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Modelling Continuous Location Suitability Scores and Spatial Footprint of Apple and Kiwifruit in New Zealand

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Abstract: Under climate change, land use suitability for horticultural production will change; this has prospects of both adverse socio-economic impacts for the industry in some regions, and beneficial impacts in others. Policy development and industry guidance are needed to develop adaptations to mitigate climate change risks and exploit new opportunities. For climate-change issues, models provide a powerful means for assessing future suitability at a patch, region or national scale in order to guide policy decisions. Here, we describe the development of a new continuous (sliding-scale) suitability modelling approach to assess the suitability of different locations for growing apple and kiwifruit in New Zealand, based on phenological and physiological considerations; these models used geographical information system (GIS) soil, land and weather data to develop maps showing the suitability of locations across New Zealand for cultivating apple and kiwifruit. The models were "ground-truthed" in an iterative process of expert parameterisation and recalibration to ensure maps aligned with current growing locations for the two crops. We estimated an econometric logit model that incorporated the continuous suitability scores as predictors of land use for apple and kiwifruit. Comparison of modelled suitability scores with industry-supplied maps of apple and kiwifruit orchards showed good consistency between predicted suitability and current land use. Compared with a range of alternative land uses, suitability for apple was highest for locations currently used to grow apple and suitability for kiwifruit was highest for locations currently used to grow kiwifruit. Our framework provides the capability to project incremental changes in the suitability of locations for apple and kiwifruit under different climate change pathways and to project consequential changes in their spatial footprints; this framework can be extended to other crops.

Keywords: climate change; econometric modelling; suitability modelling; horticulture; GIS; land use

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1. Introduction

Weather regulates plant production by direct temperature regulation of growth and development [1], through rainfall patterns [2], modulation of soil-based processes [3], and by influencing the virulence of pests and diseases [4–6]. Projected climate changes for New Zealand (NZ) are expected to have significant impacts on its primary sector. Several authors note the prospects of adverse socio-economic impacts through declining yields and profitability [7–10]. Conversely, changing climates could create opportunities for new crops, or new locations for existing crops by providing more favourable conditions.

The effects of climate change on horticulture will vary with geographical location and crop type [11], and thus the spatial footprints of crops may change over time; this will have a flow on effect on rural communities and environments as some industries contract or expand, while others exit or enter a region. Understanding how climate change would affect land use is important for improving the robustness of environmental policy by identifying future environmental issues such as nutrient leaching and water-demand pressures [12]; it would be equally important for developing social policies and to guide policy and planning by industry bodies in response to potential industry expansion or contraction within different regions.

Policy must be underpinned by reliable information, and rigorously constructed suitability models can be used to provide this for future scenarios [13]. For example, Thomas, et al. [14] proposed consideration of site suitability in relation to current climate, in order to improve Scottish woodland planning, and noted that more benefits could be obtained by choosing species suited for future climates. Modelling likely production levels could provide additional power to projection studies [15]. Indeed for issues to do with climate change, models are arguably the only tools available that have the potential for informing decision makers on outcomes under different climate-change pathways.

Key issues from this perspective are understanding: (i) current location suitability for kiwifruit and apple; (ii) how location suitability for kiwifruit and apple will change under future climates and (iii) what impact changing suitability will have on future land use.

In this paper we describe a modelling methodology to address these key issues, in particular a sliding-scale scoring system that we developed, which we consider is a novel approach to modelling continuous suitability scores; this approach was applied to both apple and kiwifruit production in NZ, and allows incremental changes in suitability to be modelled and mapped. Functions can be formulated to reflect uncertainties in the data, spatial variation within grid cells, or differences in cultivars. In our approach, we develop individual suitability scores for each set of crop-specific suitability criteria based on considerations of plant requirements and phenology. Using gridded climate, soil and terrain data (Table 1), each suitability score was mapped at the national level, and "ground-truthed" in an iterative process of expert parameterisation to check their accuracy. We then developed a method for a balanced combination of individual suitability scores to obtain a combined suitability score that reflected the relative importance of individual criteria. The development of combined suitability maps was also subject to the ground-truthing process, and was carried out for climate-related criteria to obtain a climate suitability score, for land-related criteria to obtain a land-suitability score, and for both climate- and land-related criteria combined, to obtain an overall location suitability score. Additionally, we describe the estimation of a multinomial logit model of land use that includes the continuous suitability scores as independent variables, in order to model the probability of land being used for apple or kiwifruit cultivation over alternative land uses. The logit model was developed to provide inputs to the Land Use in Rural New Zealand (LURNZ) model [16].

Table 1. Data used in the study.

Variable	Units	Spatial Resolution	Temporal Resolution
Minimum temperature	°C	5 km × 5 km	Daily
Maximum Temperature	°C	5 km × 5 km	Daily
Potential rooting depth	m	1 km × 1 km	—
Drainage class	—	1 km × 1 km	—
Slope of land	°	1 km × 1 km	—
Land use capability class	—	1 km × 1 km	—

In a companion paper [17] we used the suitability models with climate projection data to project suitability maps of New Zealand for apple and kiwifruit at the mid and late 21st century, under different climate-change pathways. We then used the projected suitability maps together with the logit model to provide inputs to LURNZ to project how the spatial footprints of these sectors might change with climate; this demonstrates the capability of combining suitability and econometric modelling to provide evidential guidance for decision-making on land-use policy and adaptations to climate change.

2. Background Theory

2.1. Criteria for Assessing Location Suitability for Apple and Kiwifruit

There are three key requirements for apple and kiwifruit production. Firstly, adequate 'winter chill' is required to ensure ample flowering occurs over a short time period to enable a compact harvest period [18]. Secondly, after flowering, adequately warm temperatures are needed to ensure that fruit crops reach maturity [19,20]. Thirdly, low frost risk is needed after bud-break for both crops [21].

