
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-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.14
0.12
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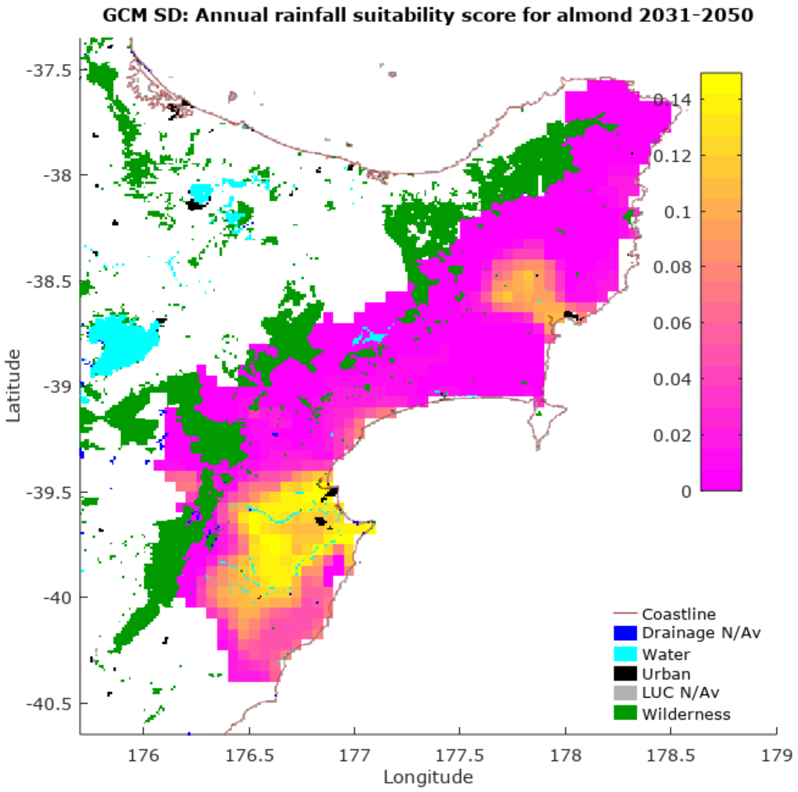
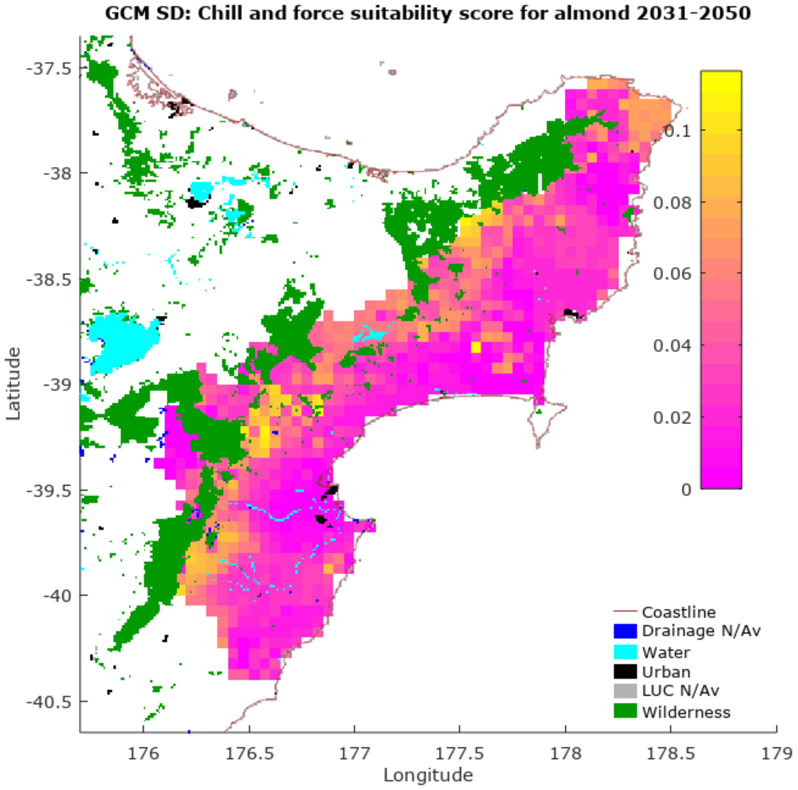
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

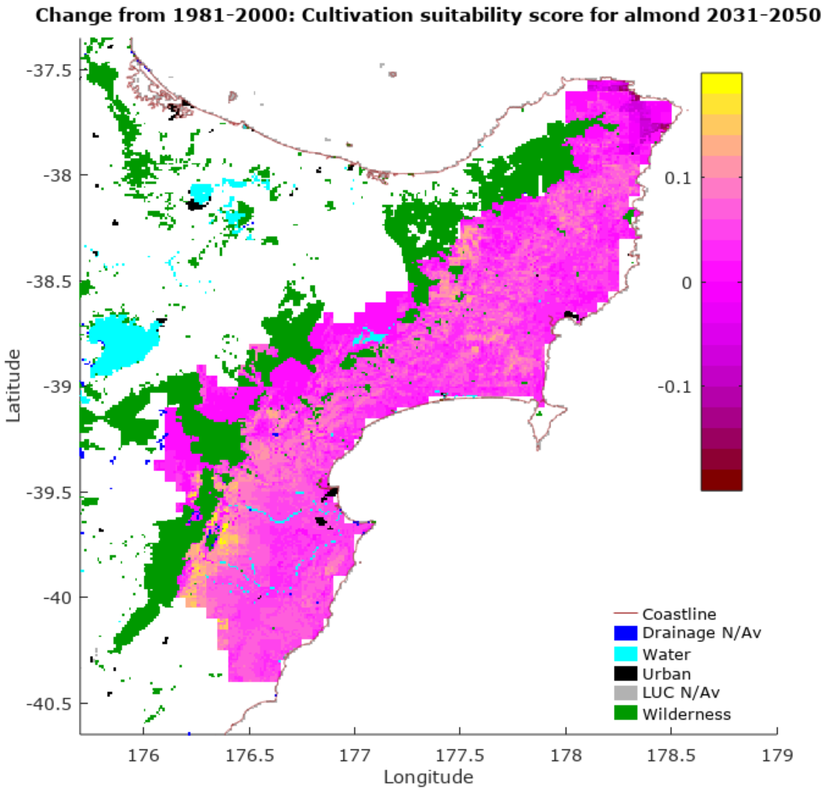


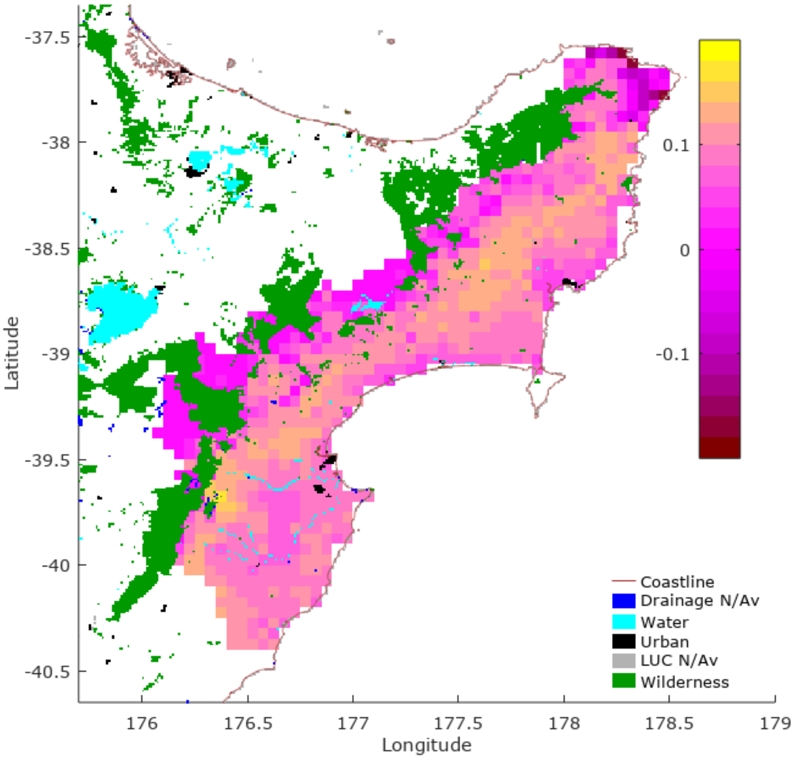
GCM SD: Annual rainfall suitability score for almond 2031-2050



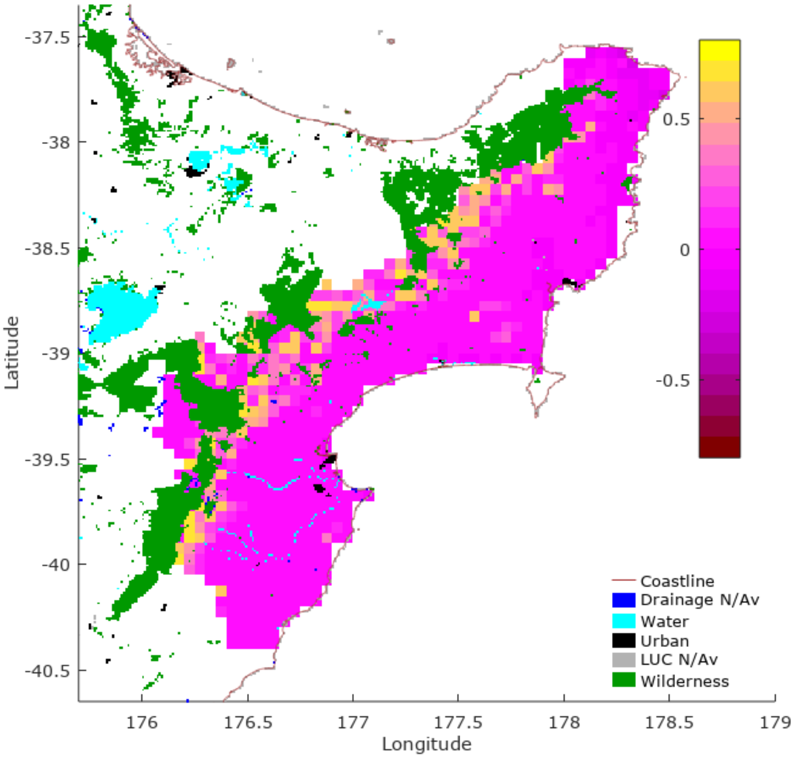
GCM SD: Chill and force suitability score for almond 2031-2050

