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Modelling Climate Change Impacts on Location Suitability for Cultivating Avocado and Blueberry in New Zealand

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Abstract: Regional suitability for growing avocados and blueberries may alter with climate change. Modelling can provide insights into potential climate change impacts, thereby informing industry and government policy decisions to ameliorate future risks and capitalise on future opportunities. We developed continuous/sliding-scale models that used soil, terrain and weather data to assess location suitability for cultivating avocado and blueberry, based on physiological and phenological considerations specific to each crop. Using geographical information system (GIS) data on soil, slope and weather, we mapped cultivation suitability for avocado and blueberry across New Zealand, and, for accuracy, "ground-truthed" these maps in an iterative process of expert validation and model recalibration. We modelled the incremental changes in location suitability that could occur through climate change using "future" GIS-based weather data from climate model simulations for different greenhouse gas (GHG) pathways that ranged from stringent GHG mitigation to unabated GHG emissions. Changes in maps over time showed where suitability would increase or decrease and to what extent. These results indicate where avocado and blueberry might replace other crops that become less suitable over time, and where avocado might displace blueberry. The approach and models can be applied to other countries or extended to other crops with similar growing requirements.

Keywords: suitability modelling; climate change; regional crop suitability; continuous scale modelling

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1. Introduction

Blueberries and avocados are recognised as healthy foods with high nutritional value. Globally, they both have very high productive and commercial projections. Before growers in Aotearoa, New Zealand (NZ), increase their currently still-modest growing areas and investments for these two industries, the effects of predicted climate change scenarios on the future suitability of different potential growing regions should be assessed.

Even though the harvesting of avocados (*Persea* spp.) and blueberries (*Vaccinium* spp.) from the wild has occurred over thousands of years, producing avocados at a larger scale started only about 150 years ago, and domestication and breeding of blueberries started at the end of the 19th century [1,2]. Both industries are relatively young globally—but even more so in NZ. The blueberry industry was established in Australasia in the 1980s [3] and the NZ Avocado Promotion Association was established in 1980 (see https://industry.nzavocado.co.nz/about-us/who-we-are/history, accessed on 24 June 2024). They are still comparatively small industries in NZ horticulture, but they are seen as emerging opportunities for export to global markets with the potential for the industries to undergo significant expansion. Both NZ avocado and blueberry industries produced less than 1% of the respective global production in 2022 (FAOSTAT) and are small contributors in comparison to Mexico, Peru and Spain. However, the industries have experienced significant growth in NZ over recent years: the area under avocado cultivation grew by 24% to more than 5000 ha from 2021 to 2022 (Fresh-Facts—December-2023.pdf (unitedfresh.co.nz)) and the area planted with blueberries has shown solid growth since the late 1990s with promising potential for increased export production [4]. Growth of both industries is driven mainly by increased global demand due to (i) growing awareness of their scientifically demonstrated human health benefits [5,6] and (ii) the introduction into new markets in Asia.

Further growth of these young industries requires careful planning considering long-term investment for establishing crops. Horticultural industries are particularly vulnerable to many weather-related risks that are exacerbated by the projected effects of climate change. The Intergovernmental Panel on Climate Change estimated global warming of between 1.2 and 3 °C in the mid-century, 2041–2060, depending on the emission scenario considered [7]. Temperature change has direct implications on various phenological development stages, fruit quality and yields, and the occurrence of pests and diseases.

Purpose of the Study

The potential impacts of climate change on horticulture are considered a significant risk. Detailed spatial analysis is required to assess expected regional impacts of climate change. Some regions might become more suitable, while others may be at risk of losing their current climate suitability for certain crops. Risks and opportunities for current plantings and future expansion in the face of climate change can only be projected through modelling.

To our knowledge, modelling the spatial impact of climate change on blueberries has not yet been carried out for NZ. Previous work has focused on breeding blueberry varieties for a wide range of climatic conditions [3]. The impact of climate change on avocado has been estimated for many of the main avocado growing areas worldwide, but not for NZ. Ramírez-Gil et al. [8] simulated the potential future distribution of 'Hass' avocados in the Americas, only considering changing climatic conditions, and concluded that its distribution on that continent was relatively stable. Others modelled the current suitability for growing avocado in Antalya, Turkey [9] and the current and future suitability for avocado production in Australia [10]. The latter also discussed adaptive management strategies for different production regions. Grüter et al. [11] assessed the future suitability for growing avocados at a global scale and considered the crop's climatic and soil requirements. Generally, they found that avocado was relatively resilient to climate change but that climate requirements resulted in greater limitations than soil requirements.

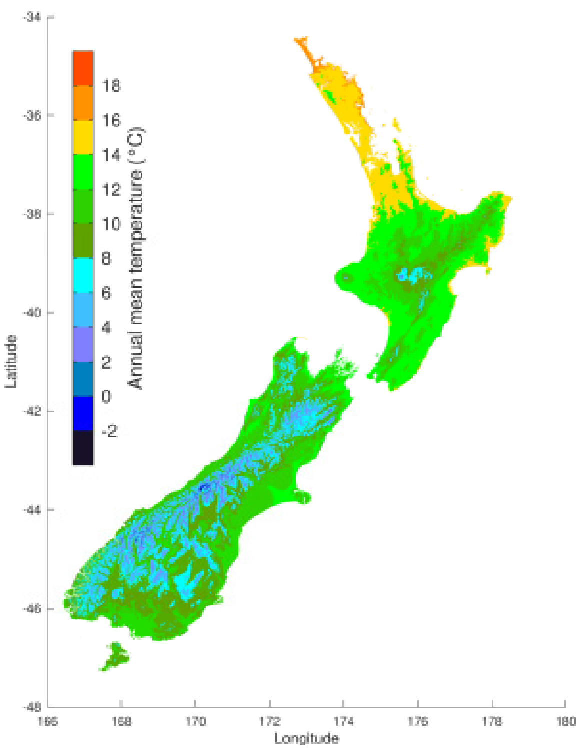
Using a previously developed continuous suitability score approach [12], this project had three main objectives: to determine (i) the current location suitability for avocado and blueberries in NZ; (ii) how location suitability will change under future climate scenarios based on considerations of historic climate data, plant biology, soil and terrain requirements; and (iii) how future land use will be affected by changing suitability. Some of the work presented here was summarised for the NZ Ministry for Primary Industries in a report [13] that has not been independently reviewed. This paper extends the report, including detailing the equations needed for simulations and the provision of some additional analyses at a regional level.

2. Materials and Methods

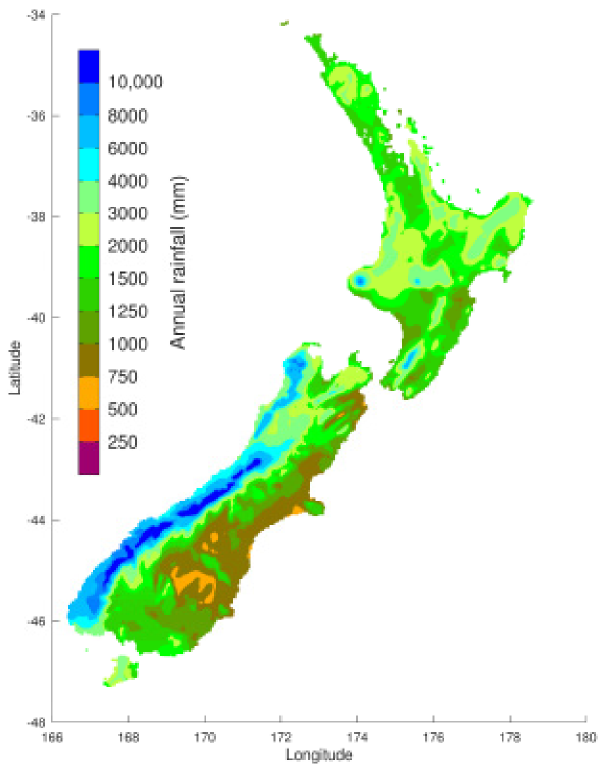
2.1. Study Area and Situation

NZ is an island nation lying between 34° and 47° in the southwestern Pacific Ocean and consists of two main land masses, the North Island and the South Island, which occupy a total land area of 264,000 km^2 [14]. NZ's climate is greatly influenced by interannual climate events such as El Niño-Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM). These atmospheric patterns are also overlain by the effects of topography and geographical location, making the climate pattern dynamic and complex [15,16]. Both islands are dominated by areas of high relief; in the North Island, the volcanic plateau rises 2797 m (ASL) and the island extends into the subtropical region, while landcover is predominantly pasture and areas of indigenous forest; in the South Island, the southwest/northeast trending Southern Alps rise steeply on the west coast of the island to a height of 3724 m (ASL) and extend into the cooler, more temperate region of the southern hemisphere; landcover consists mainly of pasture, tussock and areas of indigenous forest [14].

Most of NZ experiences a mild temperate climate with subtropical conditions in the north of the North Island and semi-arid alpine conditions in the south of the South Island [14]. Mean daytime summer temperatures typically range between 18 °C and 24 °C, mean overnight winter temperatures typically range between −2 °C and 8 °C [14] and annual mean temperatures range from −4 °C to 17 °C (Figure 1a). Precipitation in both the North Island and north of the South Island are characterised by seasonal patterns with winter (June, July, August) maxima, while other regions of the South Island tend to display either autumn maxima or bi-modal patterns (autumn/spring maxima and winter minima) [14]. For the period 1991 to 2020, the mean annual rainfall across the country varied with location from 255 mm to 12,151 mm (Figure 1b). Snow cover is also a common feature of the Southern Alps and ranges from 5% in the summer to 35% in winter [14].



(**a**)



(**b**)

Figure 1. New Zealand climates in terms of annual mean temperature (**a**) and rainfall (**b**) created using data for 1991 to 2020 that were provided by New Zealand National Institute of Water and Atmospheric Research (NIWA).

The different regions of NZ along with the planting densities for avocado and blueberry are shown in Figure 2. Most of NZ's avocado plantings are located in Northland (2169 ha), the Bay of Plenty (2124 ha) and Auckland (598 ha) with an additional 269 ha of avocados grown in the rest of the country in 2022 (https://figure.nz, accessed on 9 September 2024). Plantings extend into the south of the country but are constrained to the less mountainous regions and at a much smaller planting density (Figure 2). Blueberries had a planted area of almost 700 ha in 2022/2023 (https://unitedfresh.co.nz/assets/site/images/images/Fresh-Facts-%E2%80%93-December-2023.pdf, accessed on 6 June 2024), and are cultivated throughout the North Island and a few locations in the South Island, with the primary production areas located in the Waikato region. There is also notable production in the Bay of Plenty, Hawke's Bay and Northland in the North Island, and the Tasman/Nelson and Canterbury regions in the South Island [4].

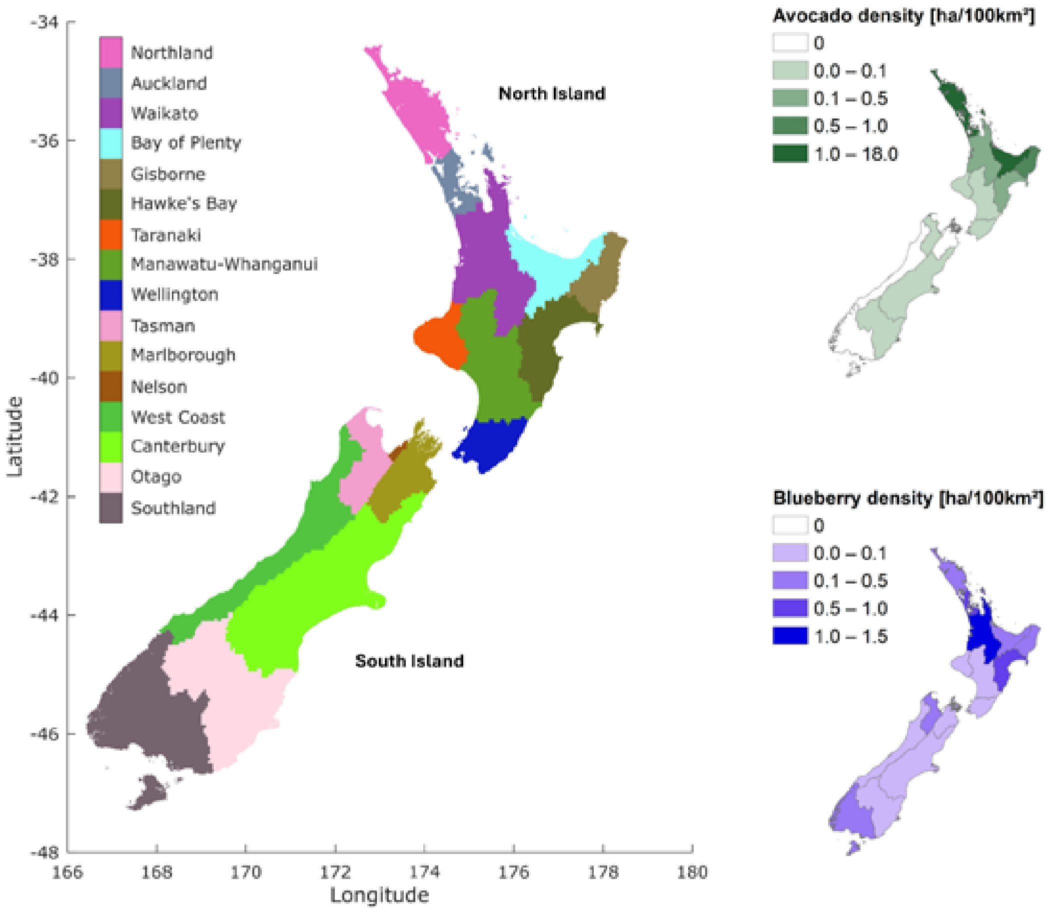


Figure 2. Regions of New Zealand based on assignment of location mappings in Virtual Climate Station Network (VCSN) data, with inset maps indicating crop densities for avocado and blueberry by region based on regional planting data made available by Statistics New Zealand (https://figure.nz/, accessed on 9 September 2024).

Crop suitability models were developed in two steps: (1) slope, soil and observation (historical) climate data were used to produce historical suitability maps; and (2) these models were assessed by horticultural experts and refined in a process of "expert calibration". The resulting suitability models were then used with climate projection data from simulations that extend from a historical (past) period into the future, and suitability maps for the past and future periods were constructed. Comparison of the past and future maps indicated the potential climate change impacts. This approach is schematised in Figure 3.

2.2. Criteria for Assessing Location Suitability for Avocado and Blueberry

Climate, land and terrain factors considered essential for successful production by experts were used to inform location suitability, and these could differ between crops. For example, adequate winter chill (the minimum amount of cold exposure needed after a dormant rest period for plants to burst bud and flower satisfactorily) is a requirement for blueberries but not avocado. Frost events after flowering and before harvest can damage both flowers and developed fruit, and while this is a consideration for both crops, avocado is also susceptible to cold damage to leaves, shoots and branches throughout the year. Both crops have warmth requirements for successful production of fruit, adequate soil depth for root development, good drainage, and appropriate soil pH. The slope of the land is important from a management perspective. An additional suitability criterion that was used is land use capability (LUC) class, a generic land descriptor, which is explained in detail by Lynn et al. [18].

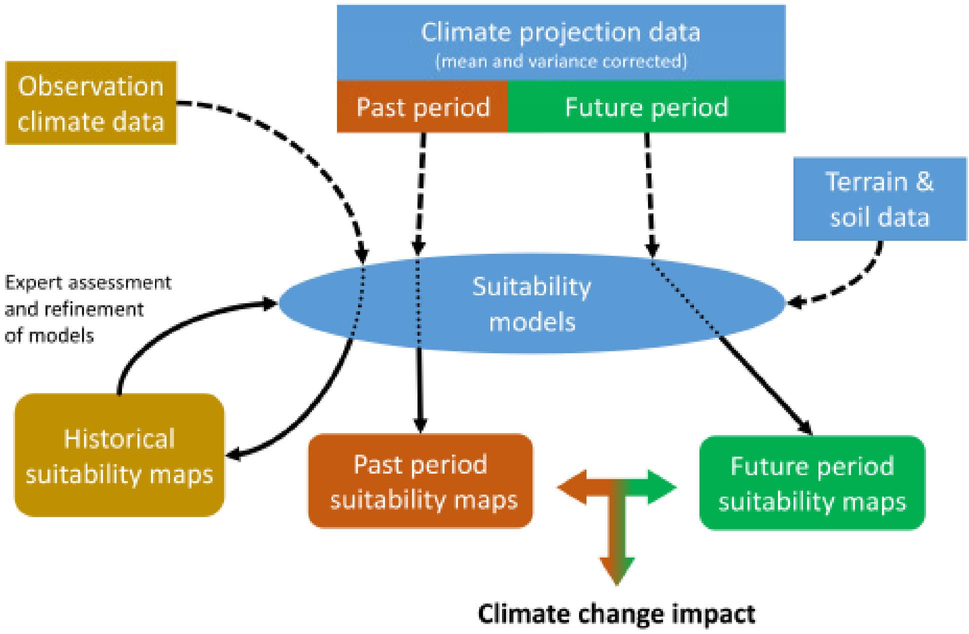


Figure 3. Schematised approach for estimating the impact of climatic change on crop suitability used. Model and procedures are represented by the oval; dashed lines from rectangles with angular corners moving to the oval indicate data inputs for modelling; solid lines from the oval to rectangles with rounded edges represent modelling outputs: (i) observed climate data together with soil and terrain data were used to construct suitability models, with feedback from experts used to refine and calibrate the models; (ii) new past period and future period maps were calculated using climate projection data that had been bias and variance corrected to the observation climate data, and this allowed climate change impacts on suitability to be projected. Historic observation, and past and future period climate model simulation data and outputs are coloured, respectively, mustard, brown and green. (Adapted from [17]).