Additionally, for apple, sufficient warmth in the weeks immediately after flowering is important for obtaining good-sized fruit [22], while excessively hot temperatures in conjunction with sunburn could damage fruit [23]. The latter is not an issue for kiwifruit since the leaf canopy protects the fruit; however, severe cold can damage kiwifruit canes [24], and this consideration was used as a separate suitability criterion for kiwifruit.

Since weather patterns will vary from year to year, climate criteria should be assessed over a range of consecutive years that can be considered representative of the period.

For both apple and kiwifruit, adequate soil drainage is important for anaerobiosis, and avoiding root disease. The depth of soil to a root-impermeable layer (potential rooting depth or PRD) must be adequate for the development of a strong root system. The slope of land affects the ease of machinery access, building structures for plants, and erosion control [25]. An additional suitability criteria that we used is the Land Use Capability (LUC) class which ranks by limitations to production [26]. The LUC class descriptor is influenced by slope, PRD and drainage considerations, but contains extra information regarding soil properties, and thus is effectively an independent variable. Insufficient rainfall, poor soil fertility and unsuitable soil pH can be mitigated by irrigation and soil management [21] and thus were not used in suitability assessments.

Crops are faced with a range of pests and diseases, each with different optimal environmental conditions [27]. There is limited understanding of how risks will vary with atmospheric CO_2 concentrations, temperature and water availability under climate change [28,29]. Warming climates could accelerate pathogen life cycles [30] and allow novel pathogens to become a threat, rendering our current understanding of phytopathology invalid [31]; these risks are more appropriately handled via qualitative discussion [21], and since they can be managed by adequate drainage and chemical control, they were not included in suitability assessments.

2.2. Sliding-Scale Suitability Models

Triantafilis, et al. [32] described a continuous modelling approach that provided suitability assessments on a sliding scale from 0 (unsuitable) to 1 (suitable). That allowed different factors to be assessed together rather than by separate rules. Continuous models have provided the basis for a geographical information system (GIS)-based allocation of land use [33] and the application of neural networks to assess land suitability for soy bean production [34]. A different continuous approach was presented and used for evaluating future suitability by Zabel, et al. [35]; these approaches are an alternative to more common discrete suitability assessments, such as that of Kidd, et al. [36], who specified categories of 'highly suitable', 'suitable', 'moderately suitable' or 'unsuitable' to characterise the suitability of land for horticultural uses. Categorical distinctions may not represent the continuity of the land [32] and require thresholds for indicator values which can result in limitations. For example, similar locations may be assigned different categories because their calculated indicator values fall either side of a threshold, while dissimilar sites at opposite ends of a range would be assigned equal merit. Consequentially, changes in climate that have a significant effect on crop cultivation might not be reflected in suitability calculations, while minor changes might be reflected as significant; however, a categorical approach does have the advantage of unambiguous delineation of good versus bad, whereas under a continuous scoring system, use or non-use is a management decision [32].

We have modified the approaches of Triantafilis, Ward and McBratney [32] and Zabel, Putzenlechner and Mauser [35] in a novel manner and developed a sliding-scale "suitability score" for each criterion, which also gives a location a value from 0 (totally unsuitable) to 1 (very highly suitable); this approach does not rule locations as suitable or unsuitable, and interpretation is criterion-dependent. For example, a lower suitability score could indicate higher establishment and/or maintenance costs, or a lower potential yield if deficiencies are not mitigated. For a criterion where there is variation between cultivars in their requirements, a lower suitability score could indicate a lower proportion of cultivars having their requirements met.

While the functions we have used to represent suitability for individual criteria have similar forms to those used by to those used by Zabel, Putzenlechner and Mauser [35], our approach differs in that it obtains an overall suitability score by combining scores for different criteria, whereas Zabel, Putzenlechner and Mauser [35] took the minimum value across criteria. Combining suitability scores for several criteria provides a more holistic view of the crop suitability of a location by balancing its pros and cons, and allows comparison and ranking of locations. For n different criteria, where each suitability score is denoted by S_i $(i = 1, \ldots, n)$, the combined score is obtained by taking the weighted geometric average:

$$\overline{S} = \prod_{i=1}^{n} S^{X_i} \, , \; X_i \equiv \frac{w_i}{\sum_{j=1}^{n} w_j} \tag{1}$$

where w_i is the weight used for criterion i, and reflects the importance assigned to it. A low score for one criterion will lower the overall score even if other scores are high, with the degree of downgrading dependent on its weight compared to others. Checking individual scores will identify poorly scoring criteria when overall suitability is lowered.

For a climate-related criterion, the suitability score is obtained by taking an ordinary arithmetic mean of score assessments for individual years; however, when combining climate-related scores the weighted geometric average is calculated for each year, before being averaged.

3. Methods

3.1. Data

Climate data were available from a grid using NZ Geodatum 1949 (NZGD49) coordinates. The growing season extends across calendar years in the Southern Hemisphere, and so modelling a growing season requires daily weather data from two calendar years. Soil and other land-related data were resampled in NZGD49 for consistency with the climate data, and all map coordinates were based on NZGD49.

3.1.1. Observed, Historic Climate Data

Virtual Climate Station Network (VCSN) data obtained from the New Zealand National Institute of Water and Atmospheric Research (NIWA) were used to provide daily maximum and minimum temperatures across New Zealand for the 1972 to 2017 period; these correspond to respectively the maximum temperature from 9 a.m. and minimum temperature up to 9 a.m. of each day. Hourly temperature data were not available. The resolution of the VCSN data are a 0.05×0.05 degree grid; this approximates a 5 km $\times$ 5 km grid, and will be referred to as such. The VCSN data are obtained from spatial interpolation of actual measurements made at physical weather stations located across NZ, and played the role of "historic, observed data". The methodology underlying the VCSN data are discussed by Tait and Macara [37].