Projected change from 1981–2000 (RCP Past period)

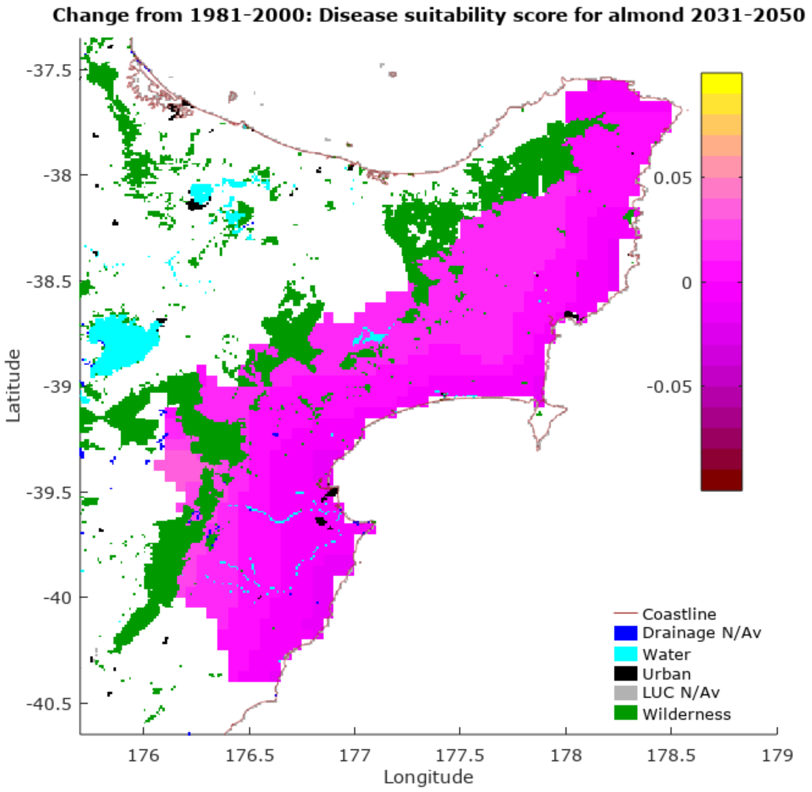


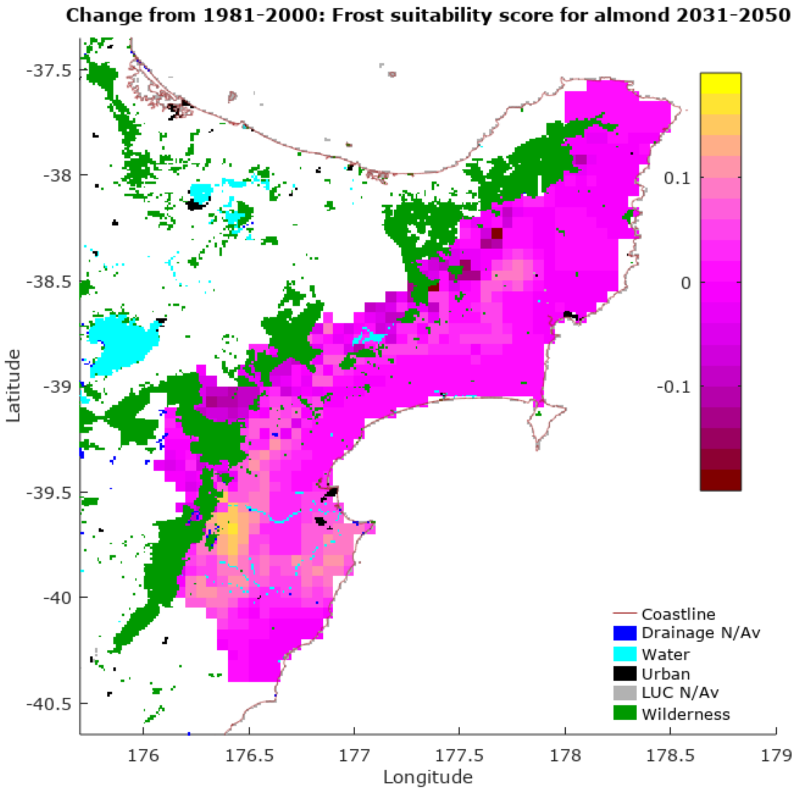


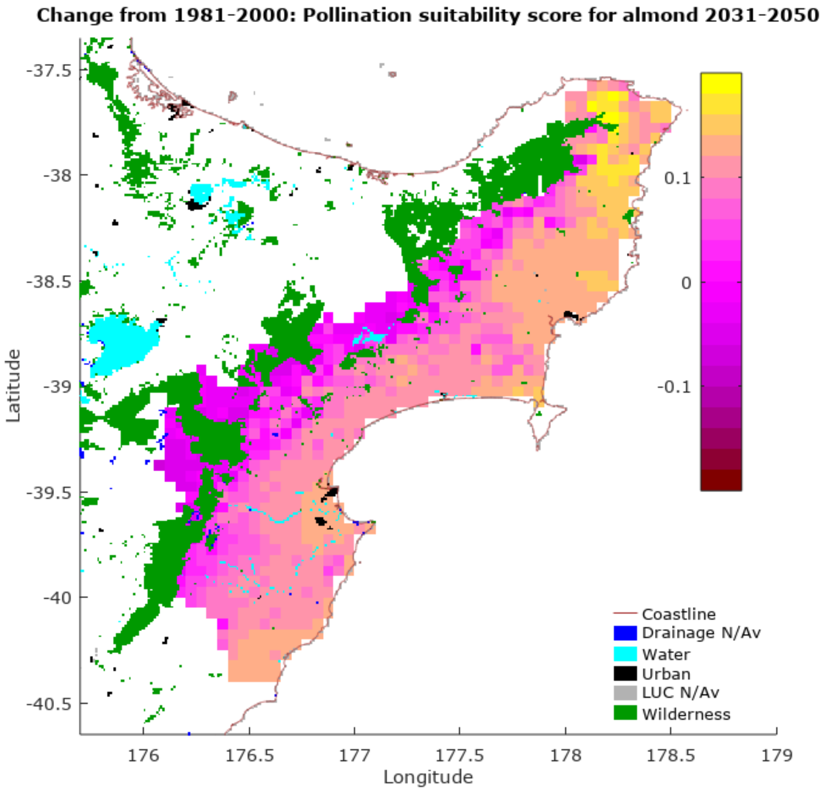
Change from 1981-2000: Climate suitability score for almond 2031-2050

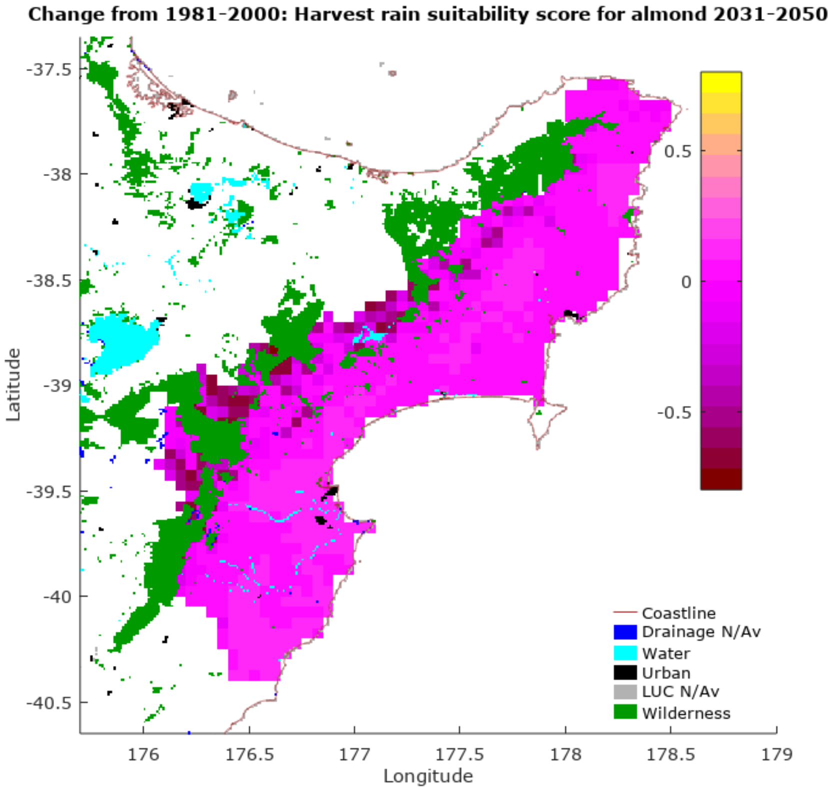


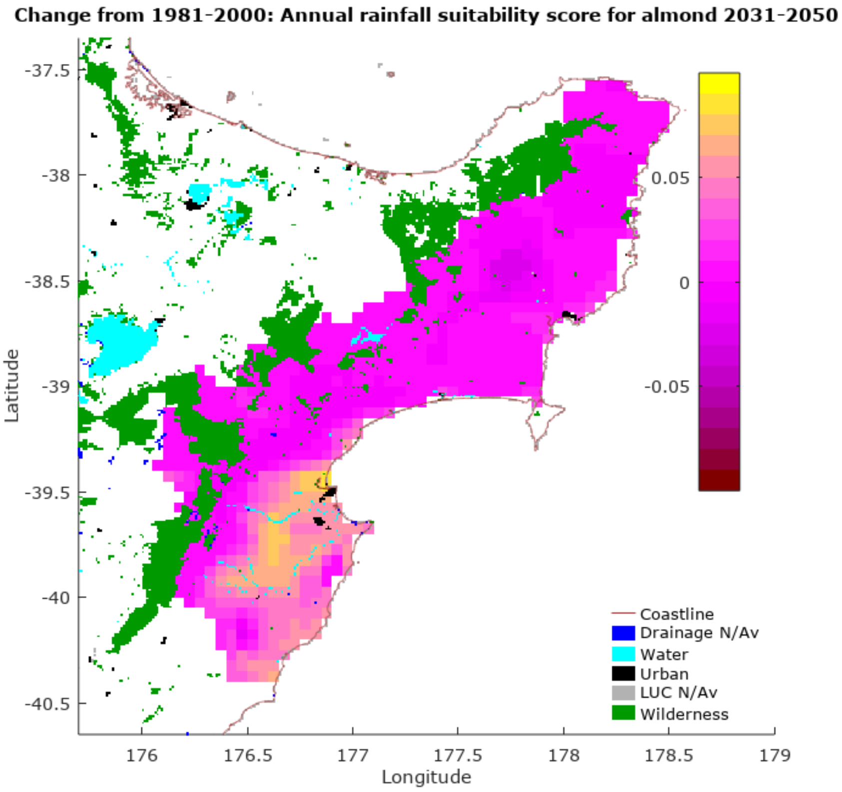
Change from 1981-2000: GDH suitability score for almond 2031-2050