While soil texture and structure are potential criteria for avocado cultivation [19,20], avocado can be successfully grown in many soil types with suitable management practices that result in adequate soil depth and drainage [21]. Thus, we excluded soil texture and structure in our considerations.

2.3. Datasets and Software Used

2.3.1. Climate Data

Observation Climate Data

Modelled, historical climate information was provided by the Virtual Climate Station Network (VCSN) data obtained from the New Zealand National Institute of Water and Atmospheric Research (NIWA). The VCSN data used NZ Geodatum 1949 (NZGD49) coordinates, on a 0.05 × 0.05-degree (approximately 5 km × 5 km) grid. More detail on the VCSN dataset, the observation climate data in Figure 3, is provided in an earlier publication [12].

Climate Projection Data

Future climate suitability modelling was performed for four Representative Concentration Pathways (RCPs), each of which represents a different scenario of greenhouse gas (GHG) emissions: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. These have approximate total radiation forcings of 2.6, 4.5, 6.0 and 8.5 Wm^{-2}, respectively, by the year 2100 relative to 1750 [22]. Climate projection data using the 5 km × 5 km VCSN grid were provided by the 'SLM (Sustainable Land Management) RCP' datasets, which we developed by performing novel bias and variance corrections [17] on climate projection temperature data that had been provided by NIWA. The NIWA climate projection datasets, which comprise six CMIP5 (Coupled Model Intercomparison Project Phase 5) global climate model simulations per RCP, have been described in detail in reference [22].

For each RCP, simulated daily data were used from 1971 to 2099 (RCP datasets), with the years 1971 to 2005 (referred to as 'RCP Past') comprising the historical period of the simulations and 2006 onwards ('RCP Future') comprising the future period. RCP Past data varied between CMIP5 models, but within each CMIP5 model, all RCPs used the same RCP Past dataset. Data from the newer CMIP6 generation of models were not available for NZ.

Bias and Variance Corrections to Climate Model Data

The NIWA climate projection datasets had been bias corrected for agreement with the VCSN datasets on annual means for maximum and minimum temperature data for the period 1986–2005 [22]. To improve the congruence between the climate projection data and the VCSN data, we developed the SLM RCP datasets by performing further adjustments separately on minimum and maximum temperature to obtain past period agreement with the VCSN data on the following metrics [17]:

1. Variance of daily temperature for each calendar month
2. Variation of the monthly mean temperature around the corresponding monthly mean for the bias-correction period, separately for each calendar month
3. Mean temperature for each calendar month.

These adjustments were carried out separately for each GIS location and for each RCP dataset. We refer the reader to our previous article and its supplementary material [17] for a detailed description of these adjustments, their outcomes and limitations.

Resolution of the Climate Data

The VCSN and climate projection datasets give daily values for weather variables. When required, we obtained hourly temperature values from maximum and minimum daily temperatures by assuming a sinusoidal variation in temperature over a 24 h period. The 25 km^2 area corresponding to each VCSN grid cell could contain different microclimates. For example, proximate sites differing in elevation by only 8 metres could differ in minimum temperature by up to 2 °C, and mean temperature by 1 °C [23]. Such variation is not included in the climate data but can be accounted for when modelling, by assuming that temperature could vary by up to ±2% around the representative value given by the climate data.

2.3.2. Land and Soil Data

Land and soil information were obtained from New Zealand Fundamental Soil Layer (FSL), New Zealand Land Resource Inventory (NZLRI), Land Environments of New Zealand (LENZ) and Department of Conservation (DOC) databases through koordinates.com. FSL and NZLRI data were reproduced with the permission of Landcare Research New Zealand Limited. We queried the land and soil information on a 0.01 × 0.01-degree (approximately 1 km × 1 km) grid aligned with the VCSN grid. More detail on these data is provided in our earlier publication [12].

2.3.3. Software

Suitability calculations, graphing, climate-change impact projections and situation and suitability mapping were carried out using versions 6.20 and 8.4.0 of the open source modelling environment GNU Octave (https://octave.org, last accessed 21 February 2024). Querying soil and terrain data on the 0.01 × 0.01-degree grid and construction of planting density maps were carried out in ArcGIS software (ArcMAP version 10.0. Redlands, CA, USA: Environmental Systems Research Institute).

2.4. Existing Crop Distributions vs. Expert Opinion for Evaluating Model Performance

The suitability assessments in this study were performed for the suitability of locations for growing crops without adaptations to mitigate soil or climate limitations, to gauge the potential impacts of climate change. We emphasise that suitability modelling is a different proposition from predicting actual orchard locations, and there is not a direct relationship between location suitability and the existence of orchards. The decision to cultivate lies with the grower.

Adaptations may allow orchards to exist under less favourable conditions, and conversely, highly suitable locations may be devoted to land uses other than the crops in the study. Such decisions will be influenced by economic, cultural, emotional, policy-based and historical factors, and by the presence of roading and other infrastructure. Additionally, the presence of microclimates within a grid cell may allow successful cultivation of a crop, despite the assessment of the grid cell being unfavourable. We note also that not all orchard locations are recorded.

Therefore, it is not appropriate to use existing crop distributions to calibrate suitability models directly or to form metrics to evaluate their predictions. Rather, we used 'expert parameterisation' in which the models were calibrated to agree with the opinions of industry experts. These experts were chosen based on on-ground experience in the avocado and blueberry industries, including the spatial distribution of orchards, and the soil and climate challenges in the study area, having had many years of research and industry experience, including orchard visits and advising growers across the country. Such experience provides familiarity with the different regions and the ability to gauge the reliability of predictions for locations where the study crops are not currently grown.

2.5. Suitability Modelling

The continuous suitability score approach that we previously developed [12] was applied, which, for each identified climate, soil, and land criteria relevant to a crop, predicted how well growing requirements were met for each location on a continuous scale from 0 (totally unsuitable) to 1 (extremely suitable). This methodology allowed suitability scores for individual criteria to be combined using weighted geometric averaging, with appropriate weights determined by horticultural experts. Calculations were performed separately for each grid location in the datasets, to obtain suitability calculations across the entire country.

For climate-related criteria, we performed calculations for the winter-to-winter growing year, 1 July to 30 June. For each climate-related criterion, a suitability calculation was made for each year of the period considered. Individual yearly scores for each criterion were averaged to obtain a criterion suitability score:

$$S_i = \frac{1}{M}\sum\nolimits_{m=1}^{M} S_{im} \tag{1}$$

where S_i is the climate suitability score for criterion i for the period of M consecutive years, and S_{im} is the suitability score for criterion i in year m, $m = 1, \ldots, M$.

A climate suitability score for the same period, S_c, was obtained by weighted geometric averaging of the yearly suitability scores for climate-related criteria, and then averaging these over the M years, i.e.,

$$S_C = \frac{1}{M}\sum\nolimits_{m=1}^{M}\left(\prod\nolimits_{i=1}^{p} {S_{im}}^{w_i}\right)^{1/w_C},\ w_C \equiv \sum_{i=1}^{p} w_i \tag{2}$$

where p is the number of climate criteria, and the weight w_i reflects the importance of criterion i, for $i = 1, \ldots, p$. Soil/land suitability scores, S_S, do not change over time, and weighted geometric averages of individual scores were taken to obtain an overall soil suitability score:

$$S_S = \left(\prod_{j=1}^{n} S_j^{w_j} \right)^{1/w_S}, \; w_S \equiv \sum_{j=1}^{n} w_j \tag{3}$$

where S_j is the suitability score for soil/land criterion, $j = 1, \ldots, n$, w_j is its corresponding weight, and n is the number for soil/land criteria. A location suitability score S that assesses the overall suitability for growing a crop was reached by weighted geometric averaging of suitability of climate and soil/land as follows:

$$S = \left({S_C}^{w_C} \times {S_S}^{w_S} \right)^{1/(w_C + w_S)} \tag{4}$$

where the weights for climate and soil suitability are the sum of the weights for their respective underlying criteria.

Suitability models were 'ground-truthed', and weights were determined, in conjunction with horticultural experts, using maps of calculated suitability scores across NZ. Ground-truthing of climate-related scores was carried out using suitability maps constructed using the most recent VCSN data available to us, for the growing years 2006 to 2016. This was a relatively recent period that expert horticulturalists could relate to.

2.6. Modelling Suitability Criteria

2.6.1. Winter Chill for Blueberries

Commercial blueberry cultivation in NZ mostly utilises rabbiteye and highbush varieties, and so we ignored lowbush varieties of blueberry. Rabbiteye chilling requirements have been listed as 400 to 700 chill hours (threshold 6–7 °C) [24] and 250 to 650 h < 7 °C [25]. Southern highbush varieties have been reported to require chill hours of 100 to 450 h < 7 °C [26] and 200 to 600 h < 7 °C [27]. In contrast, cold-adapted northern highbush varieties require 800–1000 h < 7 °C [28].

We obtained total winter chill with the calculated daily chill hours below 7 °C from May to August (late autumn to late winter), using daily maximum and minimum temperatures. Allowing for temperature variation within each 25 km^2 grid cell, as well as the variation between varieties and bush types, we used the logistic equation (Equation (5)) for the blueberry chill suitability score (y), parameterised ($a = 0.00735$ and $b = 550$) to have the values 0.05, 0.5 and 0.95 for chill hour accumulations (x) of 150, 550 and 950, respectively, as graphed in Figure 4.

$$y = \frac{1}{1 + \exp(a(x - b))} \tag{5}$$

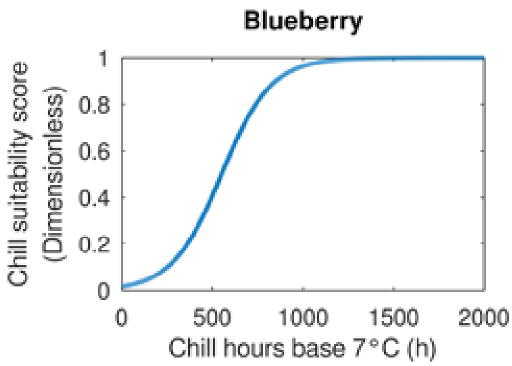


Figure 4. Blueberry: suitability curve for winter chill as a function of chill hours below 7 °C.

A higher chill score for a location can be construed as indicating more satisfactory chill accumulation, or otherwise, as signifying an increase in the range of varieties that will receive sufficient chill.

2.6.2. Frost Risk

For each crop, we modelled, as a function of the minimum temperature, what fraction of the potential fruit yield and/or foliage would survive frost damage on each day. When doing this, we assumed there would be variability in temperature within a grid of ±2 °C around the given daily temperature (e.g., for a temperature of 0 °C, the temperatures would range between −2 and 2 °C within the grid). One minus the damage rate gives a daily frost survival, which is described by the following equation, with r being the tissue/yield survival rate and x being daily minimum temperature [12].

$$r = \frac{\exp(a(x-b))}{1+\exp(a(x-b))} \tag{6}$$

An overall suitability score for frost was acquired by aggregating the daily losses over the risk period, which is determined separately for each crop:

$$y = \prod_{i=m}^{n} r_i^{\,p_i} \tag{7}$$

In the above equation r_i is the frost survival rate calculated from Equation (6) for day i; $i = 1, \ldots, m$, with m being the first day of a particular growing year on which plant tissue would be susceptible to a frost if it were to occur, and n being the last day. Both m and n are calculated separately for each year based on weather patterns and crop phenology. The power $p_i \in [0, 1]$ represents the proportion of the crop susceptible to damage. Depending on the crop, p_i could be varied from 0 to 1 and 1 to 0 for the beginning and end of the frost risk period to represent, respectively, the variation in phenological stage between plants and harvest time between blocks. The effect of protective measures could be modelled by decreasing p_i.

Avocado

Frost resistance varies with avocado variety, and conditions under −5 °C for more than 4 h are considered harmful to all varieties [9]. However, 'Hass', which accounts for 95% of plantings in NZ, has a frost resistance down to only −1.1 °C [19]. Damage was extensive for 'Hass' avocado experiencing temperatures ranging from 0 to −3.3 °C for 32 h, and from 0 to −4.4 °C for 51 h, resulting in foliage death of up to 50% within 3 weeks and of over 80% after 2 months [29]. We used the daily frost survival curve, Equation (6), with parameter values $a = 1.3\ ^\circ\mathrm{C}^{-1}$ and $b = 1.3\ ^\circ\mathrm{C}$, which gives rates of survival for leaf and flower: 21% at −4 °C, a midpoint of 50% at −3 °C, and 98% at 0 °C (Figure 5a).

Different stages of avocado fruit and leaves are present throughout the year; thus, for every day in the growing year (1 July to 30 June), the daily frost survival was calculated and multiplied to obtain an overall frost suitability score.

Blueberry

Blueberry flowers and flower buds are the blueberry tissues most sensitive to frost damage, and in some highbush-variety flowers the LT_{50} (lethal temperature for 50% kill) is −7.5 °C [30]. However, in other highbush varieties, a −8.4 °C spring frost killed less than 10% of flower buds, and young shoots were only damaged when winter temperatures fell to −23.4 °C [31]. Highbush and southern highbush varieties are considered more frost tolerant than rabbiteye [32]. The most sensitive flower part is the corolla, with LT_{50} for several highbush varieties ranging between −2.1 and −3.3 °C, and it is likely that corolla damage is inversely correlated with fruit set [33]. Corolla damage occurred in 0, 20%, 75% and 100% of 'Brightwell' rabbiteye flowers at, respectively, −2, −2.5, −3 and −3.5 °C [34]. This corresponds to an LT_{50} of −2.8 °C, which falls within the LT_{50} range (−2.1 to −3.3 °C) observed for several highbush cultivars [33]. The latter two evaluations took place in controlled environments and may not be representative of results in commercial entities involving a range of varieties. Variation in damage between cultivars can depend on the timing of flowering periods relative to frost events [35].

With consideration of LT_{50} values across studies, and placing more weight on field observations, we used Equation (6) with $a = 1.1\ ^\circ C^{-1}$ and $b = -4.5\ ^\circ C$ to obtain a frost survival curve with the following rates of survival: 90% at $-1.5\ ^\circ C$, 50% at $-4.5\ ^\circ C$ and 10% at $-7.5\ ^\circ C$ (Figure 5b).

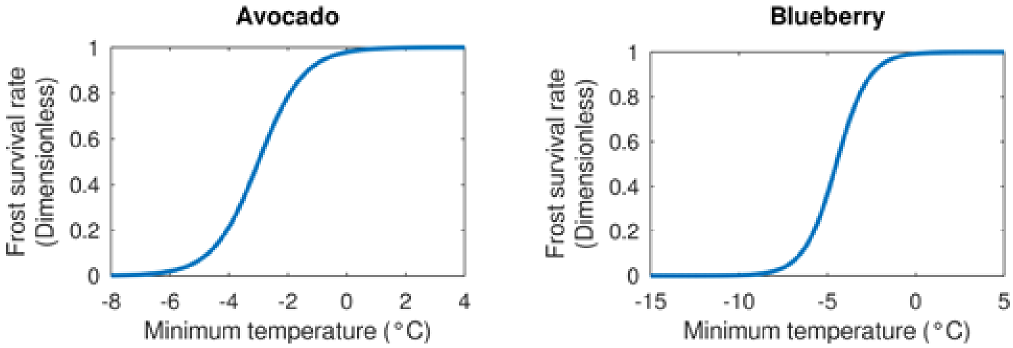


Figure 5. Daily frost survival rate as a function of minimum daily temperature for (**a**) reproductive and leaf tissues for 'Hass' avocado and (**b**) reproductive tissues across different types and cultivars of blueberry. Frost suitability scores are obtained by accumulating frost survival rates over the frost risk period for each crop using Equation (7).