Some calculations required that hourly temperatures be estimated from maximum and minimum daily temperatures. To do this we made the simple approximation that temperature would have a sinusoidal variation over a 24-h period, following the approach of Baskerville and Emin [38]. While more sophisticated models are available, these are not warranted because the VCSN data themselves are modelled and have associated uncertainties.

3.1.2. Land and Soil Information

The soil- and land-related data included PRD provided by the soil (https://lris.scinfo.org.nz/layer/48110-fsl-potential-rooting-depth/ accessed on 28 May 2019) and soil drainage (https://lris.scinfo.org.nz/layer/48104-fsl-soil-drainage-class/ accessed on 28 May 2019) from the New Zealand Fundamental Soil Layer (FSL) database. The LUC class (https://lris.scinfo.org.nz/layer/48076-nzlri-land-use-capability/ accessed on 10 June 2019) and information on the location of urban areas, quarries, rivers and lakes were taken from the New Zealand Land Resource Inventory (NZLRI) database. Slope information (https://lris.scinfo.org.nz/layer/48081-lenz-slope/ accessed on 23 May 2019) came from Land Environments of New Zealand (LENZ). The locations of public conservation areas (https://koordinates.com/layer/754-doc-public-conservation-areas/ accessed on 13 May 2019) were provided by the Department of Conservation (DOC).

Soil and topographical databases contained information for irregular polygons and were resampled to a finer 0.01 × 0.01 degree NZGD49 grid matching the VCSN grid perfectly at 25 cells to 1. The resampled grids approximate a 1 km × 1 km grid.

3.1.3. Data for Land-Use Estimation

Initial land-use information was based on the 25-hectare resolution LURNZ basemap [39] combining remote-sensing land-cover data from the 2012 Land Cover Database 4 (LCDB4) and land-use data from the Land Use NZ (LUNZ) map. Data on land ownership and land tenure were used to identify and classify privately owned land. The LURNZ land-use information was amended using confidential data on the location of kiwifruit and apple blocks provided by the two industries. The econometric modelling also relies on slope and land-use capability class as well as the location of ports and towns [40].

3.1.4. Limitations of Gridded Data

There could be significant variability in weather within the 25 km^2 area represented by a VCSN grid cell due to microclimates. For example, Ellenwood [41] found differences of 1.7 to 2.2 °C between neighbouring apple orchards with no more than a 7.5 m difference in elevation. Mason, et al. [42] found that differences between VCSN data and measurements from independent weather stations were related to the distance between estimation points and station locations, although correlations between the VCSN data and station data were good. Similarly, variation could exist in the soil and land variables reported on the 1 × 1 km grid.

3.2. Modelling Suitability Criteria

Suitability modelling was carried out in version 6.2.0 of the modelling environment GNU Octave (https://octave.org accessed on 2 March 2021). The VCSN data from 2006 to 2017 and land and soil data were used to calculate suitability scores for the growing years 2006 to 2016 and develop maps showing the suitability of different locations across New Zealand for each crop, in order to fine-tune and "ground-truth" suitability models. The VCSN data from 1972 to 2005 were also used to assess the accuracy of climate-model datasets in producing appropriate baseline maps for use in projections of change [17].

3.2.1. Winter Chill

Chilling requirements refer to the minimum period of cold weather needed for plants to break bud and flower adequately for crop production, after a dormant rest period; this will vary between crops and cultivars of the same crop.

For apple, Rai et al. [43] found a requirement of 1000–1500 chill hours (7 °C base) depending on cultivar, while Guak and Nielson [44] found that 'Gala' required 970 hours of chill (7.2 °C base). Hauagge and Cummins [45] found that the mean chill requirement ranged from 218 to 1530 chill units (CU) depending on cultivar, with 'Gala' having a requirement of 1094 CU, and the majority of cultivars requiring 800 to 1200 CU; these authors used an unconventional calculation for CU [46] which cannot be directly compared with 7.2 °C base chill hours. Nevertheless, their results highlight the huge variation in chill requirement between cultivars, with the lowest chill requirement being 80% less and the highest chill requirement 40% more than the 'Gala' requirement. The requirements for many cultivars range from 30% below to 10% above the 'Gala' requirement. Thus, a chilling suitability score that switches slowly over a large range of chill units would be appropriate to reflect this variation; this is a more nuanced way rather than the binary approach of a chill threshold, while still being understandable to a wider audience of growers, industry leaders, practitioners and decision-makers.

We chose to express chill in terms of the Richardson chill units (RCU) system for apple, as calculated according to Table 2. The RCU also have a rough equivalence with the CU definition used by Hauagge and Cummins [45,46] who provided requirement thresholds for a range of apple varieties. To reflect these data we express chill suitability as a sigmoid function (Equation (2)), using RCU as the independent variable x, and parameter values of $a = -0.008$ and $b = 700$ RCU (Figure 1).

$$y = \frac{1}{1 + \exp(a(x - b))} \tag{2}$$

Table 2. Richardson Chill Units (RCU) assigned for different temperature ranges, sourced from http://www.harvest.com/support/calculations/ accessed on 15 July 2019.