Change from 1981-2000: Disease suitability score for almond 2031-2050

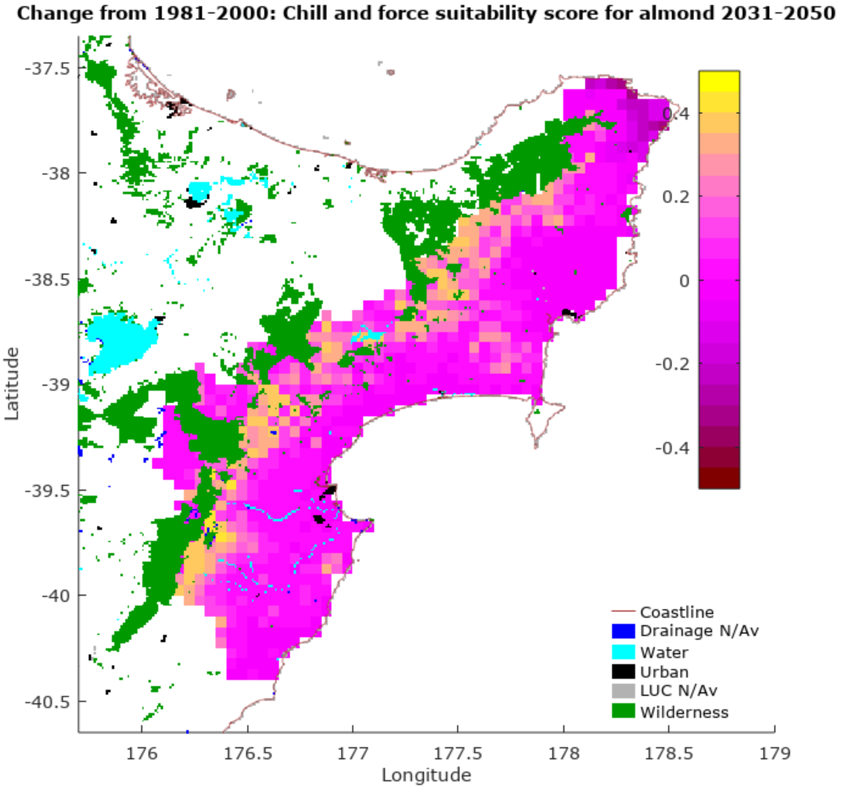

Change from 1981-2000: Frost suitability score for almond 2031-2050


Change from 1981-2000: Pollination suitability score for almond 2031-2050
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
0.1
0
-0.1
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Harvest rain suitability score for almond 2031-2050
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
0.5
0
-0.5
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness



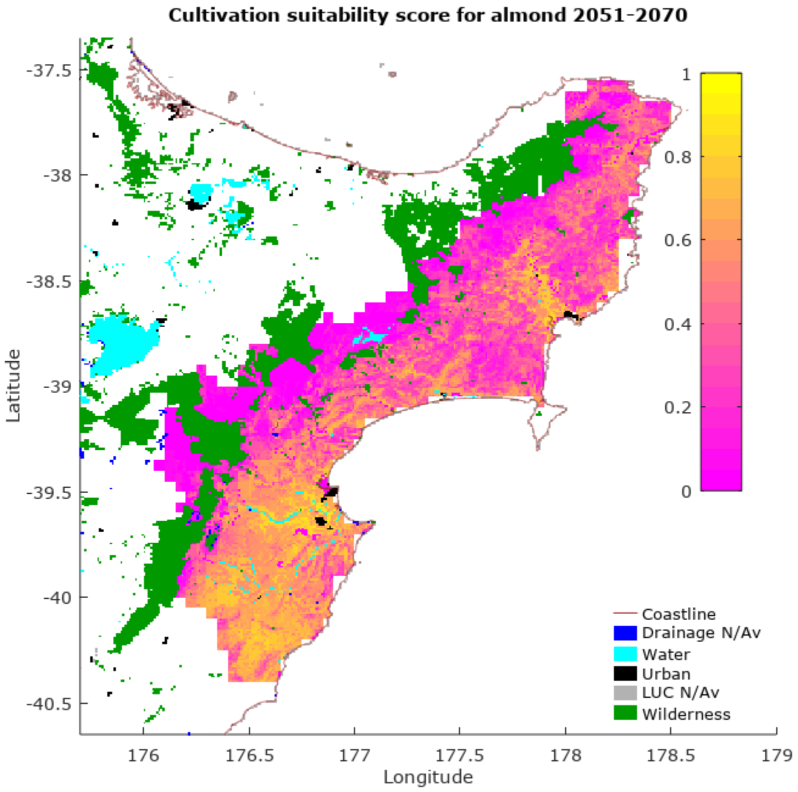
Change from 1981-2000: Annual rainfall suitability score for almond 2031-2050