Flowering for blueberries in Tasmania occurs in September and October [36], and because adequate data were not available for NZ, we characterised these months as the risk period for frost in NZ, instead of attempting to predict the different times of flowering for each variety. The calculated daily frost survival rates were multiplied for this period to obtain an overall suitability score, which is 1 minus the cumulative damage. The majority of the North Island has high suitability scores for frost, except for mountainous and high elevation inland areas, as does most of the South Island lowland areas. Consequently, high frost risk occurrences are not frequently encountered in most areas within NZ that are currently growing blueberry.

2.6.3. Temperature and Warmth for Crop Maturation

Avocado

The limiting temperature factors for avocado have been identified as frosts, minimum temperature during flowering and pollination, and heat stress during fruit development, but the literature holds conflicting views on optimal temperature ranges [19]. The lack of consensus may arise from differences between Type A and Type B varieties. In Type A varieties, the flowers open as females in the morning, at mid-day they close, and they reopen as males the next day in the afternoon, while in Type B varieties, the flowers open as females in the afternoon, in the evening they close and they reopen as males the next morning [37]. Ish-Am and Eisikowitch [38] suggested that the pollination process in Type A varieties (such as 'Hass') may be less sensitive to low temperatures than Type B varieties because Type B pollination periods are shortened by low temperatures, whereas those authors did not observe a temperature effect on Type A pollination periods. However, low temperatures overnight can delay the beginning of the female flower opening in 'Hass', resulting in flowers remaining open overnight with probable nocturnal pollination by moths [39].

Flower bud initiation is inhibited by temperatures above 20 °C [40,41]. In NZ, floral bud initiation normally occurs in April and May, but in the western Bay of Plenty it can occur in March [42], and the main flowering mainly occurs between mid-October and mid-November [43]. The range of night temperatures of 20 °C to day temperatures of 25 °C were found to result in optimal pollination and yield [43]. The length of the flowering period and open flower numbers in 'Hass' avocado decreased at higher temperatures [44], and pollen tube growth was disrupted at lower temperatures [45]. Optimal growth also occurred with temperatures of 25 and 20 °C during day and night, respectively [44]. However, these studies investigated only a small fraction of possible temperature variations and cannot be used to formulate suitability criteria. A mean temperature during flowering between 10 and 35 °C has been suggested as a suitability criterion [9].

Alternatively, Dubrovina and Bautista [19] took a less focused view by characterising climates as optimal for avocado when average annual temperatures were 15–20 °C, with lower yields outside this range, and with average annual temperatures lower than 12 °C considered unsuitable. We followed this approach, and, allowing for a variation of 2 °C within each grid cell, we used Equation (8) for warmth suitability (y) as a function of accumulated mean annual temperature (x) with parameter values $a = 2.074 \times 10^{-3}\ ^{\circ}\text{C}^{-0.25}$, $b = 17.5$ °C and $c = 4$.

$$y = \exp\left(-a(x-b)^c\right) \quad (8)$$

This gives approximate suitability values of 0.15 for average annual temperatures of 12 and 23 °C and of 0.9 for average annual temperatures of 15 and 20 °C (Figure 6a). Temperature also affects the nutritional qualities of 'Hass' avocado, such as fatty acid composition [46], but we have not considered fruit quality in our suitability modelling.

Blueberry

A heat accumulation model was proposed in which the daily contribution was graduated from negative to positive with increasing temperature [47]; however, most studies have used growing degree days (GDD), as follows. Mean interval and GDD accumulation base 7 °C from 50% open flowers to 50% fruit maturity ranged between 75 and 94 days and between 1789 and 2554 d °C, respectively, for seven rabbiteye cultivars [48] and 56 to 83 days and from 587 to 824 d °C for seven southern highbush cultivars [49]. Çelik [50] stated that northern highbush varieties require between 120 and 160 GDD for fruit ripening but did not state the base temperature for the accumulation period. For NZ conditions, a GDD accumulation of 600 d °C base 10 °C from October through to April is considered a minimum requirement across blueberry varieties [51].

We allowed for an extensive growing season across varieties, by assuming a window for maturation between October and April and GDD, base 10 °C, accumulation was calculated over this period.

We used Equation (5) for the GDD suitability score; y, as a function of accumulated GDD; x, with parameter values $a = -0.011$; and $b = 700$. This gives a score of 0.5 for 700 d °C, approximately the mean GDD for a range of southern highbush varieties, and scores of 0.25 and 0.75 for GDD accumulations of 600 and 800 d °C, respectively, which represent the approximate extremes of GDD accumulation for southern highbush varieties given above (Figure 6b). The reported rabbiteye GDD requirement noted above seemed excessive and was not considered when developing the model.

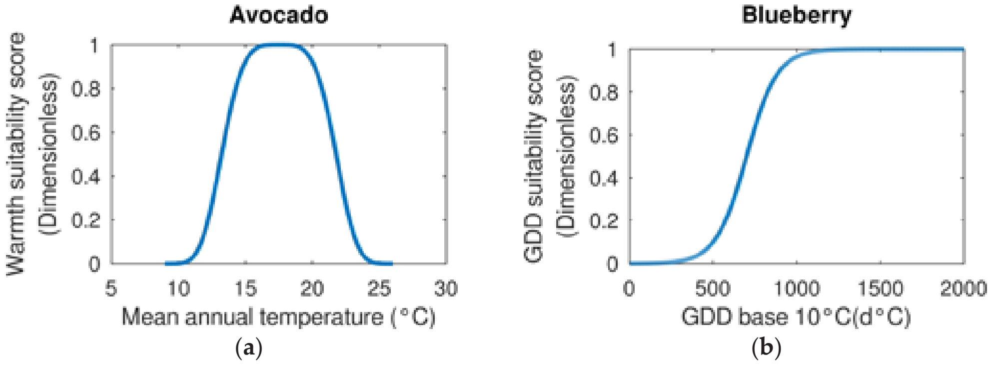


Figure 6. (**a**) Warmth suitability score for 'Hass' avocado as a function of mean annual temperature; (**b**) growing degree day (GDD) suitability score for blueberry as a function of GDD base 10 °C accumulated over October to April.

2.6.4. Potential Rooting Depth

The potential rooting depth (PRD) is the depth of soil to a root-impermeable layer, and this determines the vertical extent of a plant's root system, with deeper soils allowing a more robust root system and potentially conferring more tolerance of drought.

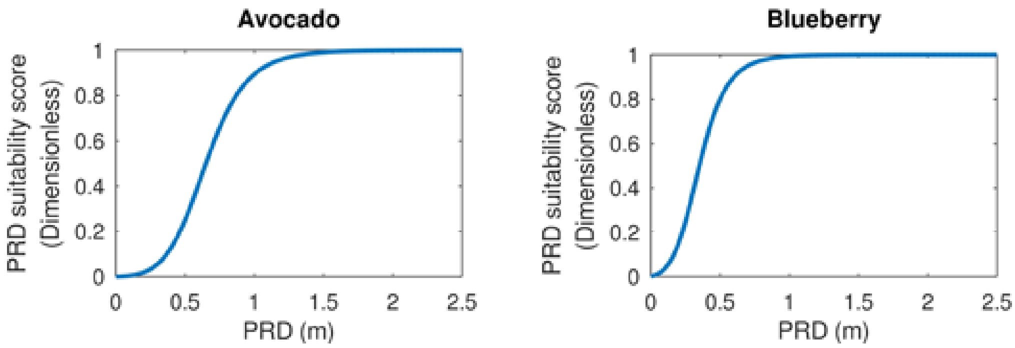
Avocado

McCarthy [21] preferred a PRD of 2 m for good performance, with 1 m being the minimum. Contrasting this, other authors have suggested that a PRD $\geq$ 0.9 m is optimal [51,52]. Dubrovina and Bautista [19] classified a PRD below 0.5 m to be not suitable, 0.5–0.8 m to be of low suitability, 0.8–1 m to be suitable and more than 1 m to be highly suitable. We used Equation (9) with parameter values of $a = -11\ \mathrm{m}^{-0.5}$ and $b = 0.65$ m to give PRD suitability values; y of 0.25, 0.5, 0.85 and 1 at respective PRDs; and x of 0.5, 0.65, 1.0 and 2.0 m (Figure 7a).

$$y = \frac{1}{1 + \exp\left(a\left(\sqrt{x} - \sqrt{b}\right)\right)} \tag{9}$$

Blueberry

Blueberry has shallow roots, with the main root mass being at a depth of 5 to 35 cm [30], and is able to grow in soils with a PRD of 0.45 m or deeper [52]. Various minimum criteria have been suggested: PRD $\geq$ 15 cm [51], PRD $\geq$ 46 cm [53] and PRD $\geq$ 61 cm [54]. We used Equation (9) with parameter values of $a = -12\ \mathrm{m}^{-0.5}$ and $b = 0.35$ m, to give PRD suitability values; y of 0.15, 0.5 and 0.9 at respective PRDs; and x of 0.2, 0.35 and 0.6 m (Figure 7b).



(**a**) (**b**)

Figure 7. Potential rooting depth (PRD) suitability as a function of PRD for (**a**) 'Hass' avocado and (**b**) blueberry varieties.

2.6.5. Drainage

Drainage was reported in the database as categories, with the drainage classifications of 'well', 'moderate', 'imperfect', 'poor' and 'very poor', reflecting factors such as permeability, depth, water-table depth, and soil structure. Avocado requires good drainage because it is not tolerant of waterlogging [19–21]. Blueberry is highly sensitive to waterlogging and should only be planted on soils that are well-drained, or, if they are only moderately well-drained, they will require artificial drainage [52,53,55]. The severity and extent of *Phytophthora* infection, which causes root rot, is correlated with the duration of flooding events [56] and can be a major cause of blueberry plant death under inadequate drainage.

We assigned crop-dependent numerical suitability scores between 0 and 1 to these drainage classes; however, the numerical assignment between crops was potentially different for each class (Table 1).

Table 1. Drainage scores for avocado and blueberry that were assigned in this study to the drainage class descriptors available in the soil database.

	Well	Moderate	Imperfect	Poor	Very Poor
Avocado	1	0.9	0.4	0.1	0
Blueberry	1	0.75	0.3	0.1	0

A lower score does not indicate that an area is not suitable for a crop, but rather indicates that mitigations to improve soil drainage are needed for successful crop production, such as subsoil ploughing, drainage system installation, mounding, application of soil amendments to improve soil structure, and minimising soil compaction by reducing orchard traffic especially when the soils are wet. However, an exception to this in our scoring is the 'very poor' class, to which we assigned a score of zero, which in turn would ensure an overall score of zero.

A poorly drained soil may not be as great a limitation in a low-rainfall area as in a high-rainfall area or low-rainfall areas that experience occasional deluges. Thus, a potential extension of these suitability scores would be to represent them as functions of precipitation and rainfall pattern.

2.6.6. Slope

Machinery cannot operate safely on slopes greater than 30° and these slopes also present an erosion risk for well-managed horticultural crops [57]. A range of slopes will likely be present within any 1-km^2 grid-square; therefore, cultivation suitability may also vary, regardless of the central latitude value.

Avocado

A maximum slope of 8.5% or 5° has been stipulated for avocado [52], although other authors have considered slopes less than 15° to be suitable for growing avocado, with greater slopes being more challenging, erosion-prone and expensive for crop production [9]. Slopes of $\leq$7° were considered optimal, slopes of $\leq$15° considered marginal and slopes of >15° considered unsuitable when criteria were being developed for slope suitability [47]. However, at least one NZ avocado orchard has been established on a slope of 30°. Thus, a slope suitability function was developed with scores close to 1 for slopes $\leq$ 8.5°, a mid-point score at 19° and a rapid drop to zero at slopes of more than 19° (Figure 8a). This curve is given by Equation (5) with parameter values $a = 0.5$ per ° and $b = 19°$.

Blueberry

Flat and gently sloping land is ideal for blueberry production, for easy and safe worker access, machinery use, infrastructure installation and to reduce erosion [52]; thus a suggested limit is slope $\leq$15° [51]. Balancing this with the 30° limit suggested by Rowland et al. [57], we used a slope suitability function with a mid-point score at 12° with a rapid drop to zero as slope increases further (Figure 8b). This curve is given by Equation (5) with parameter values $a = 0.5$ per ° and $b = 12°$.

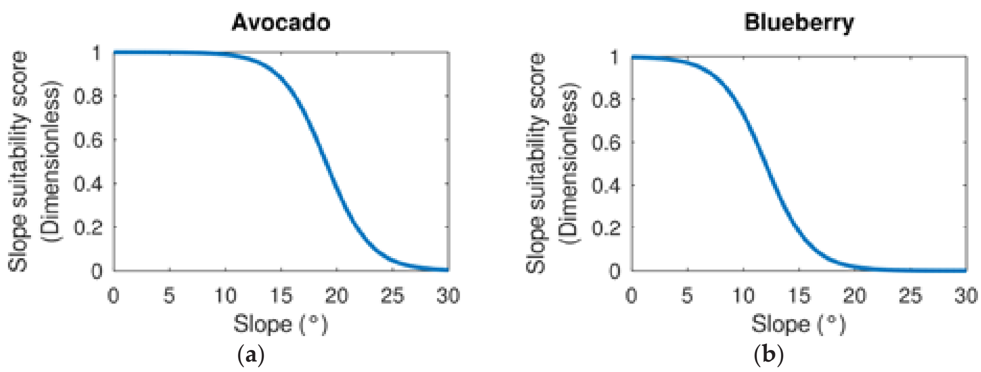


Figure 8. Slope suitability as a function of slope for (**a**) 'Hass' avocado and (**b**) blueberry.

2.6.7. Land Use Capability Class

The main categories of the land use capability (LUC) class descriptors are numbered between 1 and 8, with 1 representing land with almost no limitations for arable use and 8 representing land that is unsuitable for even forestry because of significant constraints or hazards. However, certain crops are better suited for land with a higher LUC category, depending on their specific needs. Although LUC class descriptors are influenced by PRD, drainage and slope information, they reflect additional soil property information such as soil type, past land use and nutrient supply. Thus, they are important to consider alongside the other land-related requirements. In consultation with industry experts, we assigned crop-dependent suitability scores to LUC classes (see Table 2) to facilitate combination with the suitability scores for other criteria.

Table 2. Land use capability (LUC) scores for avocado and blueberry that were assigned in this study to the LUC class descriptors of the soil database.

	Land Use Capability Class							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Avocado	1	0.95	0.9	0.8	0.65	0.5	0.05	0
Blueberry	1	0.95	0.9	0.8	0.6	0.4	0.2	0

2.6.8. Soil pH

Avocado

A soil pH between 6.0 and 6.5 is considered ideal, while between 5.5 and 6.9 is considered satisfactory [52]. In contrast, others rated a soil pH between 6.7 and 7.3 as highly suitable, and between 5.5 and 6.7 or between 7.3 and 8.0 as suitable, between 4.5 and 5.5 or between 8.0 and 9.0 as low suitability, and <4.5 or >9.0 as unsuitable. Soil should have a neutral or slightly acidic pH for avocado, as alkaline conditions are unfavourable, although incorporation of sufficient quantities of suitable organic matter into the soil before planting can reduce its pH [58]. A pH suitability score of 1 was chosen at pH 6.5, a score of 0.9 at pH 6 and 7, and a score of 0.1 at pH 4.5 and 8.5. This curve is obtained from Equation (10) below, with x representing pH and parameter values $a = 0.74$, $b = 6.5$ and $c = 1$, and is graphed in Figure 9a.

$$y = \frac{2}{1 + \exp\left(a(x^c - b^c)^2\right)} \tag{10}$$

Blueberry

In organic soils, both rabbiteye and highbush blueberry thrive best at a soil pH of 4 to 5, but in mineral soil, due to bioavailability issues of aluminium and manganese at low pH, optimal growth is achieved at a soil pH of 5 to 5.5 [55]. Various soil pH ranges have been reported for blueberry: 4.0 to 5.5 [52], 4.5 to 5.2 [54] and of 3.5 to 4.0 in peat soils [30]. Compared with production in soil with a pH of 4.5, cultivation in soils of pH 5.5 or 6.0 decreased yield by 20 and 92%, respectively, in cultivar 'Climax' and 32 and 76%, respectively, in 'Chaoyue No. 1' [59]. Ideal soil pH can differ depending on the planting medium, and in trials with five clonal lines, the ideal pH ranged between 4.2 and 5.5 across four different potting media [60]. Blueberries New Zealand Incorporated suggest a pH between 4.0 and 5.5, with an optimal pH of 4.8 (https://www.blueberriesnz.co.nz/industries/growing, accessed on 28 June 2021).