Temperature (°C)	RCU (per Hour)
T < 1.5	0.0
1.5 ≤ T < 2.5	0.5
2.5 ≤ T < 9.2	1.0
9.2 ≤ T < 12.5	0.5
12.5 ≤ T < 16.0	0.0
16.0 ≤ T < 18.0	−0.5
T ≥ 18.0	−1.0

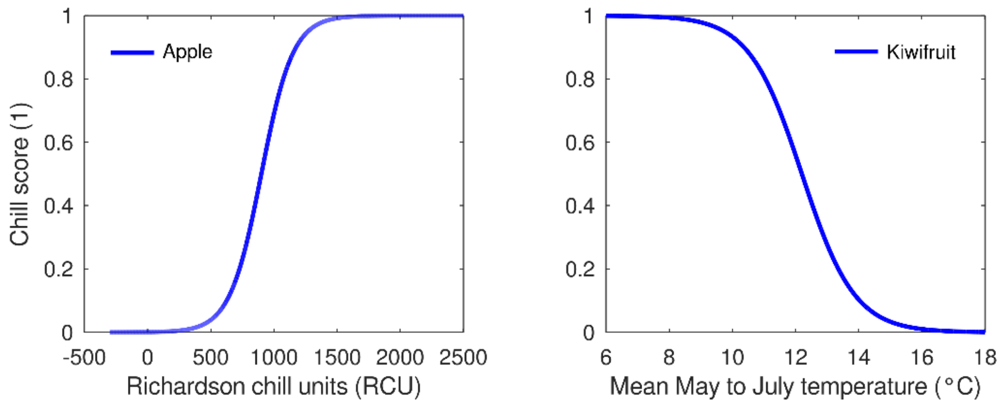

Figure 1. Chill score curve for apple production (**left**) based on Richardson chill units (RCU) and kiwifruit production (**right**) based on mean May to July temperatures. A higher score indicates a more satisfactory chilling effect.

Winter chill requirements for kiwifruit to be able to produce at least one king flower per winter bud are more successfully explained for NZ conditions by mean temperatures than by the accumulation of chill units or chill followed by thermal units [47]; however, chill hours between 0 and 7.2 °C have been used by Wang, et al. [48] to evaluate chilling requirements for kiwifruit in south China. Hall, Stanley, Müller and van den Dijssel [21] gave chill requirements as average May to July temperatures, being less than 11.7 °C for

Actinidia chinensis var. *deliciosa* 'Hayward' (a hexaploid cultivar) and 12.7 °C for a tetraploid cultivar [21,49]. The use of Hi-Cane® (an agrichemical used to break dormancy) raises this threshold by 2.3 °C for 'Hayward'. We assumed this would apply to the tetraploid cultivar also. Since these values are averages from experimental data, and to accord the likely variable conditions across a 25 km^2 grid-square, we used Equation (2) with mean May to July temperature as the independent variable. The parameter values were $a = 1.2$ and $b = 12.2$ °C to reflect differences between green kiwifruit and gold kiwifruit, and also to accommodate other cultivars (Figure 1).

3.2.2. Frost Risk

The effects of frosts occurring around flowering time and before harvest need to be taken into account for horticultural production. For each crop, we identified a frost-risk period based on the potential for frosts to cause damage and we developed a survival-rate curve based on data from the literature.

For apple, the most vulnerable stages of buds/flowers occur from open cluster to full bloom and post-bloom, with fruit survival rates of 90% and 10% after frosts of −2.2 °C and −3.8 °C, respectively [50]. Hewett and Young [51] found no frost damage to buds on newly formed kiwifruit vine shoots at −1 °C, slight damage at −2 °C, and 95% bud death at −3 °C. In contrast, dormant kiwifruit buds survived much colder temperatures. Considering a temperature variability of ±2 °C around the VCSN temperature within each 25-km^2 grid square, we used a daily fruit survival curve for apple with values of approximately 12% at −5 °C, and 88% at −1 °C, and a 50% midpoint at −3 °C. For kiwifruit, we used a frost-survival curve for buds and flowers with approximate values of 12% at −4 °C, and 88% at 0 °C, and a 50% midpoint at −2 °C (Figure 2); these curves were obtained from Equation (3) with minimum daily temperature as the independent variable, and setting $a = 1$ and respectively $b = -3$ °C for apple, and $b = -2$ °C for kiwifruit.

$$y = \frac{\exp(a(x-b))}{1+\exp(a(x-b))} \tag{3}$$

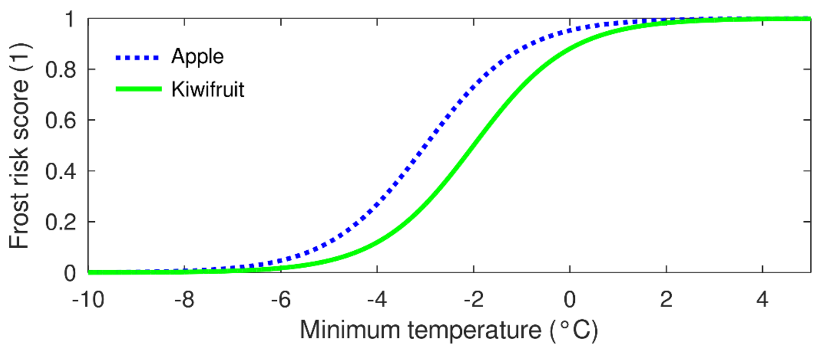

Figure 2. Frost risk score for daily minimum temperatures for apple and kiwifruit. A higher score indicates less frost risk.

Periods of Bud Break and Bloom

In a study on flowering in apple, there was a 9-day spread in the day of first bloom between 41 cultivars. Each cultivar had about a 5-day duration from first bloom to the start of full bloom, and a 3-day duration from the start to end of full bloom, with the cultivar 'Delicious' being roughly intermediate in flowering time and lagging the earliest cultivar by four days [41]. Austin, et al. [52] calculated the last day of full bloom (DFB) for 'Delicious' apple as a function of average maximum August–September temperature (New Zealand late winter/early spring). We used this function to calculate DFB for each location, and accommodated variation between cultivars and within trees by assuming the frost risk period would start 21 days before DFB, and extend until harvest, which we assumed to end no later than 30 April.