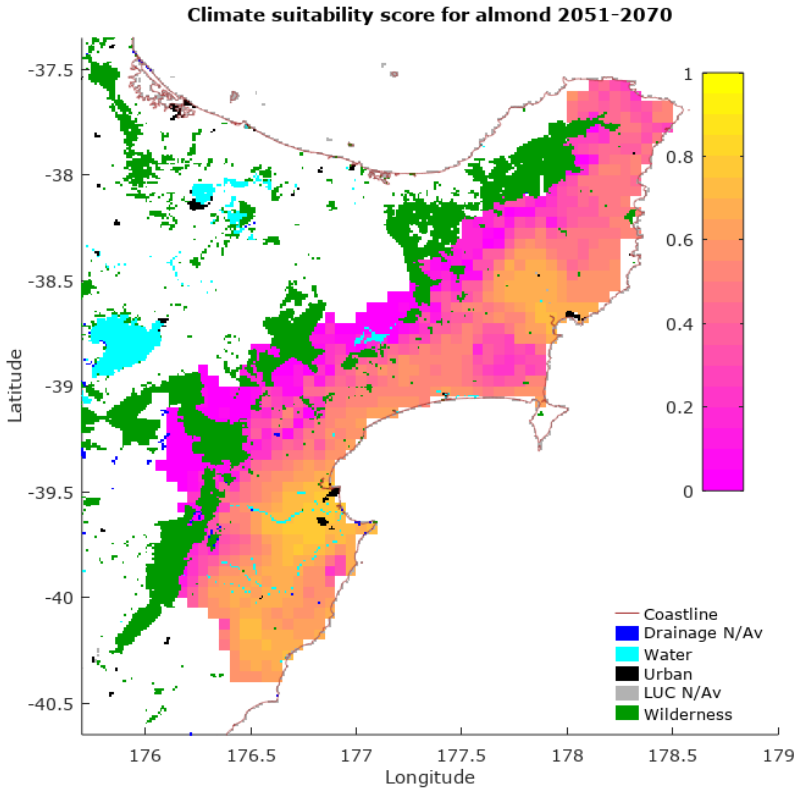


Change from 1981-2000: Chill and force suitability score for almond 2031-2050

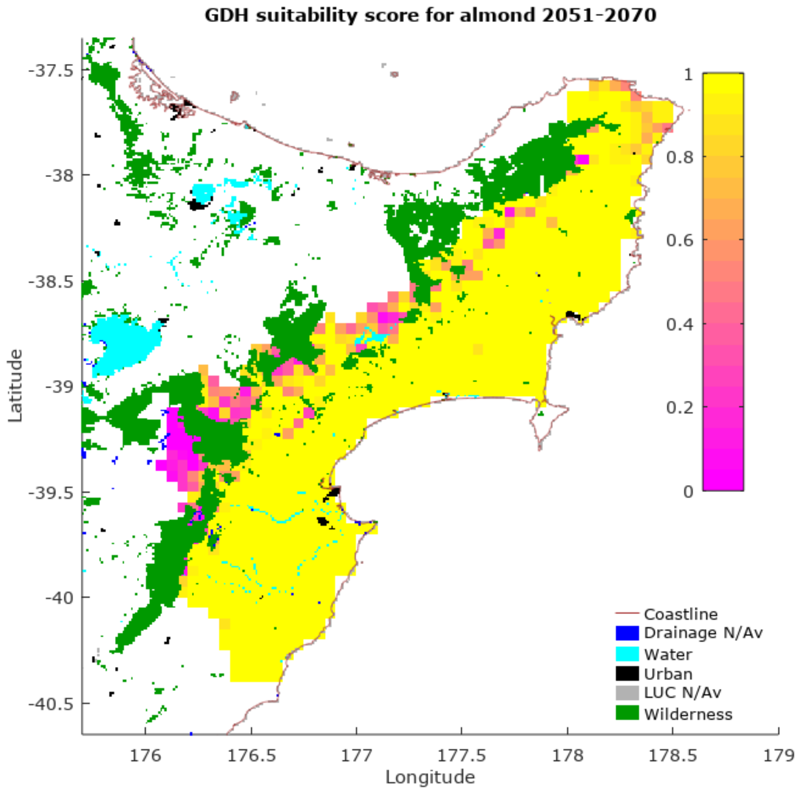
RCP 6.0 2051 to 2070

Climate suitability projections

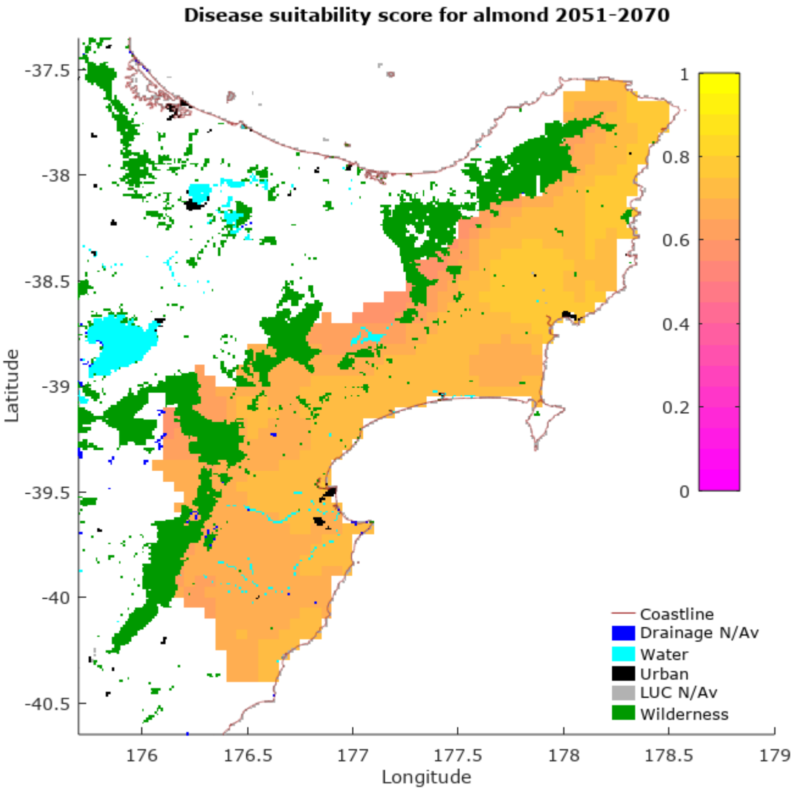


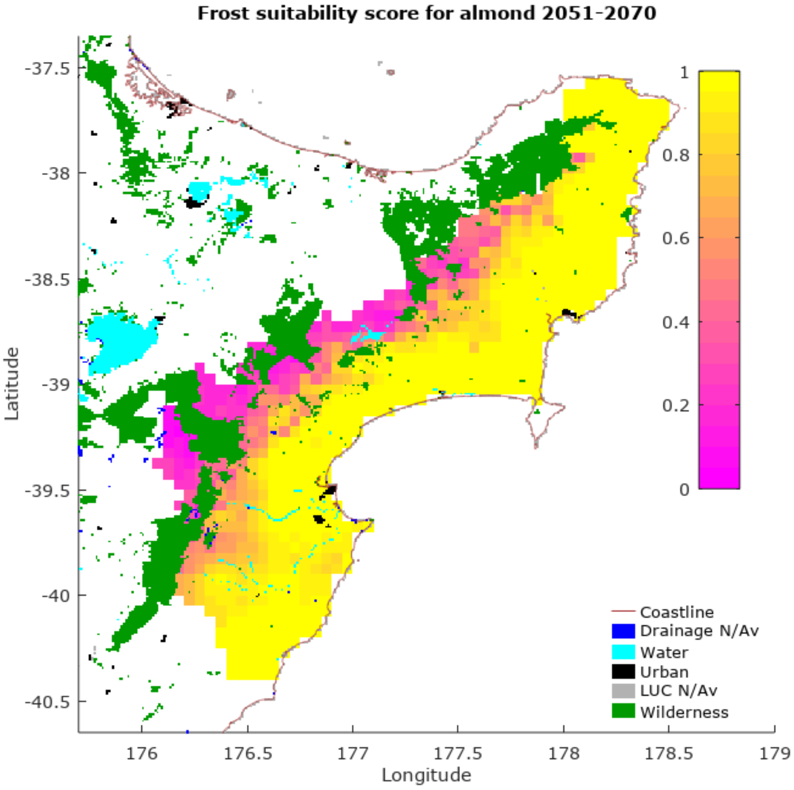


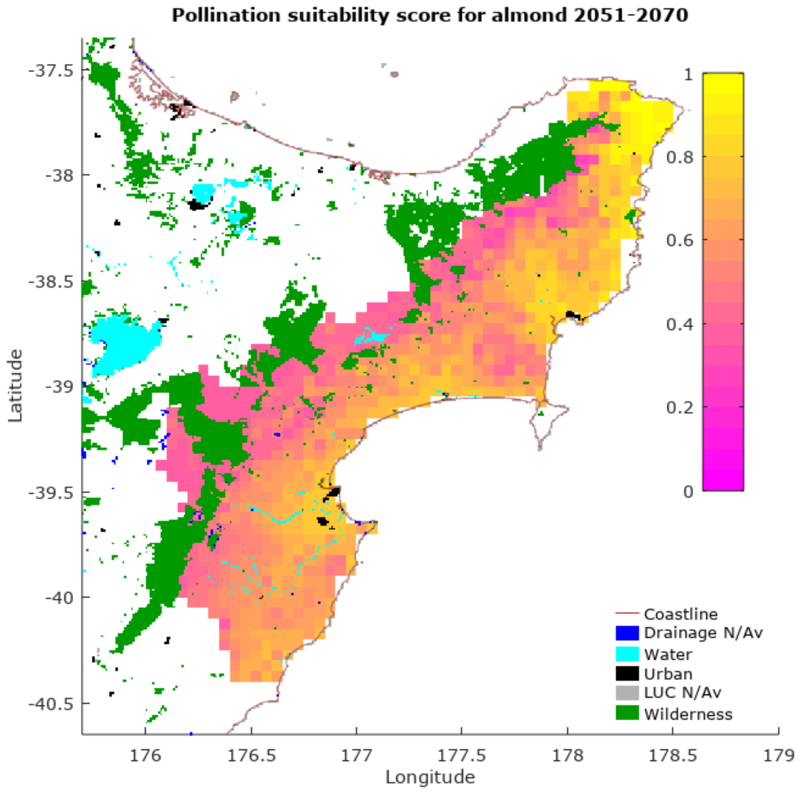
Climate suitability score for almond 2051-2070

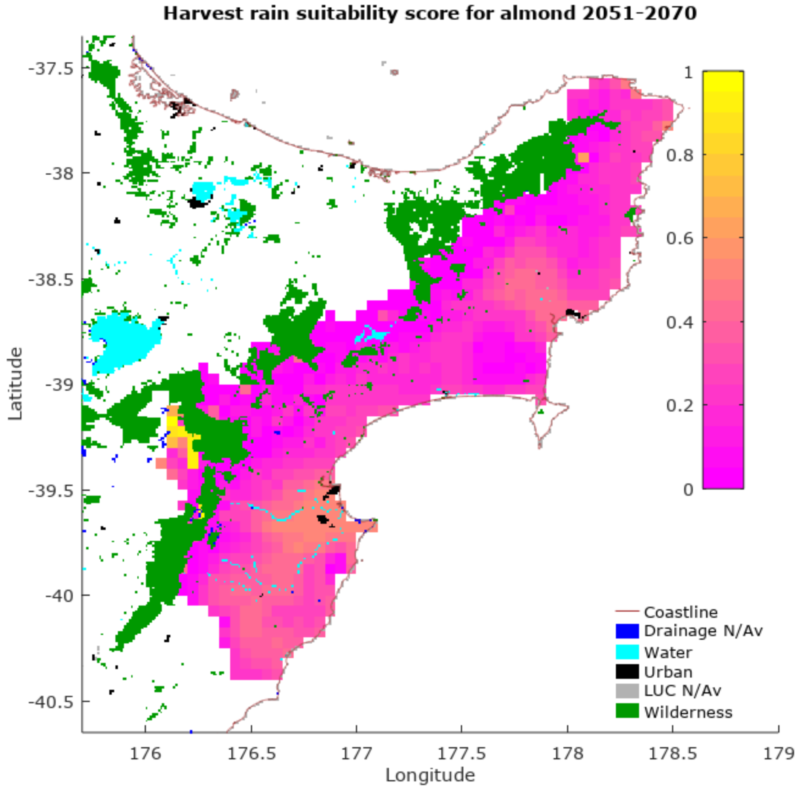


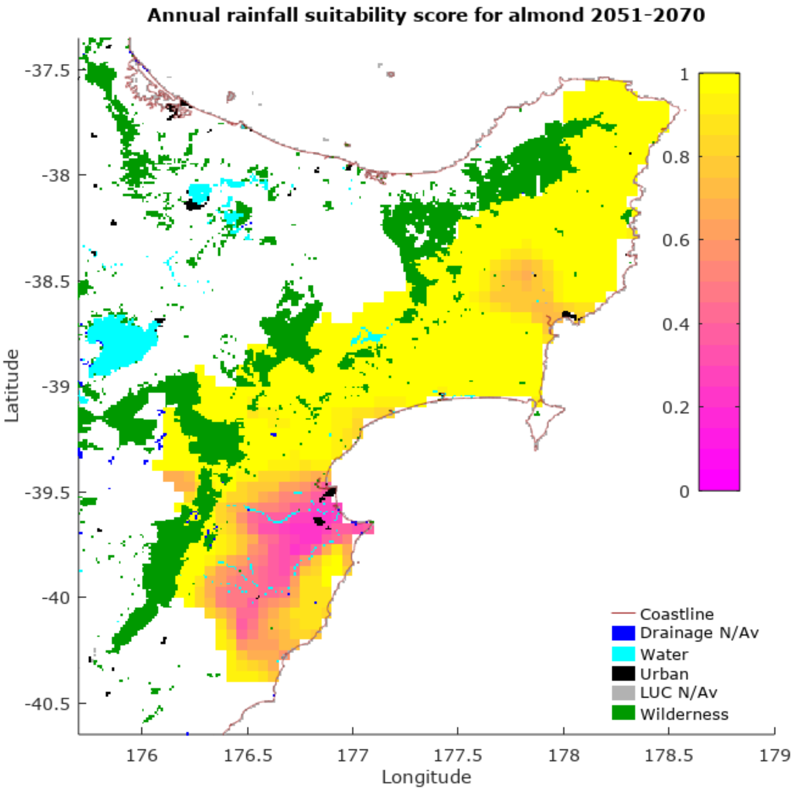
GDH suitability score for almond 2051-2070