We used a suitability score with values > 0.95 for soil pH from 4.3 to 5.1 (1.0 at.4.7), declining sharply outside that range to 0.66 and 0.13 at pH 6.2 and 7.5, respectively. This curve is given by Equation (10) with x representing pH and parameters values $a = 150$, $b = 4.7$ and $c = 0.2$, and is graphed in Figure 9b.

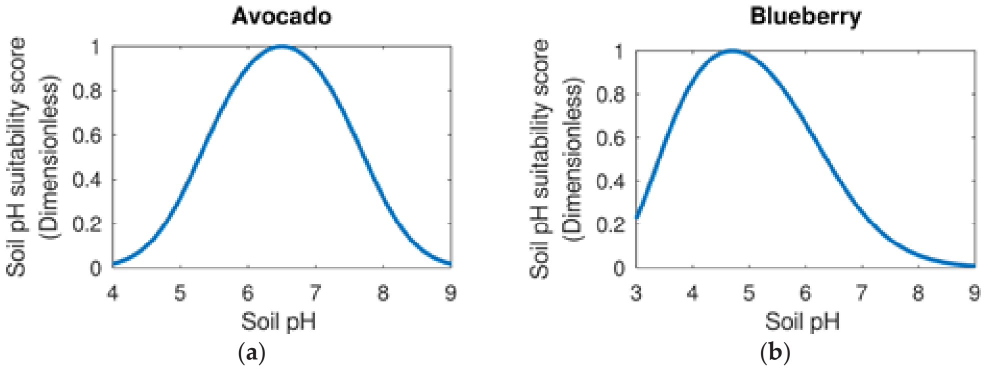


Figure 9. Soil pH suitability score for (**a**) 'Hass' avocado and (**b**) blueberry.

2.7. Combining Suitability Scores

Combining suitability scores from several criteria for each location gives a more holistic assessment than using the lowest score across criteria, because inadequacies can in principle be mitigated, and basing assessments on the lowest score can exclude locations that are suitable in terms of other criteria.

2.7.1. Climate Suitability

Climate suitability scores were obtained by geometrical averaging of the climate suitability scores for individual criteria, as described in Equation (2), with weights for each criterion based on input from industry experts. For avocado, a weight of 3 was used for both its climate criteria, warmth and frost. For blueberry, we used a weight of 2 for each of its three climate criteria, chill, frost and GDD.

2.7.2. Soil/Terrain Suitability

A soil suitability score for each location was obtained by geometrically averaging the individual soil/terrain suitability scores, as described in Equation (3). For avocado, we used a weight a of 0.25 for slope to reflect lesser importance, while highlighting the importance of drainage with a weighting of 3. The other soil/land related criteria, rooting depth, LUC and soil pH, were all given a weight of 1. For blueberry, weights of 0.5 were used for slope, 1 for rooting depth and LUC, 3 for drainage and 2 for soil pH. The latter two criteria are critical for blueberry cultivation, and although these issues can be effectively addressed through soil modification or container growing, doing so incurs additional costs, which is why the weights are high. A low rooting depth can also be mitigated by container growing, or, more cost-effectively, by mounding.

2.7.3. Location/Cultivation Suitability

Location suitability was calculated as the geometric mean of the land suitability score and average climate suitability score, weighted by a function of the underlying criteria weights, using the formula in Equation (4). This allows each criterion to contribute to the overall score according to its assigned weight.

2.8. Projecting Future Location Suitability

For each crop, location suitability scores were calculated for the SLM RCP Past dataset for each CMIP5 model, and the arithmetic average was taken to obtain an RCP past suitability score (for the period 1972–2004). For each crop and each RCP, location suitability was calculated for an early-mid-century (2028–2058) period and a mid-late-century period (2068–2098) from the SLM RCP datasets, by calculating location suitability separately from each of the six CMIP5-related SLM RCP datasets and then taking the arithmetic mean. For each crop, this gave one past period location suitability prediction and two future period location suitability projections per RCP. The difference between future and past suitability scores with an RCP gives a projection of the impact of climate change.

3. Results

3.1. Contempoarary Period, Ground-Truthed Maps

The final ground-truthed contemporary (2006–2016) suitability maps for individual criteria, climate and soil are presented in the Supplementary Materials.

3.1.1. Avocado Location Suitability

The ground-truthed cultivation suitability map for the contemporary period for avocado is shown in Figure 10. This is consistent with the map for avocado production density (Figure 2), bearing in mind that many locations suitable for avocado may be used for other primary industries, and that the density maps ascribe the average regional density to each location in that region.

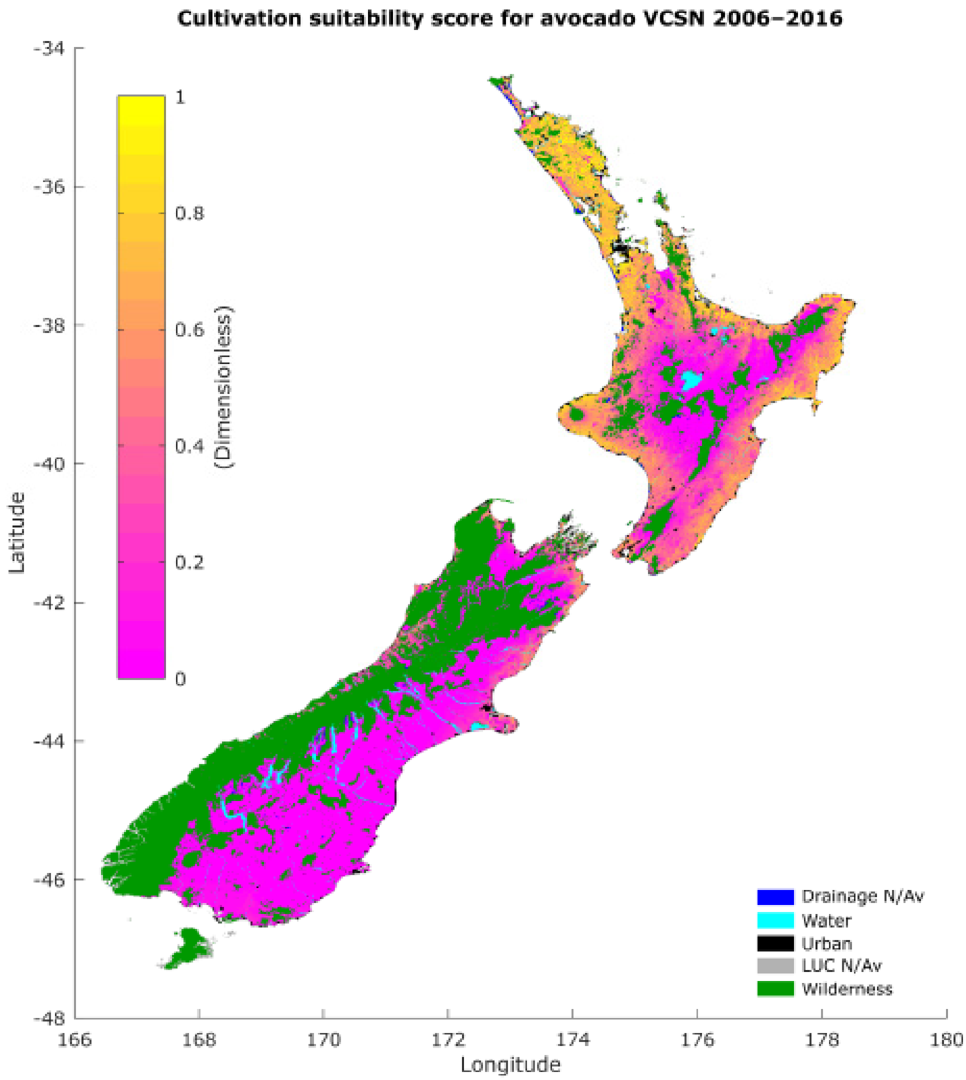


Figure 10. Avocado: overall cultivation suitability scores for locations across the country. A suitability score closer to 0 indicates the location is less suitable; a suitability score closer to 1 indicates the location is more suitable. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

3.1.2. Blueberry Location Suitability

The ground-truthed cultivation suitability map for the contemporary period for blueberries is shown in Figure 11. This map aligns with blueberry production areas (Figure 2), bearing in mind that many suitable locations will be used for other land uses.

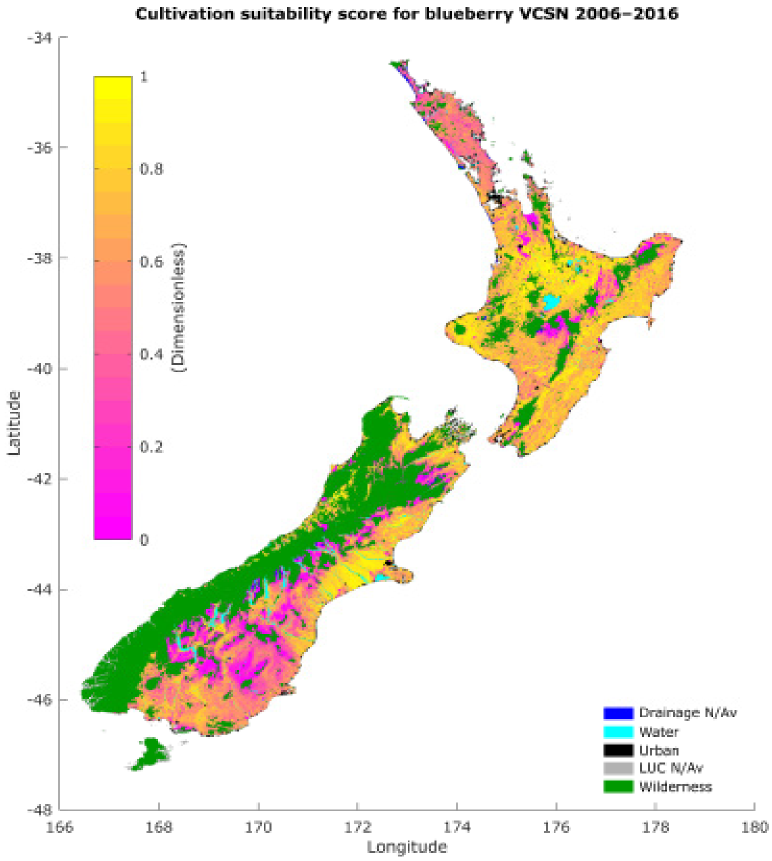


Figure 11. Blueberry: overall cultivation suitability scores for locations across the country. A suitability score closer to 0 indicates the location is less suitable and/or fewer cultivars are suitable in that location; a suitability score closer to 1 indicates the location is more suitable and/or more cultivars are suitable for that location. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

3.2. Suitability Projections

The continuous scale system can be classified to facilitate discussion. For example, previously we classified suitability scores as follows: "excellent" for the 0.9 to 1.0 range, "very good" for 0.8 to 0.9, "good" for 0.7 to 0.8, and "acceptable" for 0.6 to 0.7 [17]. Here, we further group the very good, good and acceptable categories as "viable" locations for cultivation and refer to suitability scores below 0.6 as "unviable". Locations in the viable category would likely require adaptations to be implemented in order that the crop can be grown successfully, while excellent category locations would likely require few or no adaptations. We give results for the most extreme of the four RCPs, 2.6 and 8.5, because they provide the most contrast. Results for the intermediate pathways, RCP 4.5 and 6.0, are provided in Appendix A. These results use the means of the suitability calculations from each of the six GCM datasets per RCP.

Increases or decreases in cultivation suitability result from increases or decreases in climate suitability, because soil/terrain suitability is constant. Thus, we discuss only climate change impacts in terms of cultivation suitability.

3.2.1. Avocado

Avocado RCP 2.6

Under RCP 2.6, cultivation suitability is projected to increase modestly across the entire country by mid-century, with small further increases by the late century. The maps for these periods show little difference from the RPC Past avocado suitability maps, with Northland and several areas around the coastal North Island having good suitability scores or higher (Figure 12).

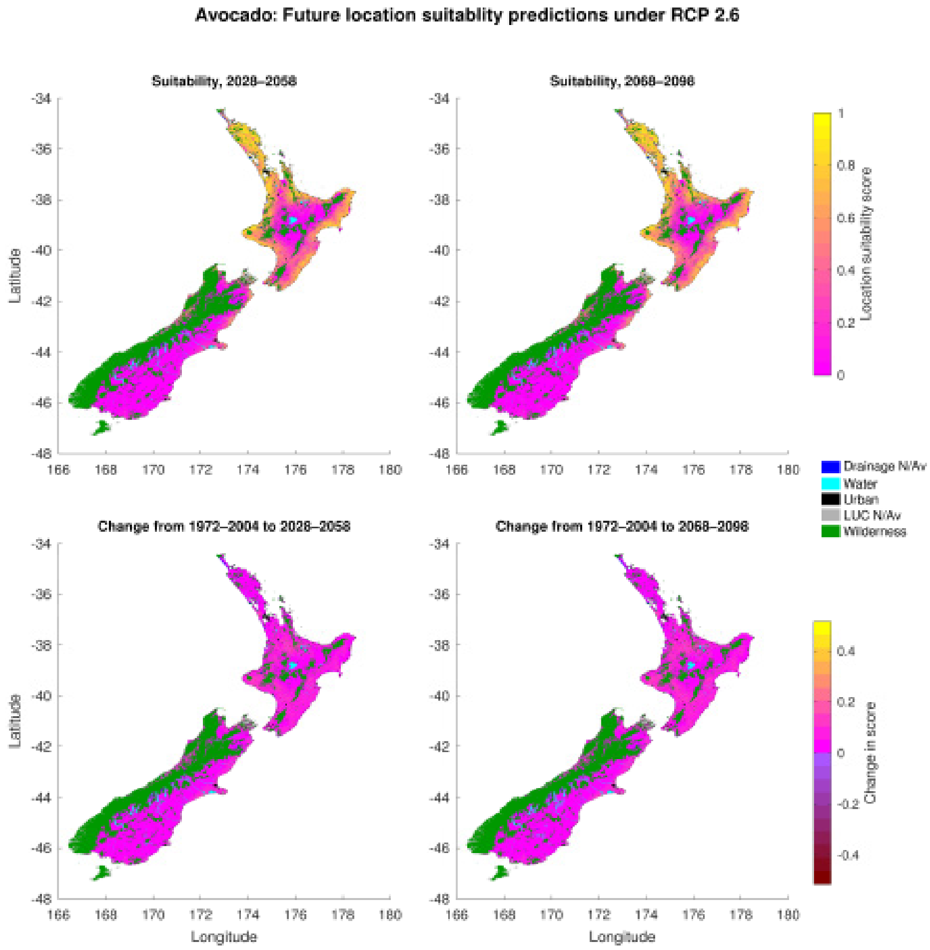


Figure 12. Projected location suitability for avocado (upper figures) and predicted changes in location suitability from the historic period (lower figures) in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 2.6. N/Av indicates that data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

At the national level, the area of excellent suitability land for avocado is projected to increase from 1154 km^2 to 2048 km^2 and 2078 km^2 at the mid- and late centuries, respectively, with almost 80% of this increase in the existing avocado strongholds of Northland, Auckland and Bay of Plenty regions (Table 3).

The 10 km^2 of excellent suitability land in the Bay of Plenty in the RCP Past period is under 50% of the current planted area for that region, indicating that many avocado orchards will be in less-than-optimal conditions. We do note that a degree of climate change will have occurred between now and RCP Past. Similarly, although Otago is indicated as having no land in the excellent or viable categories for RCP Past, about 11 ha of avocado are currently grown there. This could be consistent with (i) the existence of favourable microclimates not reflected in the climate database, (ii) a warming of climate since RCP Past or (iii) growers growing on land that falls marginally below the suitability cut-off for viable land. The latter possibility highlights a limitation of threshold-delineated suitability categories (e.g., there is little difference between a suitability of 0.59 and 0.6 but they would fall either side of the viable threshold).