For kiwifruit, the frost-risk period for fruit yield was considered to be from day of bud break (DBB) until harvest, which could be in the autumn or early winter. Based on unpublished proprietary data for *A. chinensis* var. *chinensis* 'Hort16A' (a diploid cultivar), a tetraploid cultivar, and 'Hayward' we estimated the time band from "earliest DBB" to "typical DBB" to cover current and future cultivars. For typical DBB we combined data for the tetraploid cultivar and 'Hayward' and constructed the following equation:

$$\mathrm{DBB} = \min\left(335,\ 225 + \exp\left(0.267 * T_{MJJ}\right)\right), \tag{4}$$

where T_{MJJ} is the average temperature from May to July (°C), and 335 is an arbitrary cut-off that prevents DBB occurring later than 1 December. We based the earliest DBB on data for the 'Hort16A' cultivar for which DBB ranged from 225 to 245 days from 1 January, with little sensitivity to T_{MJJ} or site. Although 'Hort16A' is no longer grown commercially in NZ, it is a useful reference. We used day 225 as the earliest DBB for any cultivar.

Frost-Risk Period

For both crops, we used the same procedure for calculating a frost suitability score. For each day i of the frost risk period, we calculated the survival rate, S_i. The production at risk from frost increases from near zero on day 1 to total potential production as buds and flowers increase their development stage. In the later stages of the risk period, the production at risk decreases as more and more fruit are harvested, accounting for varying management practices and harvest times. Thus for the early and late stages of the frost-risk period, we down-weighted the daily loss associated with the daily survival rate according to the equation $S_i \to 1 - (1 - S_i)w_i$, where w_i is a daily weighting from 0 to 1.0.

Weights for apple were increased from near 0 on the first day of the risk period, to reach 1.0 on day 8 since we assumed that from the second week onwards, unopened flower buds will have developed to a stage of being susceptible to frost damage. Weights were decreased gradually from 1.0 starting on 1 April to reach 0 on 1 May; this reflects that early cultivars will be harvested before April, and that frost risk will be negligible by the end of that month when all cultivars would have been harvested.

For kiwifruit, the weights were gradually increased from near 0 on the earliest DBB to 1.0 on the typical DBB. To reflect progressive harvesting, the weights were decreased from 0.5 in mid-March to 0 by 1 July. The weight of 0.5 instead of 1.0 for mid-March reflects the frost protection provided by leaves during autumn harvest. The sudden decrease in weights in mid-March is inconsequential since the likelihood of a frost in March is negligible.

3.2.3. Temperature and Warmth for Crop Maturation

Horticultural production requires warm conditions for fruit maturation, and depending on the crop, is expressed in terms of growing degree days (GDD), growing degree hours (GDH), or mean temperatures over a period.

For apple, van den Dijssel, et al. [53] and Clothier et al. [54] suggested a minimum GDD requirement of 800 °C d for October to April using a 10 °C base. Singh and Bhatia [19] found a 28% variation in GDD (4 °C base) requirement across 10 different cultivars. Jangra [55] found a 39% variation between two cultivars. We calculated GDD using a base of 10 °C (GDD10) as suggested by van den Dijssel, Hall, Green and Clothier [53], but accommodated the variation between cultivars found by other authors: Thus we chose a suitability score with a response curve that was approximately 0.05, 0.5, and 0.95 for GDD10 values of 500, 800 and 1100 °C d (Figure 3). The annual calculation uses the October to December temperatures for that year, and January to April temperatures for the following year. That is the GDD10 for 2008 used temperatures from 2008 and 2009.

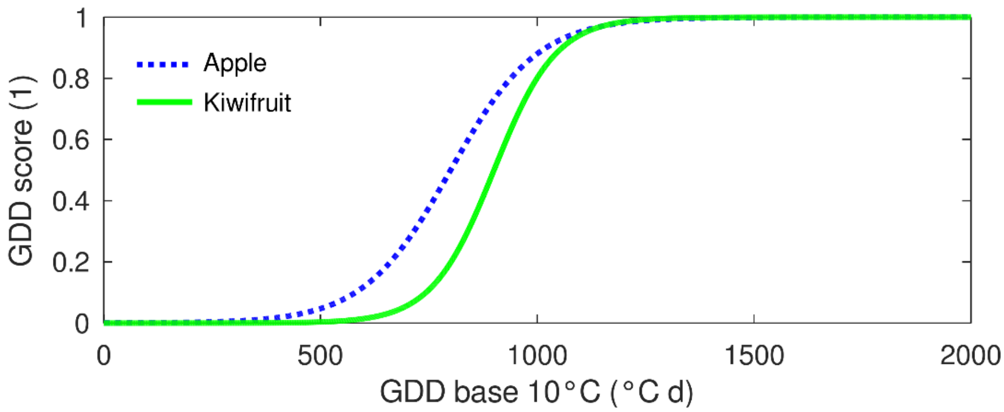

Figure 3. Growing degree days (GDD) score assigned to different GDD values base 10 °C. A higher score indicates GDD accumulation is more likely to achieve sufficient fruit growth and maturation.

Salinger and Kenny [20] suggested that the GDD10 requirements for adequate 'Hayward' kiwifruit growth to be 1100 °C d accumulated from October to April. In the absence of data of GDD requirements for other cultivars, we have used the information for 'Hayward' to construct a GDD suitability curve to represent current and future cultivars. We have assigned the values 0.05, 0.5, and 0.95 for GDD10 values of 690, 900 and 1110 °C d (Figure 3).

Both GDD suitability curves are obtained from Equation (2), with $a = -0.01$ and $b = 800$ °C d for apple and $a = -0.014$ and $b = 900$ °C d for kiwifruit.