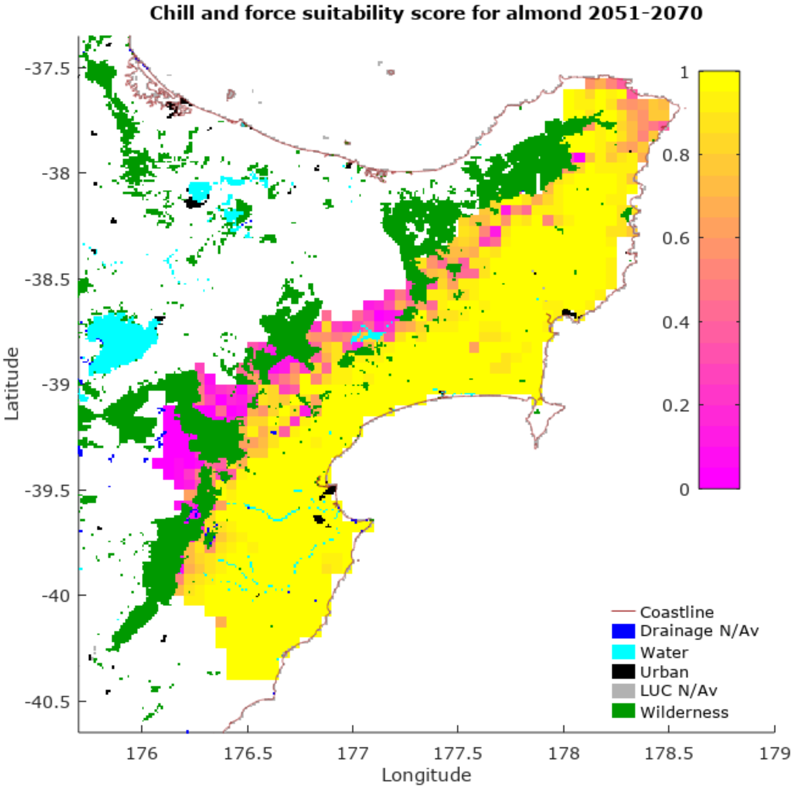

Disease suitability score for almond 2051-2070
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
1
0.8
0.6
0.4
0.2
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Frost suitability score for almond 2051-2070
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
1
0.8
0.6
0.4
0.2
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

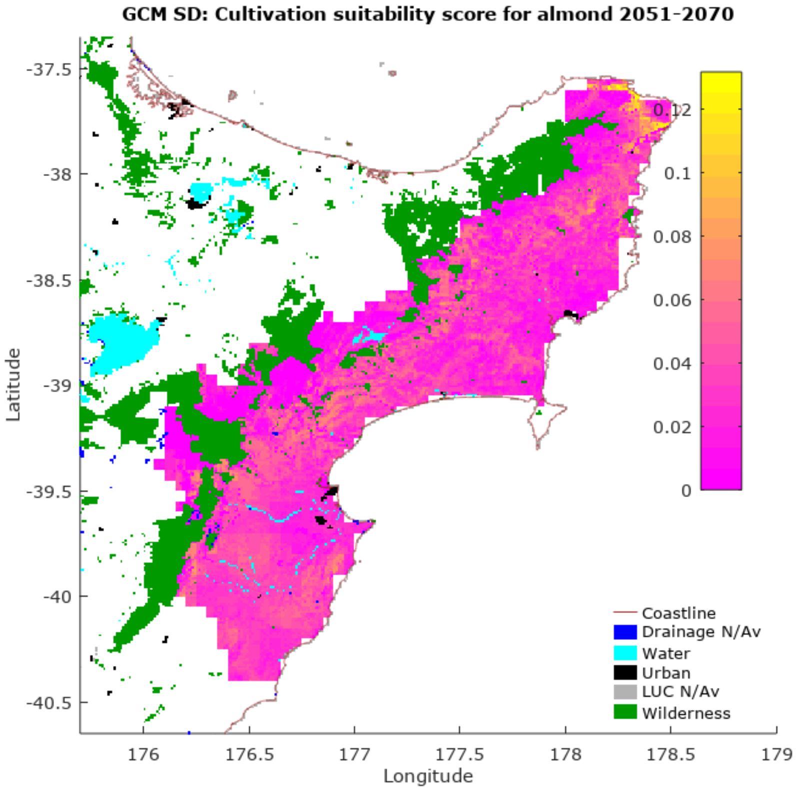

Pollination suitability score for almond 2051-2070

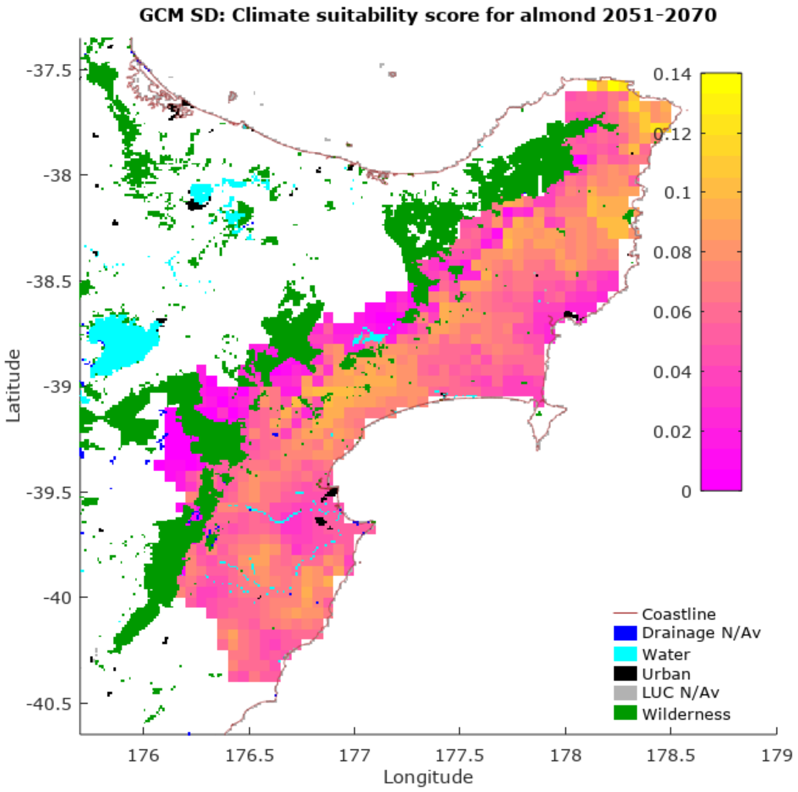

Harvest rain suitability score for almond 2051-2070

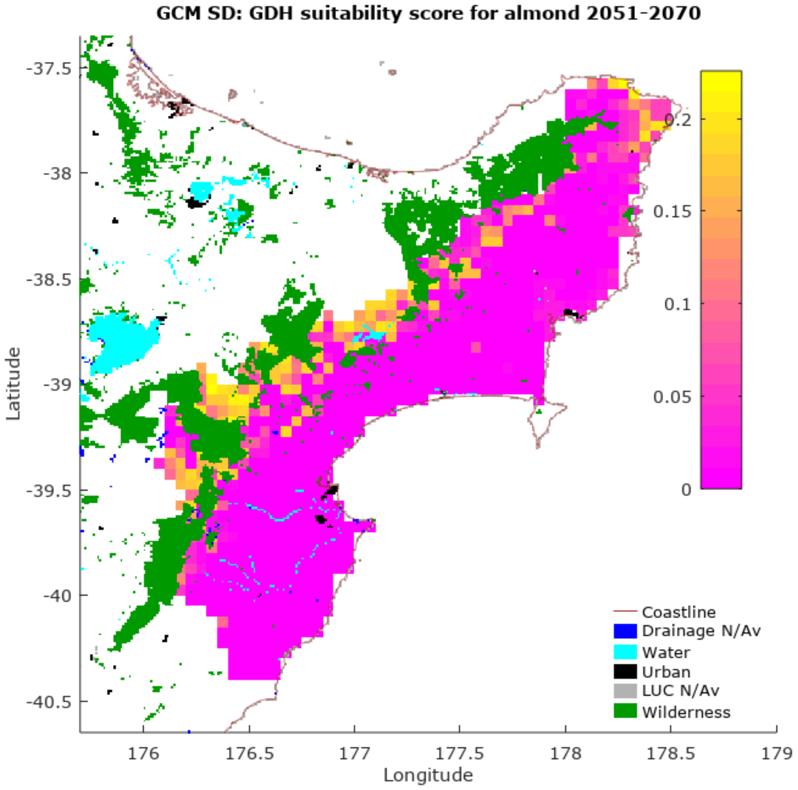

Annual rainfall suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
1
0.8
0.6
0.4
0.2
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

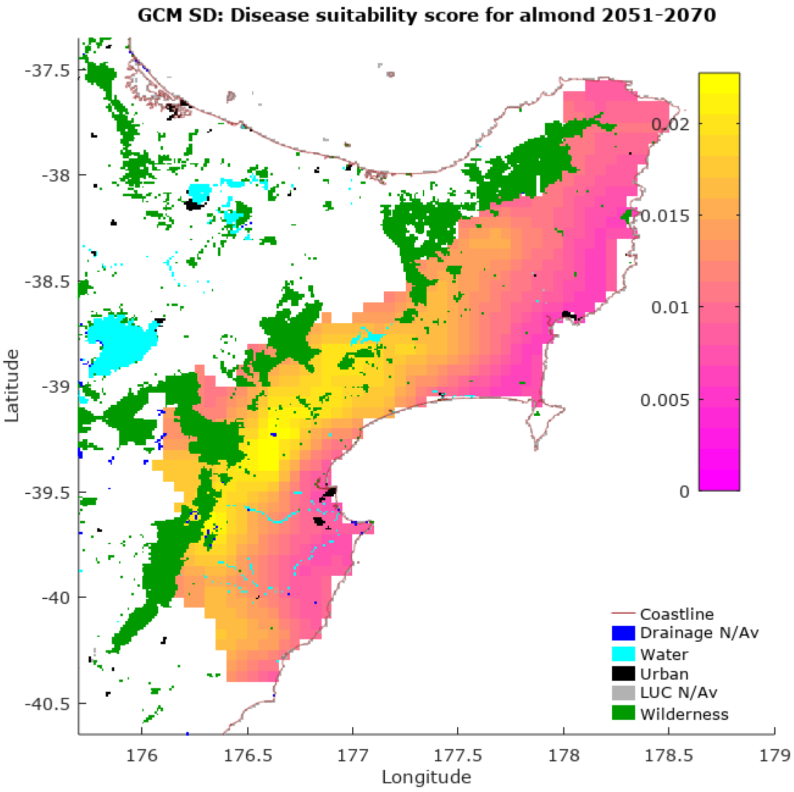

Chill and force suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
1
0.8
0.6
0.4
0.2
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