From RCP Past to the late century, the area of excellent suitability land for avocado is projected to increase by almost 50%, from 969 to 1449 km^2, in Northland; by 135%, from 132 to 311 km^2, in Auckland; and by 800%, from 10 to 93 km^2, in the Bay of Plenty (Table 3). Over the same period, Gisborne and Waikato are projected to increase in their areas of excellent suitability land from 5 to 59 km^2 and 38 to 58 km^2, respectively, while Taranaki, with no excellent category land in the RCP Past period, would see 104 km^2 of excellent quality land emerge (Table 3).

Table 3. Avocado under Representative Concentration Pathway (RCP) 2.6: Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Avocado RCP 2.6 Region		Past Area	Mid-Century Projection Loss	Gain	Area (−/+)	Late-Century Projection Loss	Gain	Area (−/+)
Northland	V	7419	436	122	7105 (−58, 60)	480	142	7081 (−65, 57)
	E	969	0	436	1405 (−87, 91)	0	480	1449 (−94, 106)
Auckland	V	2333	187	493	2639 (−175, 59)	179	518	2672 (−140, 29)
	E	132	0	187	319 (−65, 82)	0	179	311 (−92, 100)
Waikato	V	3458	64	1583	4977 (−685, 834)	54	1721	5125 (−766, 904)
	E	5	0	64	69 (−52, 158)	0	54	59 (−41, 132)
Bay of Plenty	V	1377	83	449	1743 (−216, 125)	83	459	1753 (−179, 150)
	E	10	0	83	93 (−58, 139)	0	83	93 (−58, 127)
Gisborne	V	2107	16	839	2930 (−540, 377)	20	877	2964 (−545, 351)
	E	38	0	16	54 (−12, 62)	0	20	58 (−11, 93)
Hawke's Bay	V	1381	4	945	2322 (−596, 610)	4	989	2366 (−615, 611)
	E	0	0	4	4 (−4, 17)	0	4	4 (−4, 19)
Taranaki	V	1919	104	1267	3082 (−624, 330)	104	1316	3131 (−606, 322)
	E	0	0	104	104 (−77, 199)	0	104	104 (−77, 201)
Manawatu-Whanganui	V	607	0	708	1315 (−507, 561)	0	738	1345 (−510, 585)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Wellington	V	637	0	662	1299 (−346, 336)	0	695	1332 (−320, 375)
	E	0	0	0	0 (0, 25)	0	0	0 (0, 25)
West Coast	V	22	0	124	146 (−44, 147)	0	127	149 (−58, 130)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Canterbury	V	15	0	219	234 (−160, 202)	0	236	251 (−163, 195)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Otago	V	0	0	0	0 (0, 0)	0	0	0 (0, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Southland	V	0	0	0	0 (0, 0)	0	0	0 (0, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Tasman	V	40	0	53	93 (−48, 30)	0	55	95 (−50, 33)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Nelson	V	0	0	5	5 (−3, 0)	0	5	5 (−3, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Marlborough	V	90	0	176	266 (−105, 111)	0	179	269 (−106, 135)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Total	V	21,405	894	7645	28,156 (−3989, 3664)	924	8057	28,538 (−4004, 3755)
	E	1154	0	894	2048 (−355, 773)	0	924	2078 (−377, 803)

For all North Island regions, there are significant areas of viable land (ranging from 607 km^2 in Manawatu-Whanganui to 7419 km^2 (Table 3) in RCP Past, and while there is a 5% reduction in the area of viable land in Northland by the late century (due to more viable land becoming excellent than unviable land becoming viable), viable land is significantly increased in all other North Island regions and notably so in Taranaki (Table 3). None of the South Island regions were calculated to have excellent suitability land for any period of the study; however, the West Coast, Canterbury, Tasman and Marlborough regions had small areas of viable land with increases by the late century. All land in Otago, Southland and Nelson was unviable for RCP Past, and remained so, except for 5 km^2 of viable land emerging for Nelson (Table 3).

Avocado RCP 8.5

The impacts of climate change under RCP 8.5 are more pronounced than for RCP 2.6, with the mid-century projection for RCP 8.5 resembling the patterns for the late-century projections for RCP 2.6, though slightly more favourable. Late-century projections for RCP 8.5 indicate that cultivation suitability has modest to significant increases across the country (Figure 13). Some regions, such as Northland, projected to experience a modest increase in suitability, had excellent RCP Past suitability scores already; thus, there is no potential for significant further increase. RCP 8.5 projections indicate that in addition to Northland, most areas of coastal North Island, and pockets on the South Island east and north coasts, will exhibit very good or excellent suitability.

Under the RCP 8.5 projections for avocado, the area of viable land will increase at the national level from 21,400 km^2 in RCP Past to 31,850 km^2 in the mid-century and 48,200 km^2 in the late century (respective increases of 49% and 125%); the area of excellent land will increase from 1150 km^2 in RCP Past to 2670 km^2 in the mid-century and 6100 km^2 in the late century (increases of 130% and 430%, respectively) (Table 4). This contrasts with the pattern of change under RCP 2.6, where most change had occurred by the mid-century. Similar to the RPC 2.6 scenario, these changes were mainly driven by changes in the warmth suitability and frost risk suitability scores. However, under the RCP 8.5 projections for avocado, increases in warmth suitability scores were significantly greater than under RCP 2.6, at both the mid-century and late-century stages. Increases in frost risk suitability under RCP 8.5 were also greater than for RCP 2.6 projections, and late-century frost suitability was projected to be significantly greater than the historic values. (See Supplementary File 'Comparison future vs. historic scores'). The increase in excellent suitability land for avocado under RCP 8.5 came almost exclusively from viable land increasing in suitability to excellent, with the exception of Auckland and Taranaki, where small areas of land that were unviable in RCP Past would be of excellent suitability in the late century (Table 4). The avocado strongholds of Northland, Auckland and Bay of Plenty are projected to account for two-thirds of the increase in excellent suitability land at the mid-century and only about 40% in the late-century (contrasting their 80% contribution for both periods under RCP 2.6), while Taranaki and Waikato together account for 25% of the mid-century increase and 50% of the late-century increase (Table 4), showing a potential to become dominant avocado growing areas under RCP 8.5.

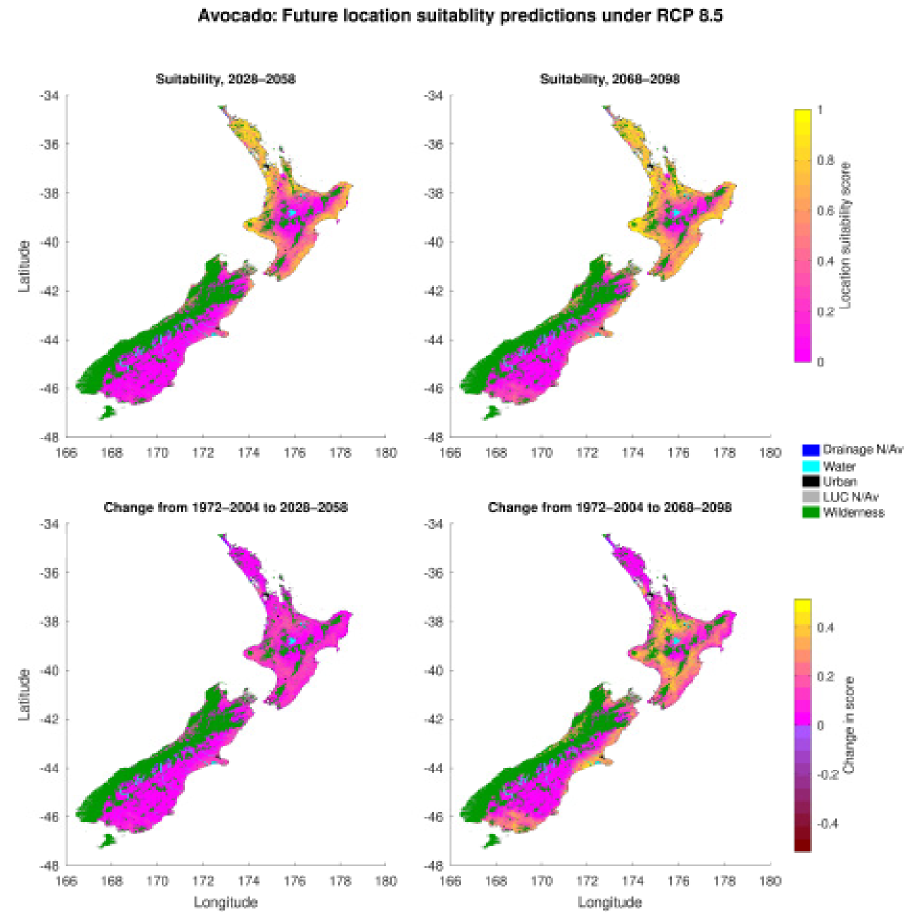


Figure 13. Projected location suitability for avocado (upper figures) and projected changes in location suitability from the historic period (lower figures) in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 8.5. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

Table 4. Avocado under RCP 8.5: Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Avocado RCP 8.5		**Past**	**Mid-Century Projection**			**Late-Century Projection**		
Region		**Area**	**Loss**	**Gain**	**Area (−/+)**	**Loss**	**Gain**	**Area (−/+)**
Northland	V	7419	595	163	6987 (−15, 63)	783	316	6952 (−21, 8)
	E	969	0	595	1564 (−86, 61)	0	783	1752 (−31, 40)
Auckland	V	2333	257	651	2727 (−56, 114)	422	935	2846 (−99, 3)
	E	132	0	257	389 (−43, 39)	0	471	603 (−34, 106)
Waikato	V	3458	135	2453	5776 (−728, 843)	1008	6830	9280 (−529, 507)
	E	5	0	135	140 (−58, 194)	0	1008	1013 (−174, 339)
Bay of Plenty	V	1377	155	677	1899 (−184, 134)	593	1560	2344 (−174, 125)
	E	10	0	155	165 (−68, 139)	0	593	603 (−90, 109)
Gisborne	V	2107	79	1168	3196 (−281, 433)	199	2473	4381 (−241, 237)
	E	38	0	79	117 (−50, 34)	0	199	237 (−36, 70)
Hawke's Bay	V	1381	12	1612	2981 (−599, 582)	182	4012	5211 (−686, 629)
	E	0	0	12	12 (−6, 12)	0	182	182 (−62, 126)
Taranaki	V	1919	271	1842	3490 (−306, 132)	1456	2989	3452 (−67, 57)
	E	0	0	271	271 (−121, 166)	0	1544	1544 (−269, 301)
Manawatu-Whanganui	V	607	0	1267	1874 (−484, 871)	52	5954	6509 (−1143, 1162)
	E	0	0	0	0 (0, 1)	0	57	57 (−25, 68)
Wellington	V	637	11	1067	1693 (−331, 354)	88	2592	3141 (−361, 311)
	E	0	0	11	11 (−11, 17)	0	88	88 (−16, 20)
West Coast	V	22	0	274	296 (−104, 73)	9	1090	1103 (−185, 329)
	E	0	0	0	0 (0, 0)	0	9	9 (−9, 12)
Canterbury	V	15	0	405	420 (−165, 235)	0	1766	1781 (−358, 516)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 9)
Otago	V	0	0	0	0 (0, 0)	0	0	0 (0, 12)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Southland	V	0	0	0	0 (0, 0)	0	0	0 (0, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Tasman	V	40	0	94	134 (−36, 53)	0	285	325 (−63, 44)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 10)
Nelson	V	0	0	5	5 (0, 4)	0	42	42 (−8, 19)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Marlborough	V	90	0	284	374 (−98, 178)	20	768	838 (−74, 99)
	E	0	0	0	0 (0, 4)	0	20	20 (−7, 18)
Total	V	21,405	1515	11,962	31,852 (−3309, 3991)	4812	31,612	48,205 (−3754, 3803)
	E	1154	0	1515	2669 (−443, 667)	0	4954	6108 (−753, 1228)

In the late century, all North Island regions are predicted to have areas of excellent suitability, ranging from 57 km^2 in Manawatu-Whanganui to 1750 km^2 in Northland, and large areas of viable suitability, ranging from 2850 km^2 in Auckland to 9300 km^2 in Waikato (Table 4).

South Island changes under RCP 8.5 show similar patterns to those under RCP 2.6, but with 60 to 120% larger increases in viable land across regions apart from Nelson, Otago and Southland in the mid-century, and 330 to 760% larger increases in viable land across regions apart from Otago and Southland in the late century (cf. Tables 3 and 4). For RCP 8.5, Otago and Southland would have no viable or excellent suitability land in any period, like the case for RCP 2.6 projections. Both Marlborough and West Coast regions would have small amounts of excellent suitability land (respectively, 20 and 9 km^2) by the late century.

3.2.2. Blueberry

Blueberry RCP 2.6

RCP 2.6 projections for blueberry suggest that cultivation suitability would either increase slightly or remain stable across the South Island (with the exception of a few coastal areas) and in elevated and central locations of the North Island (Figure 14). However, in the northern North Island down to northern Waikato, in the Bay of Plenty coastal areas and the Gisborne area of the East Cape, suitability would have modest decreases, and only slight decreases in suitability would occur in remaining locations (Figure 14). Most change would occur by mid-century. For Waikato and the Bay of Plenty, where currently a significant number of NZ's blueberry orchards are located, slight decreases in suitability are predicted, but these are unlikely to be significant. Overall, large areas of NZ are likely to be suitable or highly suitable for blueberry production, especially if appropriate varieties and mitigation strategies are chosen.

At a national level, 11,170 km^2 of land is calculated to have excellent suitability for blueberries for RCP Past (Table 5), which is far in excess of NZ's current 700 ha of blueberry plantations, indicating the potential for substantial increases for this crop. Under RCP 2.6, this is projected to increase by 6%, with a subsequent loss of about 4% of this gain by the late century (Table 5). Underlying this apparent stability is the loss of 19% and 22% of RCP Past excellent suitability land at the mid- and late century, respectively, accompanied by slightly larger areas of land improving to the excellent category (Table 5). Thus, there is the potential that many existing blueberry orchards will experience notably worse growing conditions while at the same time there would be improved opportunities for blueberry in other areas, and this could result in significant land use change.

Table 5. Blueberry under RCP 2.6: Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Blueberry RCP 2.6 Region		Past Area	Mid-Century Projection Loss	Gain	Area (−/+)	Late-Century Projection Loss	Gain	Area (−/+)
Northland	V	2160	730	0	1430 (−856, 999)	775	0	1385 (−868, 1014)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Auckland	V	1770	196	4	1578 (−473, 204)	236	4	1538 (−484, 239)
	E	4	4	0	0 (0, 4)	4	0	0 (0, 1)
Waikato	V	12,880	724	1242	13,398 (−1372, 305)	761	1484	13,603 (−1415, 80)
	E	3105	1187	350	2268 (−769, 1715)	1419	313	1999 (−587, 1791)
Bay of Plenty	V	5935	130	383	6188 (−246, 74)	133	426	6228 (−239, 60)
	E	1127	273	76	930 (−251, 410)	303	74	898 (−239, 407)
Gisborne	V	6435	214	116	6337 (−231, 4)	224	119	6330 (−261, 28)
	E	261	54	46	253 (−63, 189)	57	36	240 (−54, 171)
Hawke's Bay	V	8590	106	411	8895 (−71, 20)	113	418	8895 (−62, 14)
	E	1055	113	72	1014 (−207, 259)	132	67	990 (−198, 261)
Taranaki	V	4537	64	328	4801 (−385, 187)	64	368	4841 (−357, 187)
	E	760	323	59	496 (−200, 390)	363	59	456 (−209, 362)
Manawatu-Whanganui	V	13,363	255	621	13,729 (−147, −91)	268	665	13,760 (−131, −90)
	E	1545	62	151	1634 (−267, 415)	81	145	1609 (−300, 409)
Wellington	V	4827	68	108	4867 (−93, −41)	76	105	4856 (−97, 1)
	E	415	30	15	400 (−45, 136)	35	10	390 (−51, 105)
West Coast	V	2232	164	69	2137 (−111, 80)	162	69	2139 (−106, 81)
	E	548	29	160	679 (−94, 121)	29	158	677 (−93, 116)
Canterbury	V	16,161	1546	3629	18,244 (−420, −240)	1469	3701	18,393 (−310, −255)
	E	1557	0	1546	3103 (−1033, 1567)	0	1469	3026 (−1088, 1569)
Otago	V	5662	52	4752	10,362 (−2537, 2478)	54	5081	10,689 (−2384, 2405)
	E	7	0	52	59 (−41, 134)	0	54	61 (−43, 131)
Southland	V	6428	72	2911	9267 (−1341, 679)	82	3106	9452 (−1308, 511)
	E	0	0	72	72 (−45, 243)	0	82	82 (−37, 360)
Tasman	V	2326	116	236	2446 (−73, −10)	112	228	2442 (−52, −12)
	E	383	10	116	489 (−71, 140)	10	112	485 (−67, 130)
Nelson	V	259	0	21	280 (−10, 11)	0	21	280 (−10, 12)
	E	11	0	0	11 (0, 1)	0	0	11 (0, 1)
Marlborough	V	2960	72	371	3259 (−163, 138)	77	381	3264 (−148, 143)
	E	394	13	43	424 (−41, 45)	14	47	427 (−39, 39)
Total	V	96,525	4509	15,202	107,218 (−5559, 1827)	4606	16,176	108,095 (−5550, 1736)
	E	11,172	2098	2758	11,832 (−3127, 5769)	2447	2626	11,351 (−3005, 5853)

The area of viable suitability land at a national level is calculated at 96,500 km^2 for RCP Past, and under RCP 2.6, increases in viable land of 11 and 12% are projected for the mid- and late-century, with 5% of RCP Past viable land expected to have changed category at each of these periods with, respectively, 15,000 km^2 and 16,000 km^2 of new areas of viable land (Table 5). Land exiting the viable category in the future periods is on average 70% higher in area than land entering the excellent category (see Table 5).