3.2.4. Fruit Size in Apple

Stanley et al. [22] found a 90% increase in weight and 20% increase in diameter of fruit if GDD accumulation in the first 50 days after DFB were doubled from 120 to 240 °C d. Thus we calculated GDD10 for the first 50 days from DFB, to assess the suitability of a location for producing well-sized fruit. Different cultivars had different effective GDD reference bases, due to differences in harvest dates [56]; this suggests that cultivars would vary in their GDD10 requirements for good-sized fruit. Thus, we chose a suitability score curve that gave values of approximately 0.05, 0.5, and 0.95 for GDD10 values of 60, 120, 180 °C d in the first 50 DFB, using Equation (2) with $a = -0.05$ and $b = 120$ °C d (Figure 4).

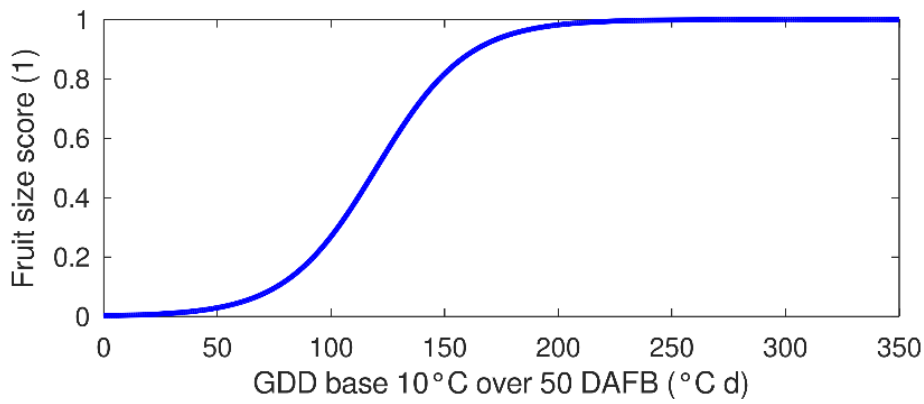

Figure 4. Fruit-size score as a function of growing degree days (GDD) base 10 °C in the first 50 days after full bloom (DFB) for apple. A higher score indicates a larger fruit.

3.2.5. Damage from Weather Extremes

Apple: Sunburn Risk

Maximum air temperature is highly correlated with the surface temperature of fruit and directly related to sunburn risk in apple [23]. Damage also depends on sunlight intensity (shading and cloud cover), wind, relative humidity and fruit acclimatisation to sunlight [23]. There is a high risk of browning damage above 35 °C, and a high risk of necrotic patches above 40 °C [57]. Fruit losses from heat waves in the Goulburn Valley in Australia have varied from 6% to 30%, depending on the season and the type of fruit, and for susceptible varieties like 'Granny Smith' and 'Gala', fruit losses can be as high as 40% to 50% [57].

We assumed that only fruit directly exposed to sunlight are prone to sunburn damage and that the risk period starts in October and ends in April. Further, we assumed that repeated non-consecutive days with temperature highs lower than threshold values may also cause cumulative damage. We represented the percent of fruit surviving sunburn by a sigmoidal curve with values of 99, 75 and 51% at maximum air temperatures of 29, 37.5 and 46 °C (Equation (2) with $a = 0.52$ and $b = 37.5$ °C). The sunburn survival score was then chosen to be one minus twice the survival rate, ensuring a range from zero to one (Figure 5). Daily sunburn scores were averaged using the same approach as for frost suitability. To account for differences management practices and varying harvest times, April weightings for sunburn effects were progressively declined from 1 to zero to reflect the decreased exposure of fruit as harvest progresses to completion.

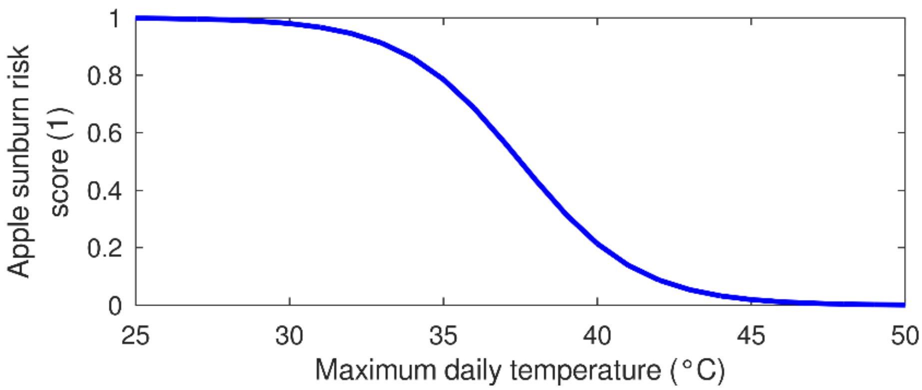

Figure 5. Sunburn survival score for apple as a function of maximum temperature. A higher score indicates less sunburn risk.

Kiwifruit: Cane Damage from Extreme Cold

Pyke et al. [24] found that in May, temperatures below −7 °C killed some dormant kiwifruit vines, and frosts of −9 °C and −11 °C killed 100% of 1-year-old plants; however, in June, no plants were killed by a frost of −7 °C, and respectively 17%, 33% and 67% of 1-year-old plants were killed by frosts of −9 °C, −11 °C and −13 °C. The cultivar 'Hayward' survived winter temperatures of −18 °C, albeit with some shoot damage [58]. To reflect this variation in response, we assigned a suitability score of 0.5 to a temperature of −13 °C, with a slow sliding scale as shown in Figure 6, using Equation (2) with $a = -1.2$ and $b = 13$ °C.