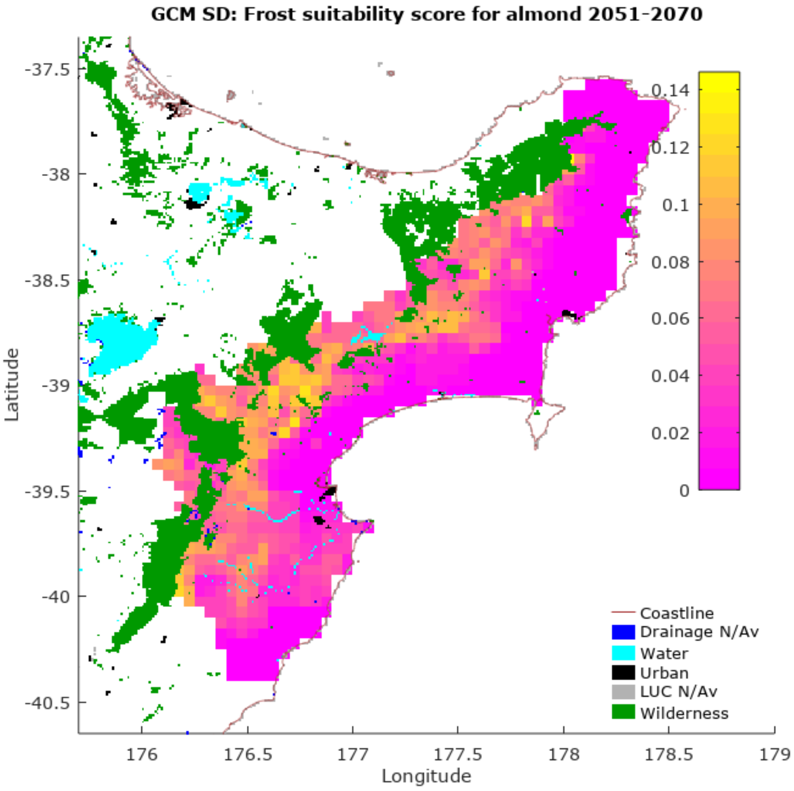
Standard deviation (SD) of projections

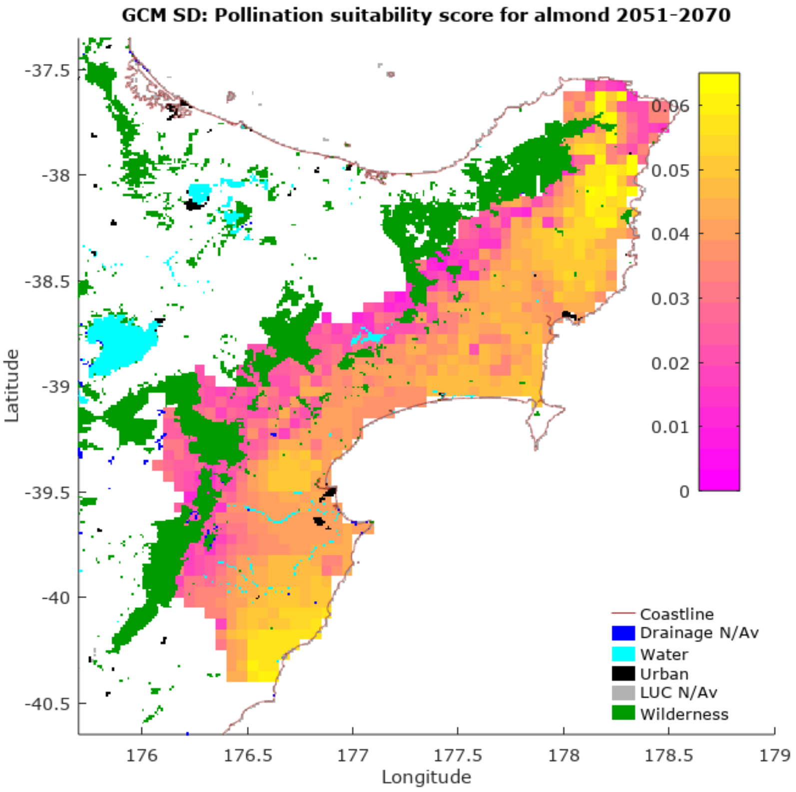


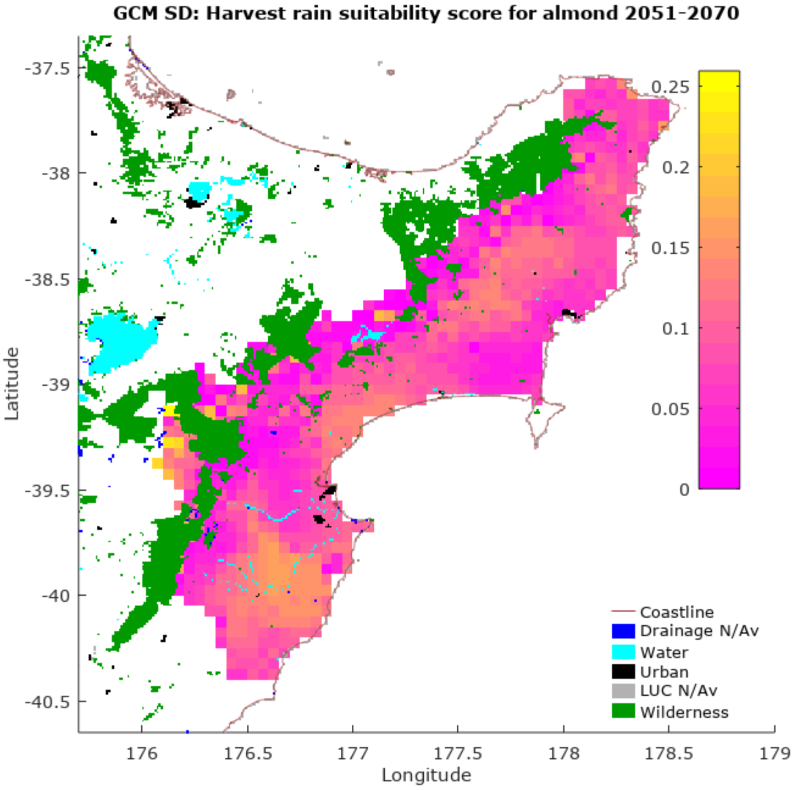

GCM SD: Climate suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

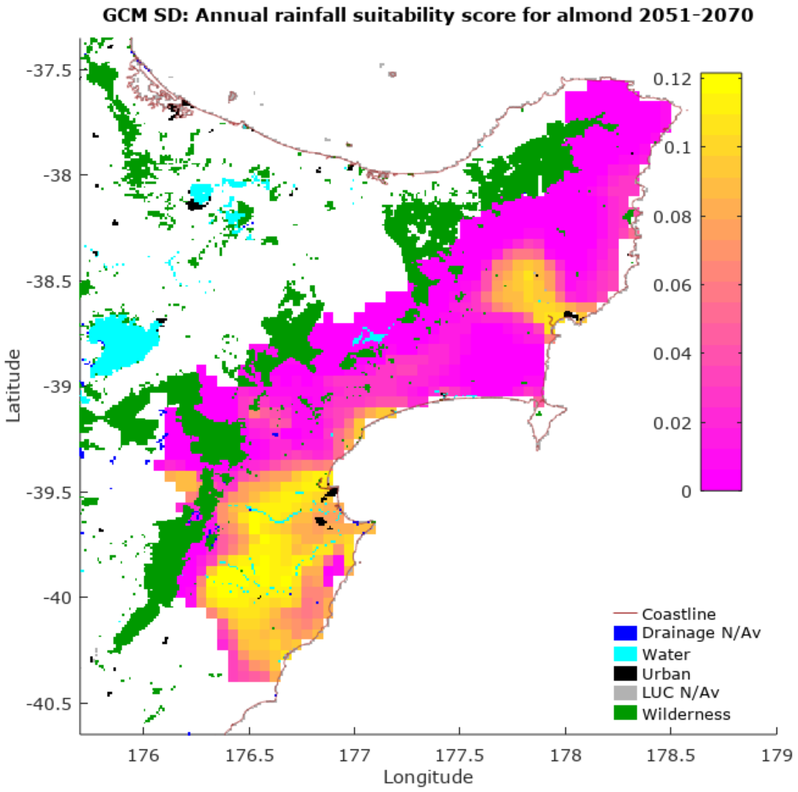

GCM SD: GDH suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.2
0.15
0.1
0.05
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

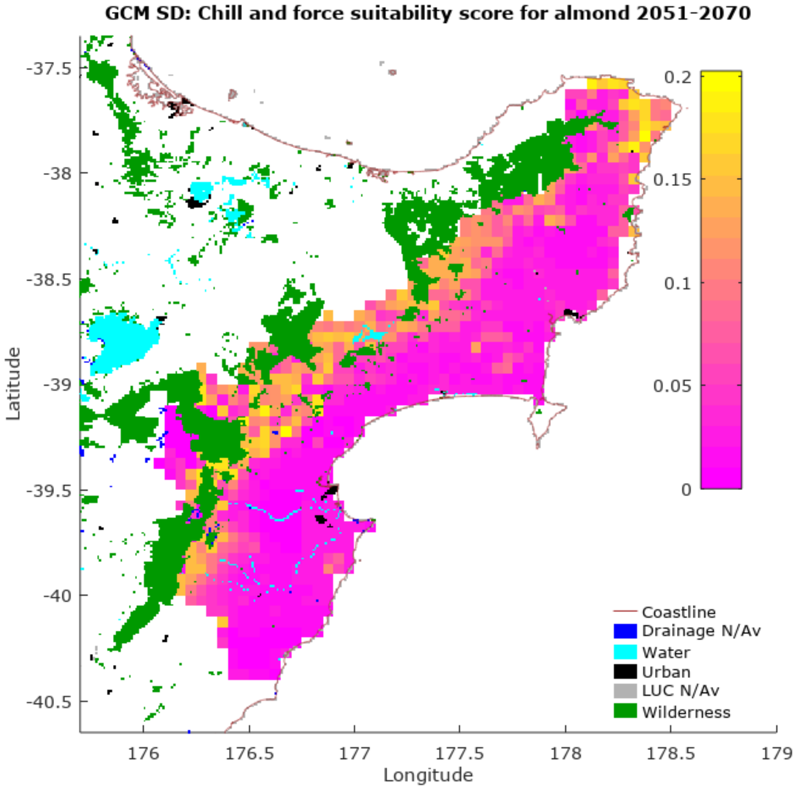

GCM SD: Disease suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.02
0.015
0.01
0.005
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