Waikato, the main production region for blueberry, has the largest areas (over 3000 km^2) of excellent land in the RCP Past period, while in the notable blueberry regions, Hawke's Bay, Bay of Plenty and Canterbury, about one-third to one-half of that area each is classified as excellent suitability (see Table 5), and the two other big blueberry regions, Tasman and Nelson, have only 383 km^2 and 11 km^2 of excellent land, respectively (see Table 5). Northland, another notable blueberry production area has no excellent suitability land for blueberry, though over 2000 km^2 of viable land (Table 5). This reflects a limiting factor in Northland's subtropical climate, which is a lack of winter chill, thus an adaption when growing blueberries in Northland is the use of lower-chill cultivars.

Waikato is projected to lose 38% and 46% of its RCP Past excellent land by the mid- and late century, respectively, with much smaller gains of new excellent land, resulting in a 36% reduction in area of excellent land by the late century; these trends are repeated for most other North Island regions, with Taranaki and Bay of Plenty seeing reductions of, respectively, 40% and 20% in area of excellent land by the late century, and Wellington, Gisborne and Hawke's Bay having 6 to 8% reductions in their excellent land, and Auckland losing all its small area of RCP Past excellent land (see Table 5). Northland and Auckland are projected to have reductions of 36 and 13% in viable land, respectively, by the late century, while other North Island regions would have small gains or losses of 5% or less.

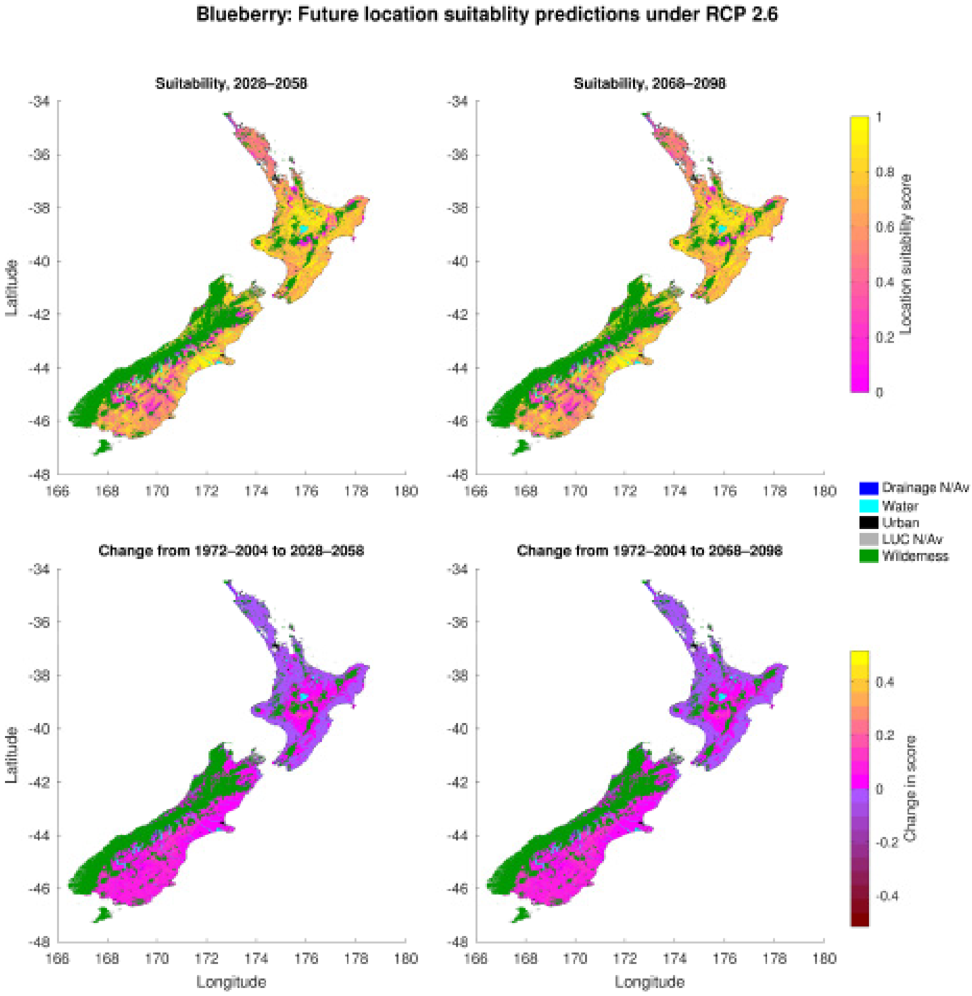


Figure 14. Projected location suitability for blueberry (upper figures) and projected changes in location suitability from the historic period (lower figures) for blueberry in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 2.6. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

Excellent suitability land is projected to double in area in Canterbury to 3100 km^2 by the mid-century, with no loss of existing excellent land, and little further change projected for the late century. This positions Canterbury to become the dominant blueberry region in

NZ. All other South Island regions would have small to modest increases in excellent land, except for Nelson, which would experience no change. By the late century, viable land in Otago and Southland are projected to increase by 10,700 km^2 and 9500 km^2, respectively, and in other South Island regions by one or two orders of magnitude lower, with most of this change occurring by the mid-century (see Table 5).

Blueberry RCP 8.5

Under RCP 8.5, the mid-century projected changes in suitability scores displayed spatial patterns similar to those predicted for RCP 2.6 in the late century, although with a much greater magnitude (Figure 15). These trends were predicted to persist into the late century, with cultivation suitability declining moderately in most of the North Island, except for central, elevated locations where it would mainly be unchanged, or increase moderately in a few locations.

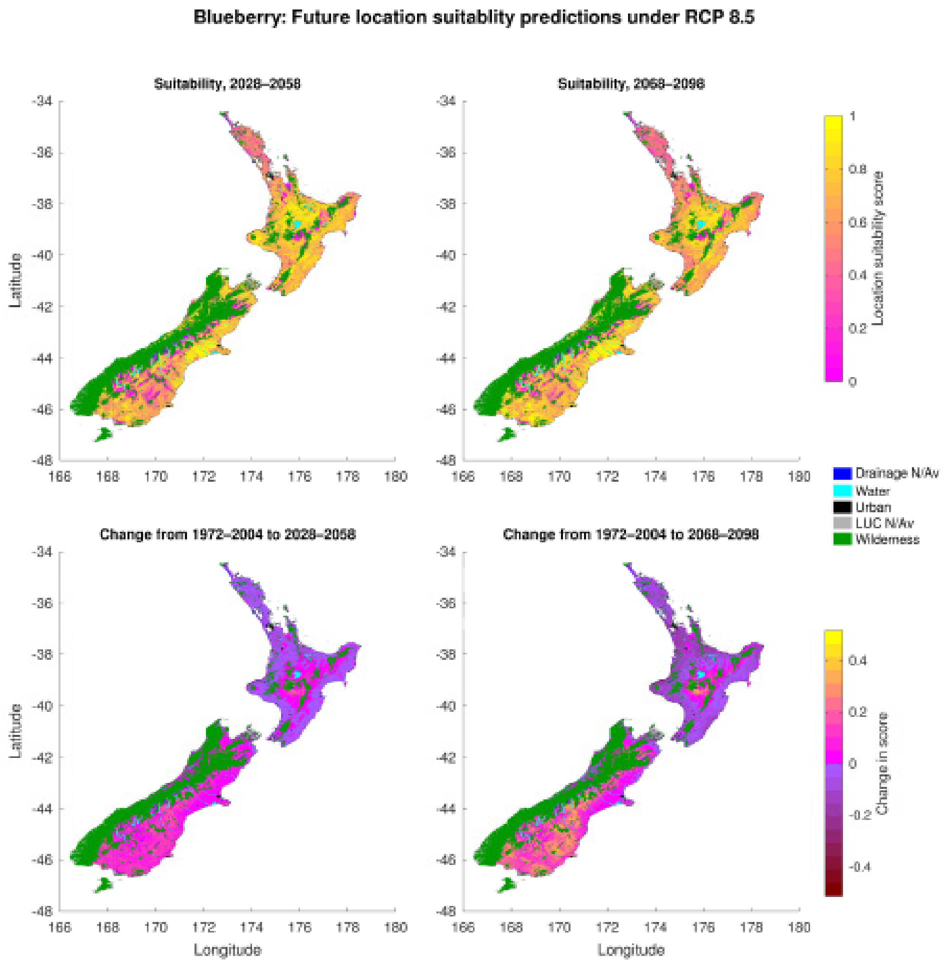


Figure 15. Projected location suitability for blueberry (upper figures) and projected changes in location suitability from the historic period (lower figures) for blueberry in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 8.5. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

Under RCP 8.5, the national area of excellent suitability land for blueberry is projected to increase from RCP Past by 8% and 24% at the mid- and late century, respectively, and viable land to increase by 15% by the mid-century, with very few further late-century increases (see Table 6). However, by the late century, 60% of the RCP Past excellent land will have exited this category and 70% of excellent land will be "newly excellent" (see Table 6), indicating the potential for large fluxes in the spatial footprints for blueberry cultivation.

Table 6. Blueberry under RCP 8.5 Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Blueberry RCP 8.5 Region		Past Area	Mid-Century Projection Loss	Gain	Area (−/+)	Late-Century Projection Loss	Gain	Area (−/+)
Northland	V	2160	1011	0	1149 (−649, 825)	2091	0	69 (−69, 649)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Auckland	V	1770	365	4	1409 (−458, 259)	1346	4	428 (−211, 542)
	E	4	4	0	0 (0, 0)	4	0	0 (0, 0)
Waikato	V	12,880	1018	1705	13,567 (−871, −181)	3269	2676	12,287 (−598, 505)
	E	3105	1619	389	1875 (−306, 1217)	2572	341	874 (−341, 408)
Bay of Plenty	V	5935	194	519	6260 (−174, 16)	723	967	6179 (−73, 143)
	E	1127	391	107	843 (−151, 296)	821	163	469 (−168, 160)
Gisborne	V	6435	353	144	6226 (−225, 89)	1306	238	5367 (−479, 408)
	E	261	68	58	251 (−48, 103)	141	56	176 (−36, 36)
Hawke's Bay	V	8590	183	574	8981 (−65, 38)	614	1142	9118 (−141, 14)
	E	1055	193	105	967 (−182, 203)	583	163	635 (−147, 209)
Taranaki	V	4537	69	471	4939 (−194, 188)	624	765	4678 (−486, 328)
	E	760	466	58	352 (−216, 201)	760	0	0 (0, 1)
Manawatu-Whanganui	V	13,363	406	924	13,881 (−94, −77)	1816	1939	13,486 (−348, 144)
	E	1545	156	201	1590 (−271, 325)	1053	393	885 (−260, 392)
Wellington	V	4827	114	138	4851 (−76, 42)	1005	403	4225 (−422, 360)
	E	415	57	10	368 (−33, 56)	339	5	81 (−66, 147)
West Coast	V	2232	199	85	2118 (−57, 60)	240	345	2337 (−50, 63)
	E	548	37	194	705 (−68, 61)	289	179	438 (−84, 83)
Canterbury	V	16,161	2220	4828	18,769 (−314, −237)	4380	8139	19,920 (−42, −22)
	E	1557	0	2217	3774 (−678, 1104)	101	4367	5823 (−540, 546)
Otago	V	5662	132	6809	12,339 (−1626, 1575)	669	12,455	17,448 (−827, 600)
	E	7	0	132	139 (−55, 104)	0	669	676 (−122, 159)
Southland	V	6428	243	3740	9925 (−444, 132)	2922	5122	8628 (−532, 229)
	E	0	0	243	243 (−111, 386)	0	2938	2938 (−404, 670)
Tasman	V	2326	141	299	2484 (−73, 5)	225	471	2572 (−77, 75)
	E	383	16	141	508 (−49, 112)	85	220	518 (−97, 89)
Nelson	V	259	0	32	291 (−12, 2)	2	35	292 (−2, 5)
	E	11	0	0	11 (0, 0)	1	0	10 (−1, 0)
Marlborough	V	2960	91	501	3370 (−125, 102)	257	903	3606 (−79, 105)
	E	394	19	52	427 (−12, 25)	93	65	366 (−45, 37)
Total	V	96,525	6739	20,773	110,559 (−3803, 1184)	21,489	35,604	110,640 (−3410, 3122)
	E	11,172	3026	3907	12,053 (−2180, 4193)	6842	9559	13,889 (−2311, 2937)

Waikato is projected to have a reduction in the area of excellent suitability land of 40% and 72% of the RCP Past value at the mid- and late century, respectively, with over 80% of RCP Past excellent land exiting that category by the late century and smaller amounts of newly excellent land partially buffering this loss. This pattern is repeated for all North Island regions with varying degrees of reduction in excellent suitability land, ranging from a 33% decline for Gisborne to 100% declines in Taranaki and Auckland by the late century, noting that Auckland started with a paucity of excellent land for RCP Past. Additionally, for North Island regions, projected changes in viable land area by the late century are significant for Northland and Auckland (respectively, 97% and 76% declines), moderate for Gisborne and Wellington (respectively, 17% and 12% declines), and increases or decreases of 5% or less are expected for the other regions (see Table 6).

In contrast, Canterbury is projected in have an increase in the area of land with excellent suitability for blueberry, increasing from its RCP Past value by 140% to 2200 km^2 at the mid-century and by 280% to almost 4400 km^2 at the late century; only about 100 km^2 of RCP Past excellent land exits this category by the late century, and none at the mid-century. Southland is projected to increase from no excellent suitability land in the RCP Past period to 240 km^2 by the mid-century, and then to 2900 km^2 by the late century (Table 6). Canterbury and Southland would, between them, account for 63% of excellent suitability land in the late century, while the next two regions for areas of excellent land, Manawatu-Whanganui and Waikato, would together account for only 13% of excellent land, highlighting the potential for a significant transformation in the spatial footprint for blueberry from the North Island to the South Island under RCP 8.5. Improved growing conditions for Otago and Tasman would see increased opportunities regarding excellent suitability land by the late century, while the area of excellent land in the West Coast and Marlborough would decrease by 20% and 7%, respectively, with little change in Nelson (Table 6). The amount of viable land is projected to increase for each South Island region, and very substantially (200%) for Otago (Table 6), indicating additional growing opportunities if growers implement the appropriate adaptations.

Blueberry: Key Criteria Underlying Change

Compared with historic values, chill suitability scores for blueberry had a moderate decrease under RCP 2.6 for both mid- and late century, and had a moderate and substantial increase over the same time periods under RCP 8.5. Frost risk suitability increased moderately under RCP 2.6 and had moderate and significant increases under RCP 8.5 for the mid- and late-century periods, respectively. GDD suitability significantly increased under RCP 2.6, with significant and substantial increases under RCP 8.5 for the mid- and late-century, respectively (see Supplementary File section "Comparison future vs. historic scores").

The changes led to either moderate decreases or increases in overall climate suitability under RCP 2.6. Under RCP 8.5, climate suitability had either moderate decreases or significant increases by the mid-century, and by the late century suitability was predicted to have either substantial increases or modest to significant decreases.

Even with the projected increase in overall climate suitability in most areas, there will need to be a focus on low-chill varieties to take advantage of the greater GDD accumulation.

4. Discussion

The formulation of the models was carried out primarily using considerations reflecting the physiology and phenology of avocado and blueberry, with function choice being governed by "first principles" and informed by international publications. These models and the methodology in this paper could be applied to consider avocado and blueberry cultivation suitability and climate change impacts in any country or region for which suitable GIS soil, slope and climate data are available. Recalibration of the models may be needed to reflect geographical differences that affect the sensitivity of the crops to variables. Thus, the suitability study for avocado and blueberry in NZ should be considered as a case study that demonstrates an approach with wider applicability.