3.2.6. Potential Rooting Depth

Potential rooting depth (PRD) gives the depth of topsoil to an impervious barrier such as rock or heavy clay. Based on the opinion of horticultural experts, we chose a suitability curve to give values of 0.15, 0.5 and 0.8 for PRDs of 0.25, 0.45 and 0.65 m for both crops (Figure 7); this reflects that while a deeper soil is preferable, both apple trees and kiwifruit vines can perform well over a range of different soil depths, and that a shallow PRD can be mitigated, for example, by mounding, ripping or irrigation. The function used to capture this response is given in Equation (5), using PRD as the independent variable x, and parameter values $a = -10.3$ and $b = 0.45$ m, the latter being the PRD for a mid-point score.

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

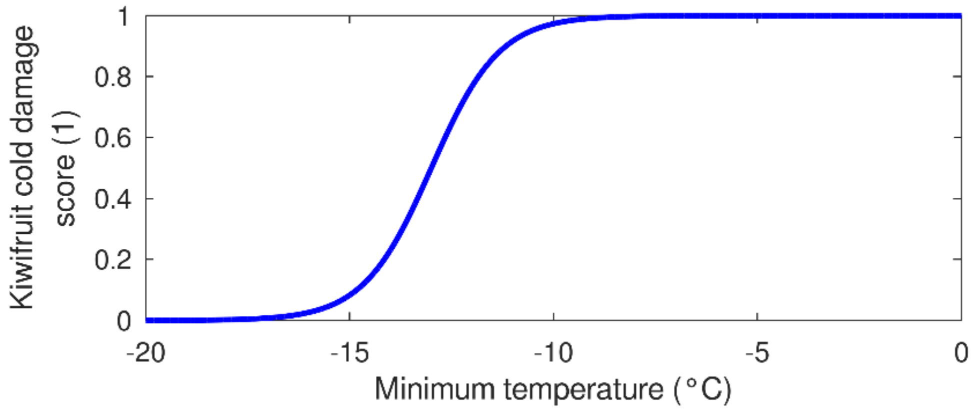

Figure 6. Cane damage score for kiwifruit as a function of minimum temperature. A higher score indicates less cold damage.

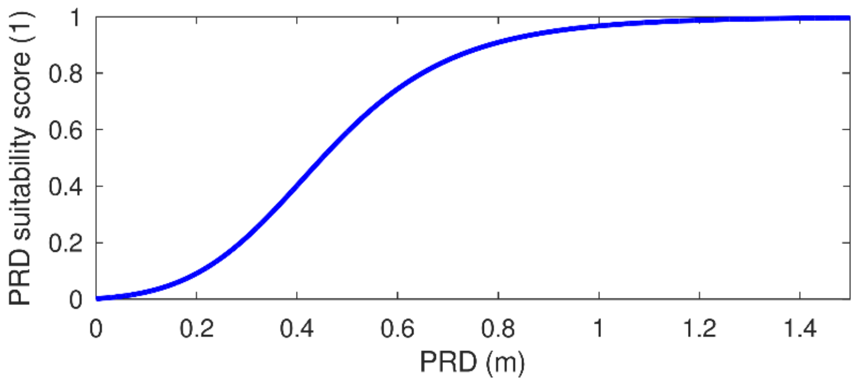

Figure 7. Rooting depth score vs. potential rooting depth (PRD) for both apple and kiwifruit. A higher score indicates a more suitable PRD.

3.2.7. Drainage

Drainage assessments were available for the same locations as PRD, and they are reported as one of the following drainage classes: well, moderate, imperfect, poor and very poor; these reflect factors such as soil structure, depth, permeability, and water-table depth. We assigned numerical suitability scores from 0 to 1 to the drainage classes for each crop, with differences reflecting that kiwifruit is more susceptible to waterlogged conditions than apple. Kiwifruit fares worse in soil that is not "well-drained" (Table 3). A lower score does not rule out an area for a crop, but rather indicates that extra effort and cost would be needed for successful crop production; this could include, for example, improving soil drainage through subsoil ploughing, installation of surface or subsurface drainage systems, mounding or long-term improvements of soil health through application of soil amendments, and minimising soil compaction through reducing traffic in orchards.

Table 3. Drainage scores assigned to drainage class descriptors for different crops.

	Well	Moderate	Imperfect	Poor	Very Poor
Apple	1	1	0.6	0.3	0
Kiwifruit	1	0.9	0.4	0.1	0

3.2.8. Slope

Slopes greater than 30° are not suitable for machinery, and pose an erosion risk for well-managed horticultural crops [25]. Slopes are currently less of a problem for growing apple than kiwifruit, since traditionally only the latter requires construction of support structures. Our suitability curves to reflect this took the value 0.5 at slopes of 19° for apple and 12° for kiwifruit, with high values for slopes $\leq 8.5°$, and a rapid descent to zero as the slope increases past the mid-point slope values (Figure 8); these responses are captured in Equation (2) with $a = 0.5$ and respective settings of $b = 19°$ and $b = 12°$ for apple and kiwifruit.

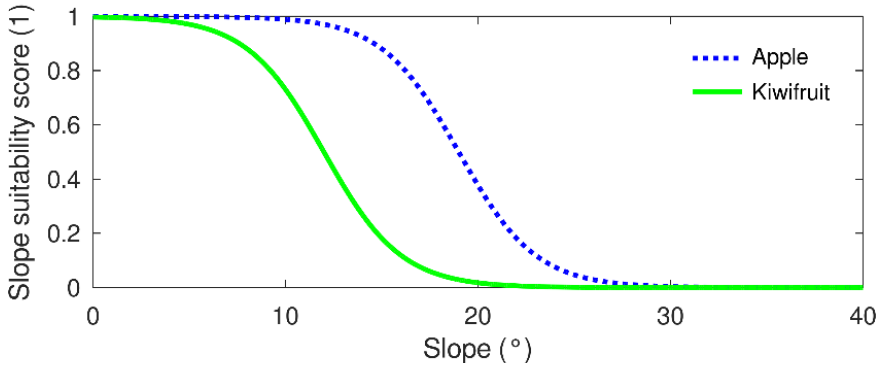

Figure 8. Slope-suitability score assigned to slope for apple and kiwifruit, with higher scores being assigned to flatter slopes.