GCM SD: Frost suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

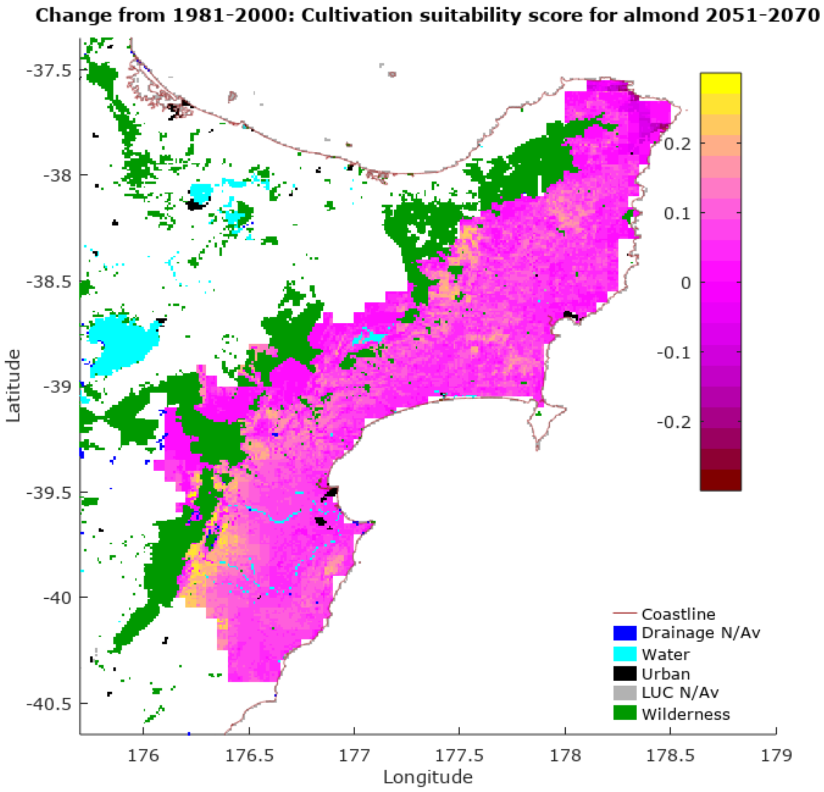

GCM SD: Pollination suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.06
0.05
0.04
0.03
0.02
0.01
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

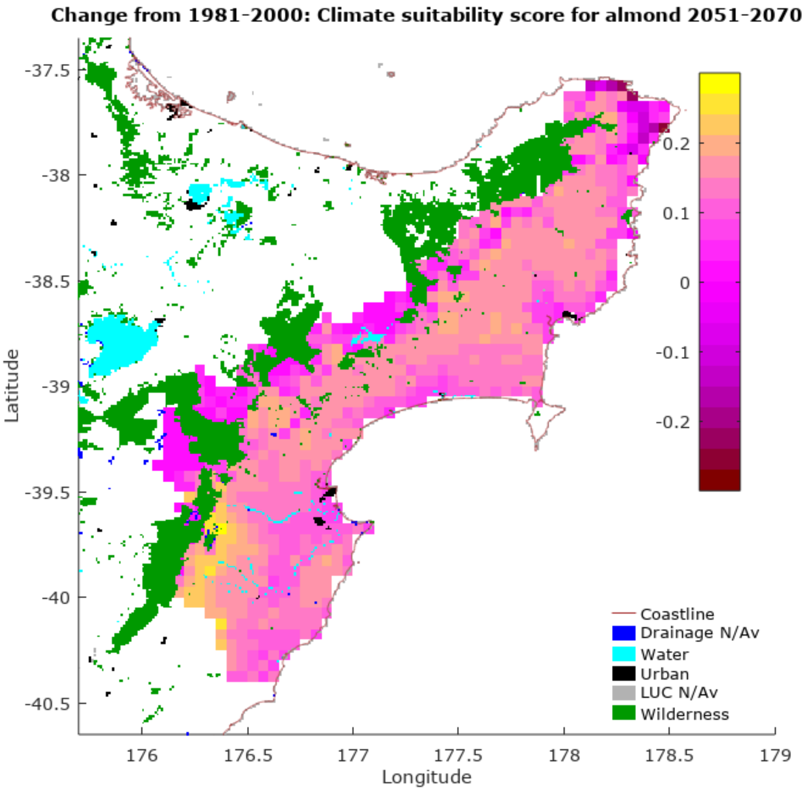

GCM SD: Harvest rain suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.25
0.2
0.15
0.1
0.05
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

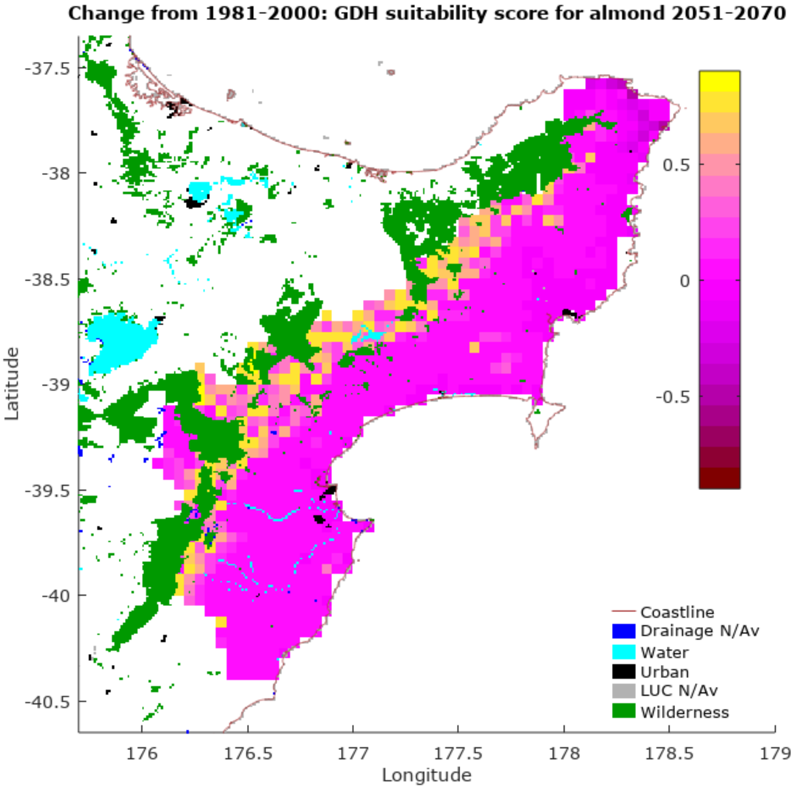

GCM SD: Annual rainfall suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.12
0.1
0.08
0.06
0.04
0.02
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

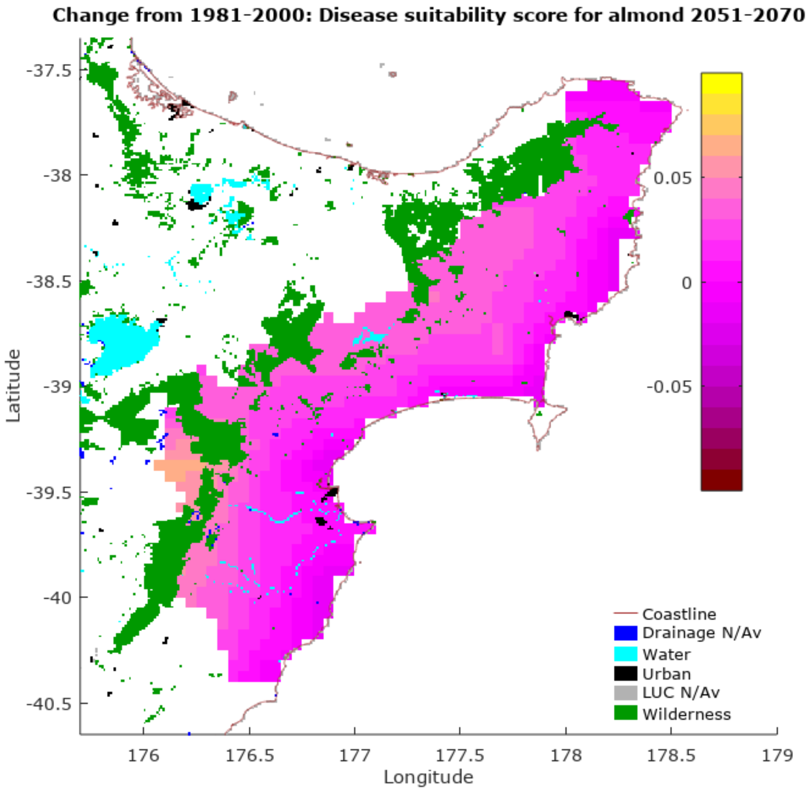

GCM SD: Chill and force suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.2
0.15
0.1
0.05
0
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness

Projected change from 1981–2000 (RCP Past period)