The projected increases in cultivation suitability for avocado under RCP 2.6, and more so under RCP 8.5, will see not only improvements in locations where avocado is currently grown, but also new areas for potential future cultivation. The prospects for the avocado industry are promising and there is scope for future industry expansion, and this could also occur through the replacement of other horticultural endeavours.

For example, the spatial footprint of the kiwifruit industry is projected to change under future climates, and this would entail the loss of 975 ha (RCP 2.6) to 5425 ha (RCP 8.5) of existing kiwifruit plantations in the Bay of Plenty, Northland, Auckland, Waikato and Gisborne regions by the end of the century [17]. The avocado industry has a presence in all these regions, with the first two representing its strongholds; thus, conversion to avocado could be an attractive transformational adaptation for growers exiting the kiwifruit industry because of reduced winter chill in these areas.

The expansion of the avocado industry, especially at the expense of the kiwifruit industry, would change income streams in these regions and have an impact on the number of both permanent and seasonal work opportunities, and affect the timing of the latter. This would also have flow-on effects on rural economies and societies. Additionally, conversion to avocado from kiwifruit could have significance for environmental impacts, such as GHG emissions, water scarcity and water quality, and these can vary with climate and location [61–63].

The implications of our projections for avocado thus extend to both economic and policy considerations, both for local government and horticultural industries. The modelling results could inform the industry/government about potential climate change effects on land use suitability and thus the crop ecosystems, which in turn has implications for employment, revenue streams, resource demands and competition, environmental pressures and infrastructure requirements.

While suitability for blueberry is anticipated to decrease slightly in its primary growing regions in Waikato and the Bay of Plenty under RCP 2.6, suitability will continue to be high, and footprints may not be affected significantly. However, under RCP 2.6, the footprint of the apple industry in Hawke's Bay is projected to have a 175 ha loss of existing orchard land countered by 125 ha of new orchard land elsewhere in the region [17] and this may provide an opportunity for the blueberry industry to expand within that region. A further exception is Northland, where blueberry varieties with low-chill traits are already required: the decrease in suitability there combined with an increase in suitability for avocado may be conducive to land use change from blueberry to avocado.

Under RCP 8.5, the projected suitability decrease for blueberry in Northland and North Island coastal locations, and the increase in highly suitable land across Southland, Canterbury and in pockets in Otago could result in an increase in the blueberry footprint, particularly in the South Island, combined with more displacement of blueberry by avocado in warmer areas than under RCP 2.6.

Land use changes involving blueberry would entail similar economic and environmental issues to those discussed above. Thus, these projected changes will be useful for informing policy development by local government and industry. Planning for associated infrastructure would be required in regions where there are currently only small pockets of horticultural crops requiring cold storage and cold transportation.

Disease risk under current and future climates is a key issue for horticulture, but one whose complexity was out of scope for the resources of the current study. This is an area where our suitability modelling could be improved, together with applying econometric modelling to predict land use change as a function of competing land uses under different climates and resource limitations. Additionally, as we have noted earlier [17], a valuable extension to suitability modelling under changing climates is yield predictions that include the influence of management strategies and impact of climate change adaptations.

Extreme weather events like storms, floods and hail can cause severe damage to the horticultural sector. Unfortunately, the climate projection datasets that we had access to do not simulate such extreme events; thus, we do not have the capacity to project their frequency and impact into the future.

Supplementary Materials: Further results and maps can be downloaded at: https://www.mdpi.com/article/10.3390/land13111753/s1.

Author Contributions: Conceptualization, I.V., C.J.S. and K.M.; Data curation, C.v.d.D.; Formal analysis, I.V.; Funding acquisition, K.M. and C.J.S.; Investigation, I.V., M.C. and C.J.S.; Methodology, I.V., C.J.S. and K.M.; Resources, C.v.d.D.; Software, I.V. and C.v.d.D.; Visualisation, I.V. and C.v.d.D.; Writing—original draft, I.V., M.C. and K.M.; Writing—review and editing, C.J.S., K.M., C.v.d.D., M.C. and I.V. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data on soil and land properties are available from the URLs in the data section of our previous publication [12]. To protect IP and privacy rights, we cannot share the VCSN datasets, climate projection datasets or confidential industry data. Code for equations will be made available on request.

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Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

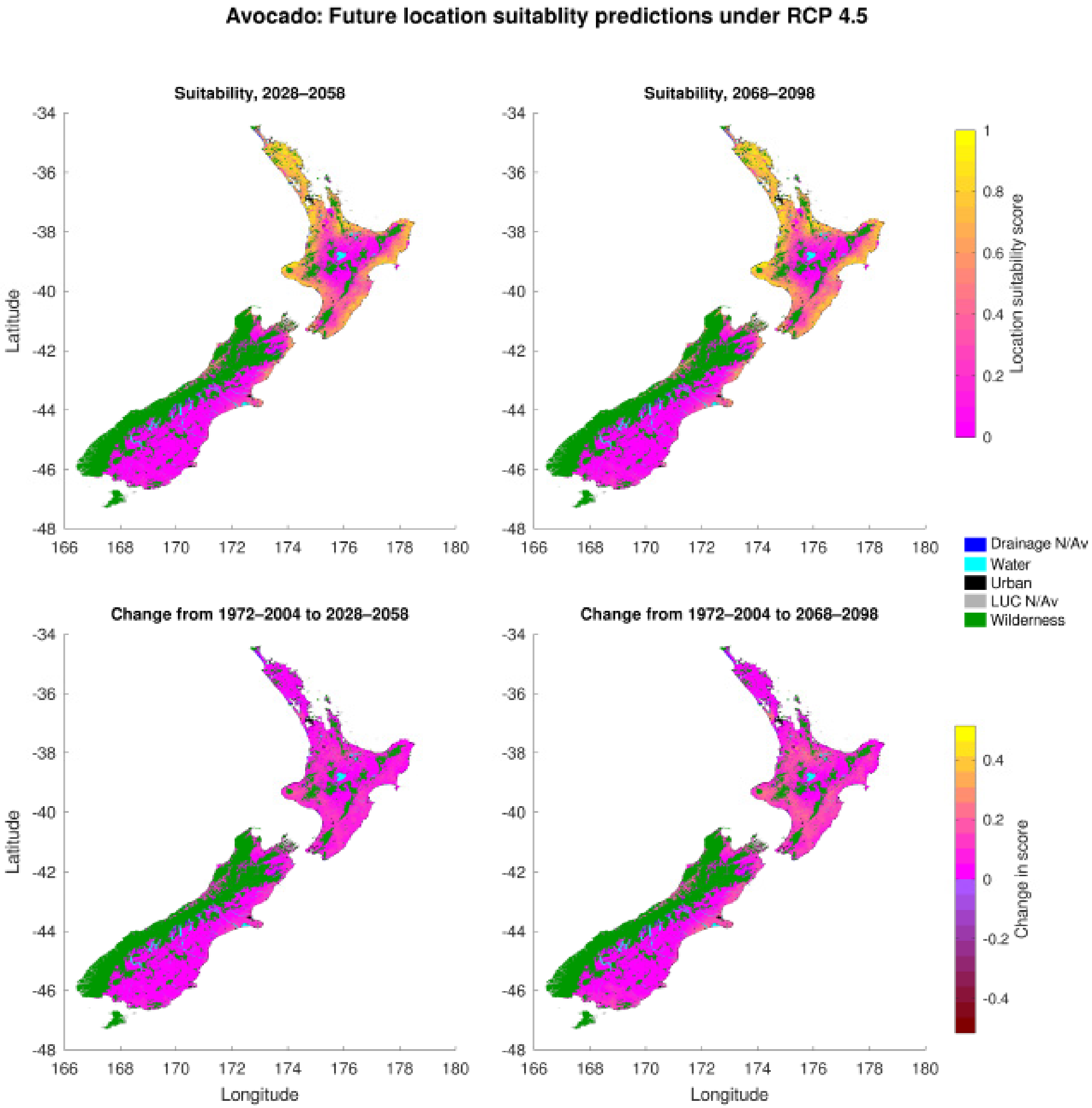

Figure A1. Projected location suitability (upper figures) and projected changes in location suitability from the historic period (lower figures) for avocado in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 4.5. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas encompass national parks, reserves, conservation areas and marginal strips.

Table A1. Avocado under RCP 4.5: Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Avocado RCP 4.5		Past	Mid-Century Projection			Late-Century Projection		
Region		Area	Loss	Gain	Area (−/+)	Loss	Gain	Area (−/+)
Northland	V	7419	509	144	7054 (−20, 32)	636	203	6986 (−7, 25)
	E	969	0	509	1478 (−60, 82)	0	636	1605 (−63, 53)
Auckland	V	2333	211	513	2635 (−129, 82)	258	734	2809 (−76, 80)
	E	132	0	211	343 (−63, 49)	0	258	390 (−46, 42)
Waikato	V	3458	79	1767	5146 (−666, 928)	194	2984	6248 (−935, 816)
	E	5	0	79	84 (−36, 142)	0	194	199 (−101, 212)
Bay of Plenty	V	1377	106	494	1765 (−127, 218)	185	778	1970 (−214, 160)
	E	10	0	106	116 (−50, 108)	0	185	195 (−61, 107)
Gisborne	V	2107	52	1020	3075 (−373, 420)	61	1367	3413 (−318, 421)
	E	38	0	52	90 (−36, 48)	0	61	99 (−40, 50)
Hawke's Bay	V	1381	8	1195	2568 (−611, 641)	17	1817	3181 (−472, 707)
	E	0	0	8	8 (−4, 14)	0	17	17 (−6, 31)
Taranaki	V	1919	199	1545	3265 (−311, 334)	371	2056	3604 (−209, 31)
	E	0	0	199	199 (−133, 156)	0	371	371 (−105, 253)
Manawatu-Whanganui	V	607	0	917	1524 (−495, 646)	0	1814	2421 (−666, 1022)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 1)
Wellington	V	637	10	857	1484 (−357, 397)	28	1290	1899 (−342, 452)
	E	0	0	10	10 (−10, 18)	0	28	28 (−17, 5)
West Coast	V	22	0	198	220 (−97, 106)	0	315	337 (−51, 185)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Canterbury	V	15	0	303	318 (−165, 209)	0	539	554 (−191, 295)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Otago	V	0	0	0	0 (0, 0)	0	0	0 (0, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Southland	V	0	0	0	0 (0, 0)	0	0	0 (0, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Tasman	V	40	0	63	103 (−42, 62)	0	125	165 (−46, 39)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Nelson	V	0	0	5	5 (0, 2)	0	7	7 (−2, 12)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Marlborough	V	90	0	225	315 (−108, 167)	0	364	454 (−139, 183)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 4)
Total	V	21,405	1174	9246	29,477 (−3449, 4192)	1750	14,393	34,048 (−3636, 4396)
	E	1154	0	1174	2328 (−392, 617)	0	1750	2904 (−439, 758)

Table A2. Avocado under RCP 6.0: Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Avocado RCP 6.0		Past	Mid-Century Projection			Late-Century Projection		
Region		Area	Loss	Gain	Area (−/+)	Loss	Gain	Area (−/+)
Northland	V	7419	519	147	7047 (−58, 36)	705	265	6979 (5, 13)
	E	969	0	519	1488 (−73, 89)	0	705	1674 (−68, 38)
Auckland	V	2333	240	576	2669 (−86, 80)	355	890	2868 (−33, −1)
	E	132	0	240	372 (−79, 36)	0	355	487 (−45, 31)
Waikato	V	3458	79	1839	5218 (−661, 864)	476	4430	7412 (−916, 776)
	E	5	0	79	84 (−26, 127)	0	476	481 (−126, 254)
Bay of Plenty	V	1377	91	480	1766 (−167, 179)	339	1068	2106 (−154, 200)
	E	10	0	91	101 (−22, 101)	0	339	349 (−58, 89)
Gisborne	V	2107	34	946	3019 (−470, 353)	148	1758	3717 (−387, 396)
	E	38	0	34	72 (−19, 49)	0	148	186 (−17, 35)
Hawke's Bay	V	1381	6	1083	2458 (−598, 628)	48	2488	3821 (−462, 667)
	E	0	0	6	6 (−2, 8)	0	48	48 (−19, 52)
Taranaki	V	1919	176	1438	3181 (−436, 327)	709	2411	3621 (−47, −25)
	E	0	0	176	176 (−96, 149)	0	709	709 (−197, 352)
Manawatu-Whanganui	V	607	0	887	1494 (−490, 558)	1	2969	3575 (−836, 1223)
	E	0	0	0	0 (0, 0)	0	1	1 (0, 7)
Wellington	V	637	10	800	1427 (−322, 366)	33	1798	2402 (−383, 372)
	E	0	0	10	10 (−10, 18)	0	33	33 (−5, 19)
West Coast	V	22	0	182	204 (−86, 114)	0	569	591 (−198, 126)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Canterbury	V	15	0	269	284 (−136, 196)	0	852	867 (−252, 349)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Otago	V	0	0	0	0 (0, 0)	0	0	0 (0, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Southland	V	0	0	0	0 (0, 0)	0	0	0 (0, 0)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Tasman	V	40	0	67	107 (−38, 51)	0	172	212 (−29, 48)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Nelson	V	0	0	5	5 (−1, 0)	0	18	18 (−10, 10)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Marlborough	V	90	0	207	297 (−112, 128)	4	565	651 (−178, 96)
	E	0	0	0	0 (0, 0)	0	4	4 (0, 9)
Total	V	21,405	1155	8926	29,176 (−3567, 3786)	2818	20,253	38,840 (−3850, 4220)
	E	1154	0	1155	2309 (−327, 577)	0	2818	3972 (−535, 886)

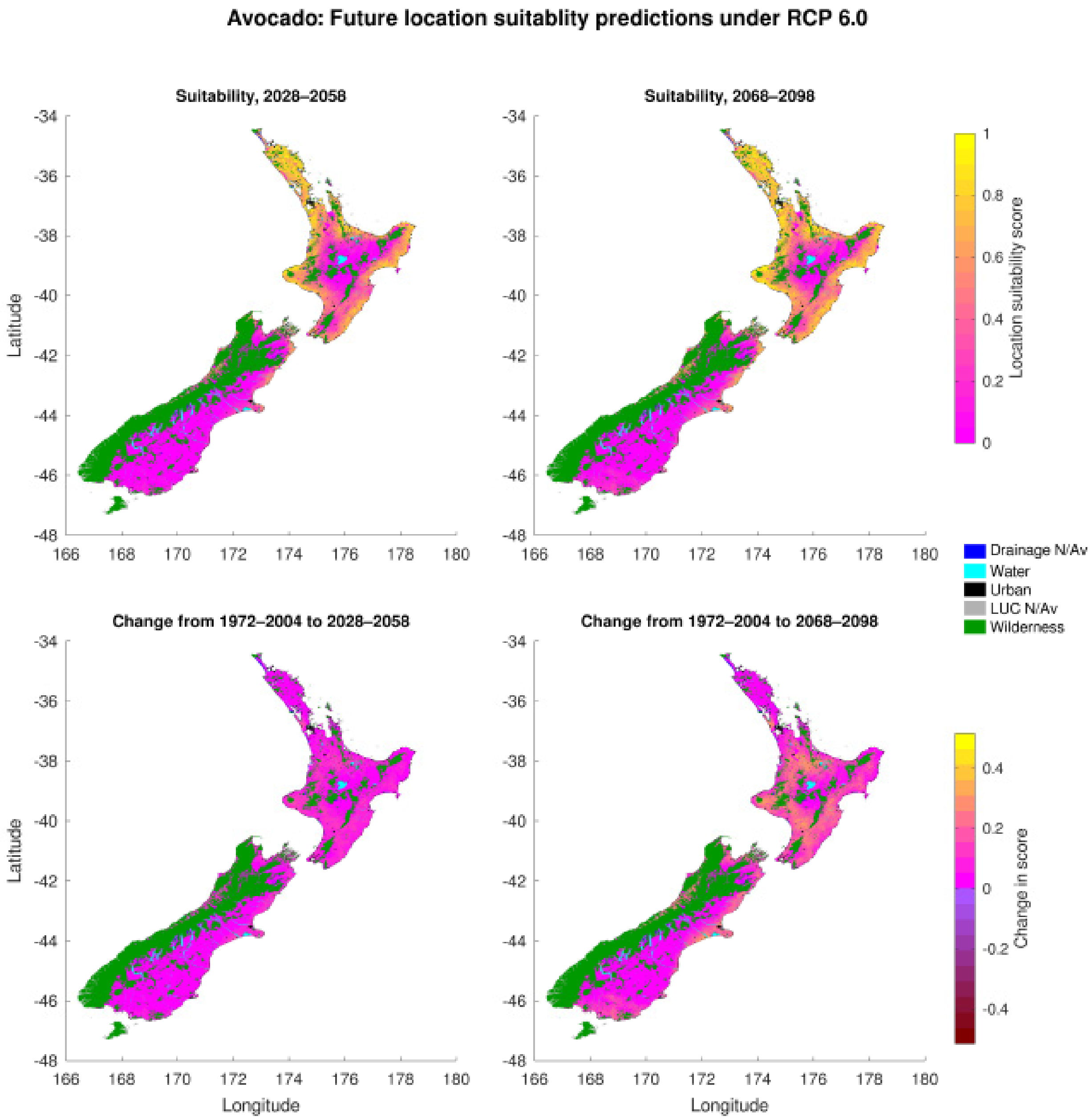

Figure A2. Projected location suitability (upper figures) and projected changes in location suitability from the historic period (lower figures) for avocado in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 6.0. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