Change from 1981-2000: Climate suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.2
0.1
0
-0.1
-0.2
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: GDH suitability score for almond 2051-2070
Latitude
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Longitude
176
176.5
177
177.5
178
178.5
179
0.5
0
-0.5
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Disease suitability score for almond 2051-2070
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
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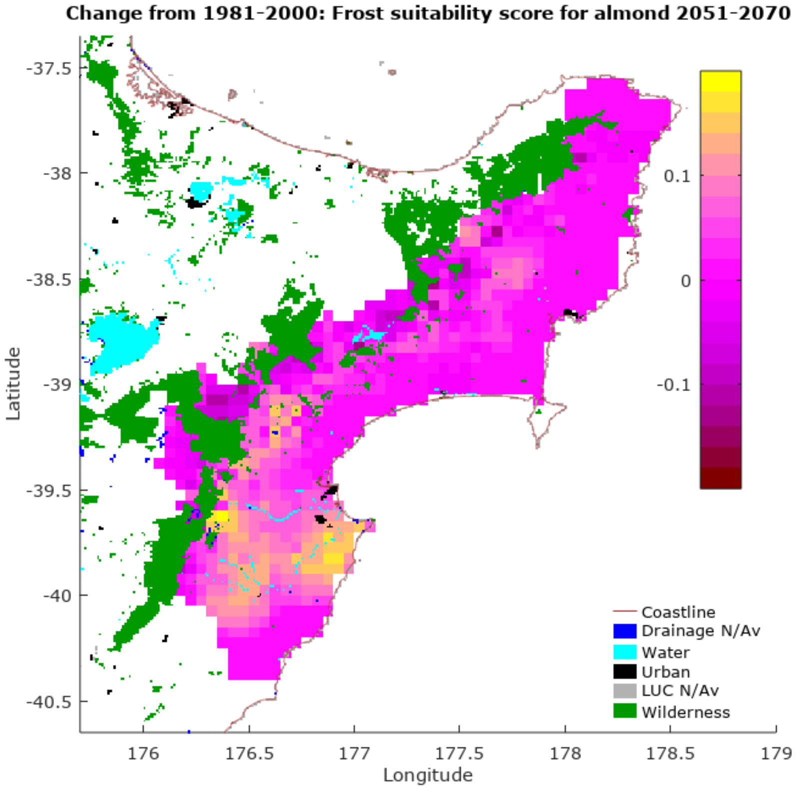
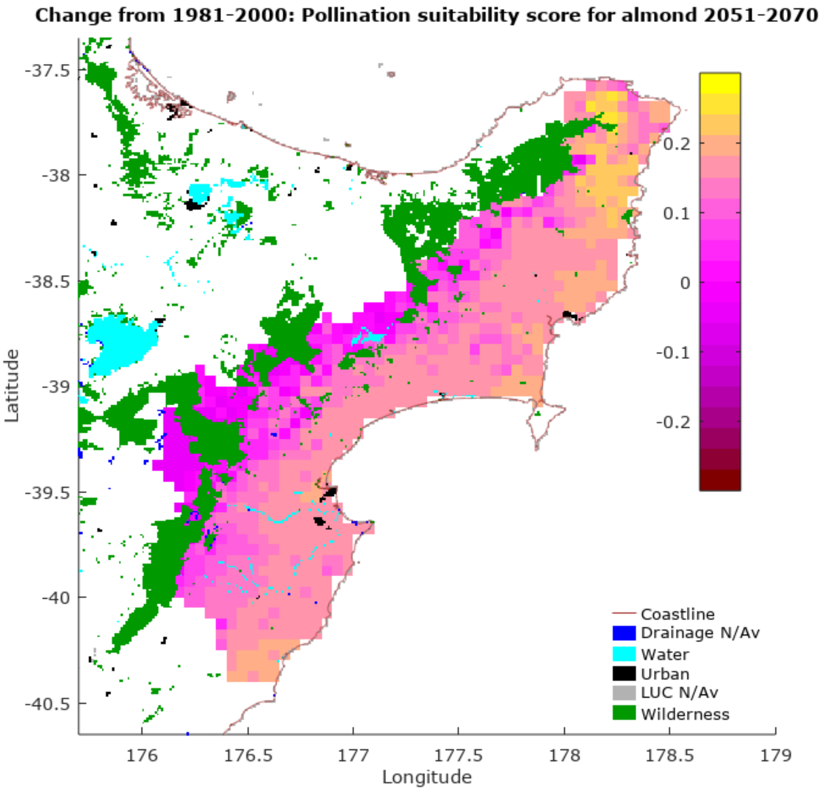
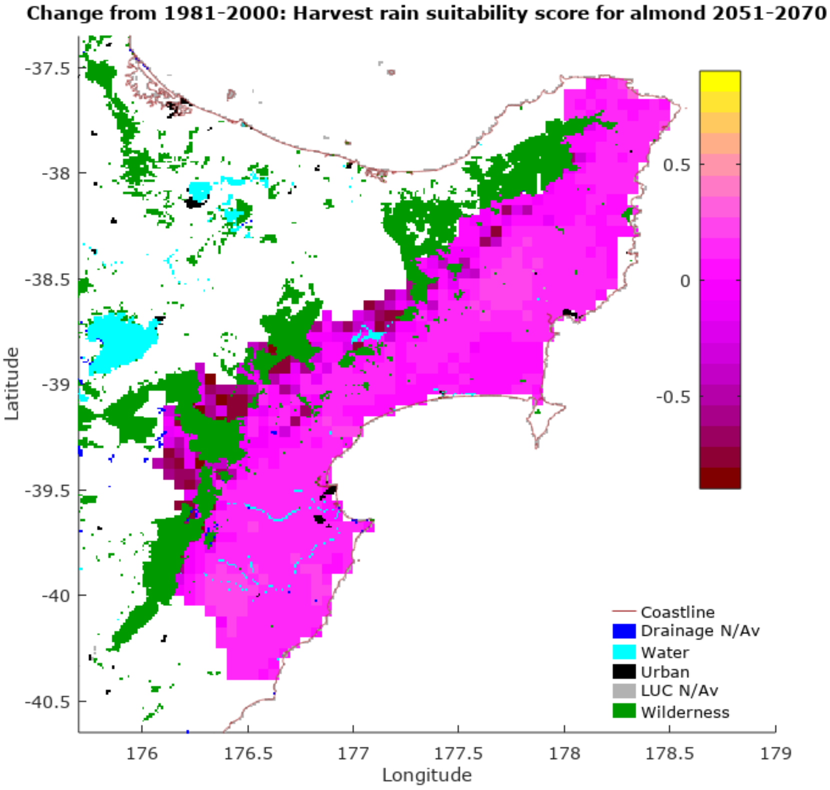
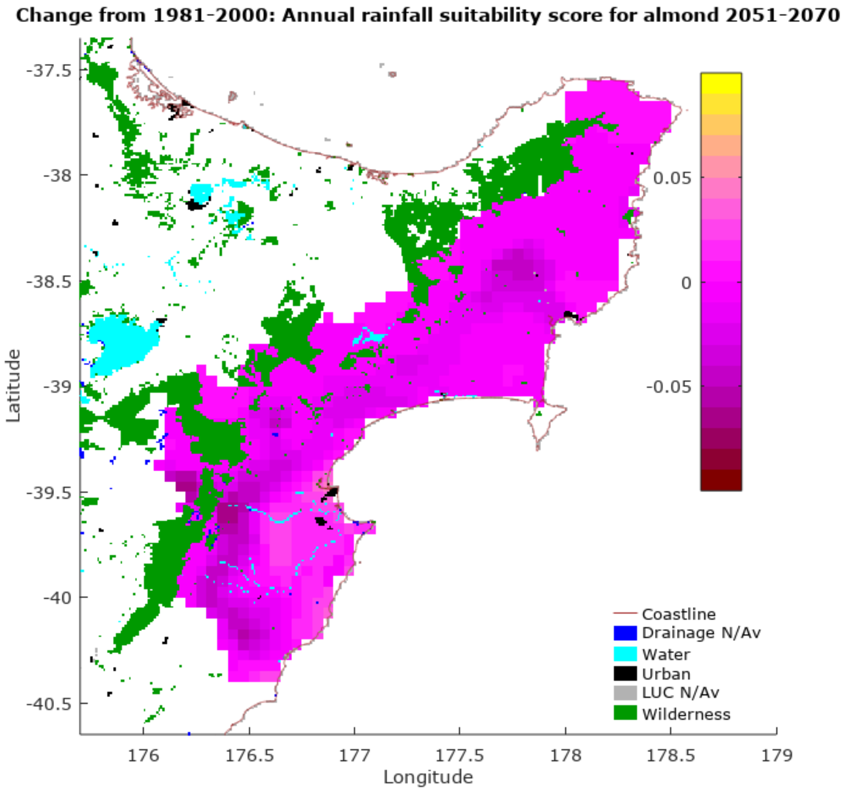
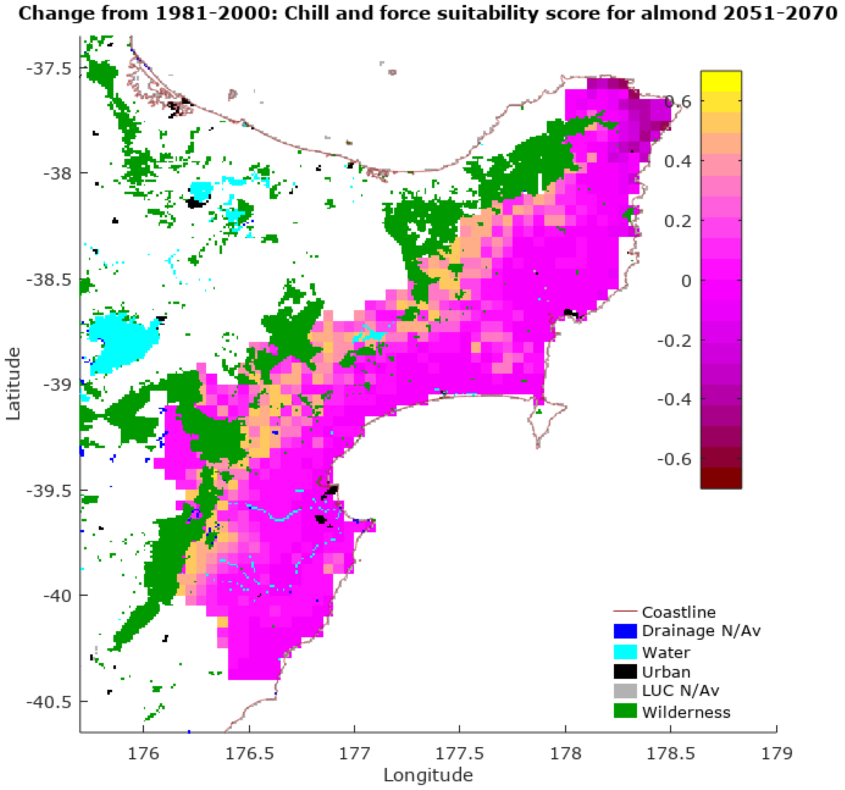
0
-0.05
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Frost suitability score for almond 2051-2070
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
0.1
0
-0.1
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Pollination suitability score for almond 2051-2070
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
0.2
0.1
0
-0.1
-0.2
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Harvest rain suitability score for almond 2051-2070
-37.5
-38
-38.5
-39
-39.5
-40
-40.5
Latitude
176
176.5
177
177.5
178
178.5
179
Longitude
0.5
0
-0.5
Coastline
Drainage N/Av
Water
Urban
LUC N/Av
Wilderness


Change from 1981-2000: Annual rainfall suitability score for almond 2051-2070


Change from 1981-2000: Chill and force suitability score for almond 2051-2070

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