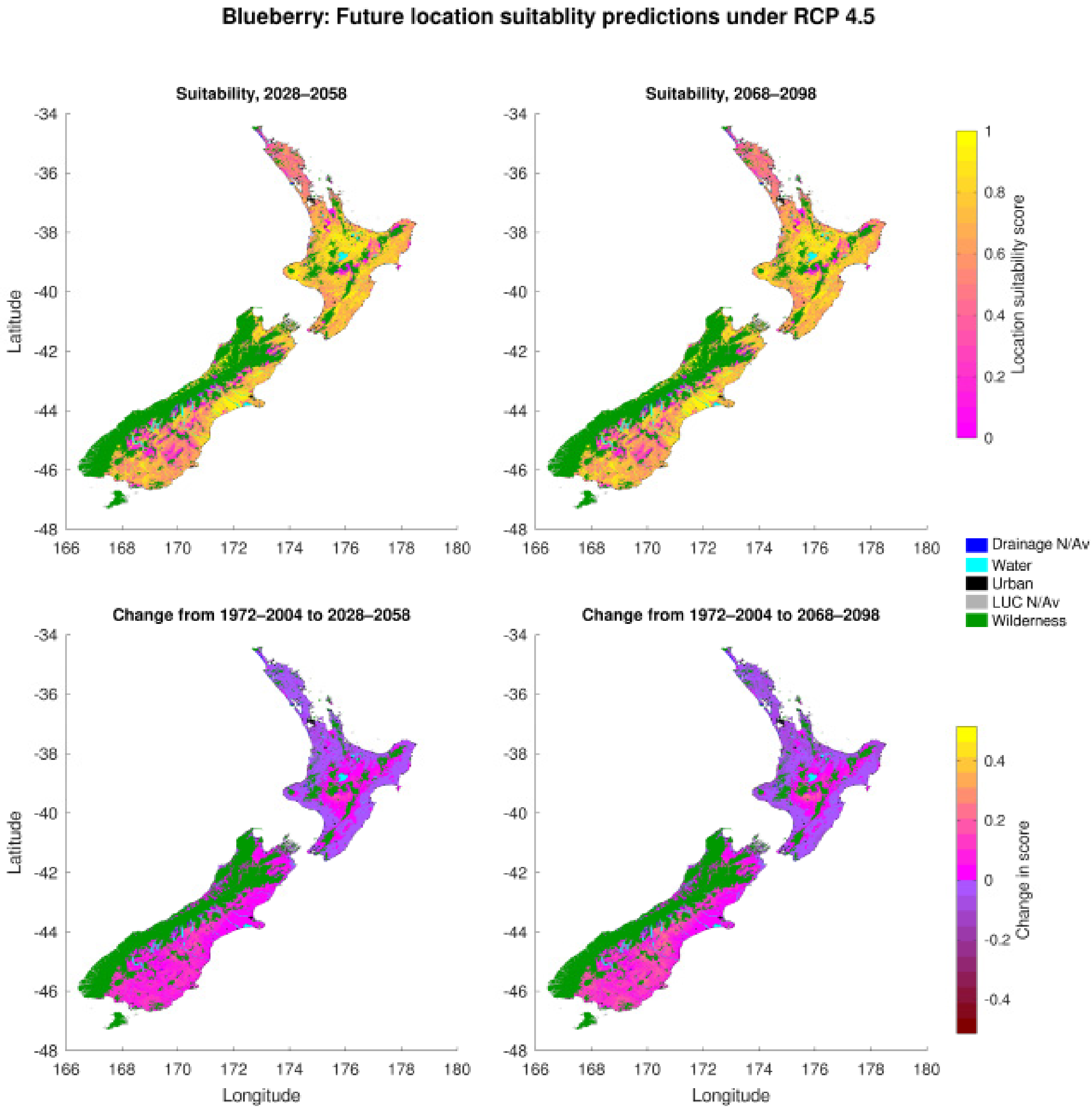

Figure A3. Projected location suitability (upper figures) and projected changes in location suitability from the historic period (lower figures) for blueberry in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 4.5. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

Table A3. Blueberry under RCP 4.5: Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Blueberry RCP 4.5		**Past**	**Mid-Century Projection**			**Late-Century Projection**		
Region		**Area**	**Loss**	**Gain**	**Area (−/+)**	**Loss**	**Gain**	**Area (−/+)**
Northland	V	2160	887	0	1273 (−757, 967)	1243	0	917 (−712, 1001)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Auckland	V	1770	270	4	1504 (−465, 251)	491	4	1283 (−605, 338)
	E	4	4	0	0 (0, 0)	4	0	0 (0, 0)
Waikato	V	12,880	852	1425	13,453 (−1110, 89)	1319	1876	13,437 (−448, −406)
	E	3105	1358	361	2108 (−561, 1470)	1788	424	1741 (−310, 933)
Bay of Plenty	V	5935	144	466	6257 (−201, 21)	253	627	6309 (−144, −36)
	E	1127	336	79	870 (−186, 333)	476	116	767 (−153, 300)
Gisborne	V	6435	270	131	6296 (−227, 54)	422	160	6173 (−404, 143)
	E	261	60	50	251 (−49, 135)	79	33	215 (−32, 112)
Hawke's Bay	V	8590	142	476	8924 (−67, 24)	211	676	9055 (−59, −4)
	E	1055	138	84	1001 (−189, 237)	265	106	896 (−180, 247)
Taranaki	V	4537	70	348	4815 (−253, 160)	78	644	5103 (−259, 52)
	E	760	343	63	480 (−179, 259)	639	49	170 (−153, 282)
Manawatu-Whanganui	V	13,363	336	768	13,795 (−95, −71)	640	1115	13,838 (−78, 13)
	E	1545	96	180	1629 (−257, 353)	304	227	1468 (−322, 460)
Wellington	V	4827	98	122	4851 (−85, 17)	178	165	4814 (−157, 57)
	E	415	39	14	390 (−42, 80)	84	6	337 (−57, 78)
West Coast	V	2232	177	72	2127 (−87, 57)	186	103	2149 (−91, 88)
	E	548	29	172	691 (−65, 95)	54	180	674 (−101, 98)
Canterbury	V	16,161	1764	4162	18,559 (−395, −191)	2916	5531	18,776 (−47, 192)
	E	1557	0	1763	3320 (−740, 1291)	7	2904	4454 (−1106, 980)
Otago	V	5662	79	5731	11,314 (−1989, 2045)	190	7939	13,411 (−1765, 1921)
	E	7	0	79	86 (−39, 122)	0	190	197 (−80, 155)
Southland	V	6428	147	3321	9602 (−890, 450)	467	4167	10,128 (−367, −323)
	E	0	0	147	147 (−91, 308)	0	467	467 (−248, 807)
Tasman	V	2326	128	276	2474 (−82, −15)	168	338	2496 (−101, 30)
	E	383	11	128	500 (−53, 124)	22	168	529 (−70, 129)
Nelson	V	259	0	25	284 (−9, 8)	1	33	291 (−12, 2)
	E	11	0	0	11 (0, 0)	0	0	11 (0, 0)
Marlborough	V	2960	84	437	3313 (−130, 117)	122	573	3411 (−114, 113)
	E	394	17	50	427 (−20, 28)	29	53	418 (−20, 33)
Total	V	96,525	5448	17,764	108,841 (−4682, 1823)	8885	23,951	111,591 (−4207, 2025)
	E	11,172	2431	3170	11,911 (−2471, 4835)	3751	4923	12,344 (−2832, 4614)

Table A4. Blueberry under RCP 6.0: Land area (km^2) falling into viable (V) and excellent (E) categories for the RCP Past period (1972–2004: 'Past') and projected change to the mid- (2028–2058) and late (2068–2098) century. Loss and gain refer to different locations in a region. Parentheses show 'best' and 'worst' case deviations based on the estimated error.

Blueberry RCP 6.0		**Past**	**Mid-Century Projection**			**Late-Century Projection**		
Region		**Area**	**Loss**	**Gain**	**Area (−/+)**	**Loss**	**Gain**	**Area (−/+)**
Northland	V	2160	794	0	1366 (−685, 848)	1618	0	542 (−508, 863)
	E	0	0	0	0 (0, 0)	0	0	0 (0, 0)
Auckland	V	1770	254	4	1520 (−355, 232)	876	4	898 (−393, 557)
	E	4	4	0	0 (0, 0)	4	0	0 (0, 0)
Waikato	V	12,880	905	1339	13,314 (−1026, 224)	1914	2118	13,084 (−468, 345)
	E	3105	1272	437	2270 (−613, 1339)	2019	425	1511 (−304, 329)
Bay of Plenty	V	5935	151	446	6230 (−197, 7)	346	721	6310 (−87, −39)
	E	1127	322	86	891 (−155, 314)	574	133	686 (−124, 207)
Gisborne	V	6435	265	122	6292 (−176, 45)	688	177	5924 (−364, 272)
	E	261	55	52	258 (−54, 129)	91	52	222 (−49, 72)
Hawke's Bay	V	8590	130	435	8895 (−55, 47)	309	877	9158 (−107, −65)
	E	1055	121	84	1018 (−185, 211)	366	128	817 (−143, 277)
Taranaki	V	4537	70	360	4827 (−213, 143)	127	750	5160 (−185, −67)
	E	760	355	63	468 (−155, 219)	745	21	36 (−35, 145)
Manawatu-Whanganui	V	13,363	341	724	13,746 (−77, −48)	904	1419	13,878 (−129, −80)
	E	1545	86	201	1660 (−238, 307)	511	277	1311 (−311, 412)
Wellington	V	4827	94	113	4846 (−59, 20)	323	227	4731 (−198, 118)
	E	415	37	14	392 (−43, 69)	144	6	277 (−84, 75)
West Coast	V	2232	178	72	2126 (−77, 51)	171	183	2244 (−163, 55)
	E	548	29	173	692 (−59, 84)	131	157	574 (−70, 174)
Canterbury	V	16,161	1730	4108	18,539 (−403, −182)	3377	6205	18,989 (103, 121)
	E	1557	0	1730	3287 (−598, 1162)	15	3360	4902 (−908, 704)
Otago	V	5662	103	5590	11,149 (−1752, 1859)	306	9629	14,985 (−1518, 1320)
	E	7	0	103	110 (−60, 82)	0	306	313 (−100, 139)
Southland	V	6428	131	3247	9544 (−839, 453)	1185	4614	9857 (−713, 187)
	E	0	0	131	131 (−75, 239)	0	1185	1185 (−551, 940)
Tasman	V	2326	130	270	2466 (−74, −10)	182	376	2520 (−91, 31)
	E	383	11	130	502 (−53, 111)	33	182	532 (−54, 115)
Nelson	V	259	0	25	284 (−11, 8)	1	37	295 (−7, 1)
	E	11	0	0	11 (0, 0)	0	0	11 (−1, 0)
Marlborough	V	2960	84	422	3298 (−112, 115)	162	688	3486 (−82, 94)
	E	394	17	51	428 (−19, 25)	41	57	410 (−29, 38)
Total	V	96,525	5360	17,277	108,442 (−3978, 1679)	12,489	28,025	112,061 (−3561, 2364)
	E	11,172	2309	3255	12,118 (−2307, 4291)	4674	6289	12,787 (−2763, 3627)

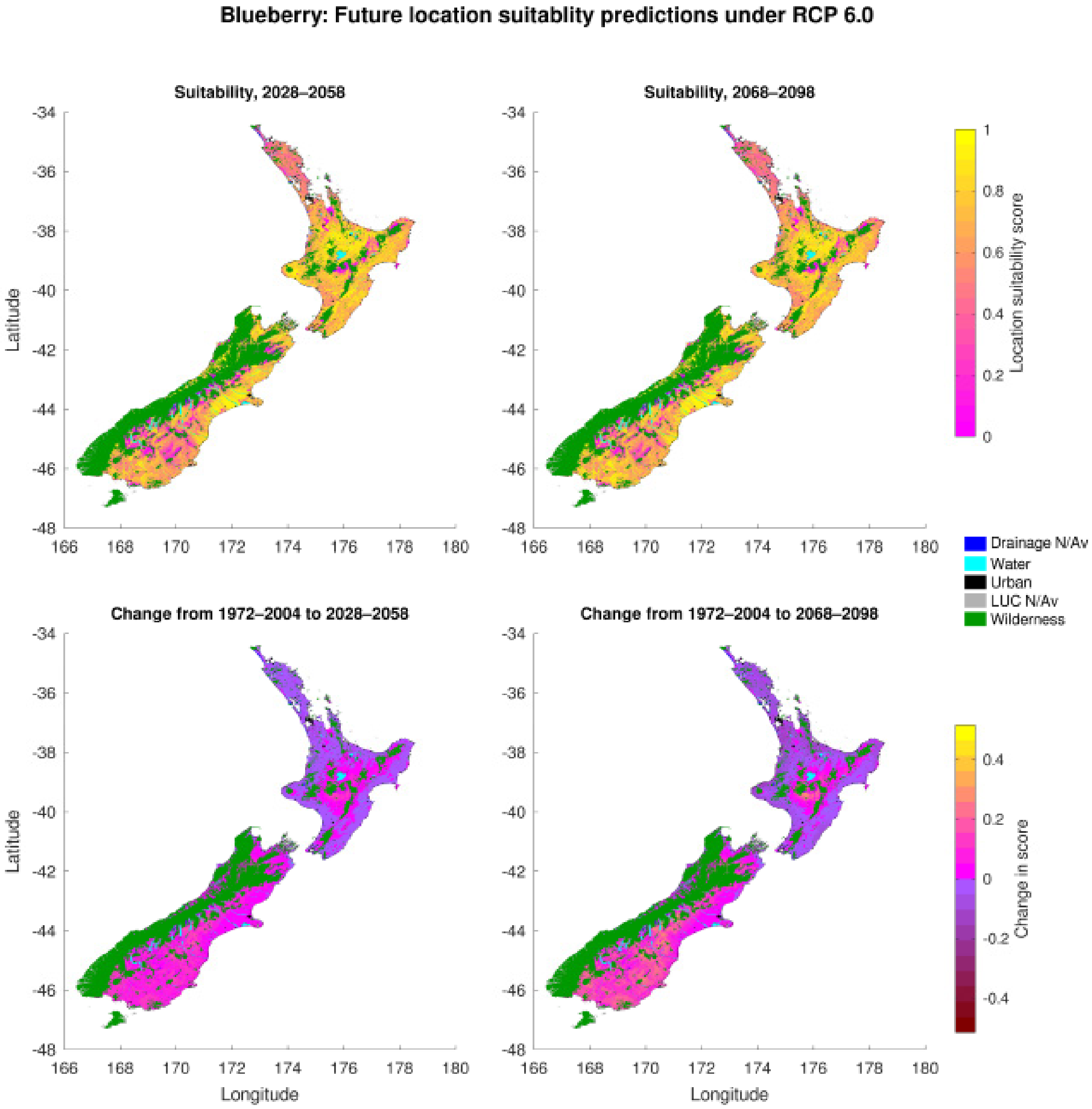

Figure A4. Projected location suitability (upper figures) and projected changes in location suitability from the historic period (lower figures) for blueberry in the mid-century (left figures) and late century (right figures) in New Zealand under Representative Concentration Pathway (RCP) 6.0. N/Av indicates data were not available. LUC = land use capability classification. Wilderness areas include conservation areas, reserves, national parks and marginal strips.

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