3.2.9. Land-Use Capability Class

Land use capability (LUC) class descriptors [26] are divided into eight main categories (numbered 1 to 8), with 1 indicating land considered to have virtually no limitations for use and 8 indicating land considered to have very severe limitations or hazards that make it unsuitable for cropping, pasture or forestry.

Over 10% of apple orchards whose locations were known to us were on land identified with the LUC classes 4 to 6, which typically are not considered suitable for horticulture. Thus these classes were generally given moderate to moderately low scores rather than very low scores. For both crops, LUC classes 1 to 8 were assigned the respective score values of 1, 0.95, 0.9, 0.8, 0.65, 0.5, 0.05 and 0, based on consultation with crop experts.

3.3. Suitability Scores for Combined Criteria

3.3.1. Combining Climate-Related Suitability Criteria

We chose weights for each criteria based on feedback during consultation with industry experts. For kiwifruit, we chose weights of 1.0 for chill, GDD and frost suitability, and an increased weight of 2.0 for cold-damage because damage to canes could have long-term consequences for vine health. For apple, we chose weights of 1.0 for chill, GDD and fruit-size suitability, 2.0 for frost suitability which is considered the main crop-loss risk, and 0.5 for sunburn suitability which is considered to be of minor importance.

For each climate criterion, yearly suitability values were calculated for each year of a given period, and the arithmetic average then taken to obtain an average suitability score for that period. Climate-suitability scores to reflect combined criteria were obtained, first on a yearly basis by weighted geometric means of criteria suitability scores for each year, and then the yearly climate suitability scores were averaged using arithmetic means to get a climate suitability score for the period.

3.3.2. Combing Soil/Land-Related Suitability Criteria

For both apple and kiwifruit, suitability for PRD and LUC were given weights of 1.0, and a weight of 2.0 was used for drainage, indicating its importance for good plant health and survival. Slope suitability was considered of more importance for kiwifruit than apple and given respective weights of 1.0 and 0.5.

3.3.3. Location Suitability Scores

The location suitability score for a period was computed as the weighted geometric mean of the land suitability score and the climate score for that period. The weight for the land suitability score was the sum of weights for the individual land criteria, and the weight for the climate suitability score was sum of weights for the individual climate criteria

3.4. Ground-Truthing of Suitability Models

We constructed suitability maps for individual criteria for overall location suitability for a contemporary period from 2006 to 2016. We calibrated the suitability models using expert opinion on where crops could likely be grown and not be grown, in an iterative process to ensure that the maps accurately reflected suitability of locations for the individual and combined criteria; this process involved adjustment of function parameters, and occasionally the functions themselves.

The ground-truthed suitability map for apple in Figure 9 is consistent with New Zealand apple production occurring mainly in the Hawke's Bay, Nelson and the Central Otago regions of New Zealand, with minor production occurring in other areas found suitable around the North Island and in Canterbury. The ground-truthed suitability map for kiwifruit in Figure 10 reflects the current kiwifruit footprint, which has its heartland in the Bay of Plenty, with strong production in Northland, Gisborne, the Hawke's Bay and Nelson. Additionally, Taranaki is indicated as having high suitability for kiwifruit, and some areas of North Canterbury are predicted to have moderately high suitability.

3.5. Econometric Modelling

3.5.1. Assigning Baseline Land Use

A key step was developing a baseline land use that represented the current spatial footprints of apple and kiwifruit, and this relied on industry-supplied maps; however, the industry maps reported property boundaries rather than true block boundaries, and thus over-estimated the land area under kiwifruit and apple cultivation; this also resulted in some blocks being simultaneously classified as apple and kiwifruit when the corresponding properties were growing both crops. Compared with data reported by Stats NZ for 2019 (http://infoshare.stats.govt.nz/Default.aspx accessed on 18 March 2021), the industry-supplied maps overestimated kiwifruit area by more than a factor of two, and apple area by about a third.

This anomaly was resolved by taking the intersection of each block map with a layer identifying horticulture land use from the LURNZ basemap; this allowed a more accurate identification of areas under apple and kiwifruit land use. When doing this, we assigned apple land use to only those cells in horticulture that were uniquely identified as apple blocks, excluding blocks identified simultaneously as apple and kiwifruit. Kiwifruit land use was assigned to all cells identified as kiwifruit blocks. The resulting land-use areas for both sectors are highly consistent with Stats NZ figures. The regional distribution of land use in the updated LURNZ basemap is displayed in Table 4.

Table 4. Land use (ha) by region and outside regional council (RC) boundaries.

Region	Kiwifruit	Apple	Horticulture	Dairy	Sheep-Beef	Forestry	Scrub
Auckland	375	75	11,050	45,175	148,450	52,300	51,000
Bay of Plenty	11,625	0	18,075	100,575	113,475	275,400	54,525
Canterbury	0	50	252,200	275,375	1,718,475	130,075	297,675
Gisborne	600	150	15,825	650	329,150	171,950	130,900
Hawkes Bay	350	5900	28,550	29,275	624,850	156,850	127,625
Manawatu-Wanganui	100	0	17,500	165,425	1,012,900	148,925	182,025
Marlborough	0	0	32,950	9900	236,175	77,075	113,200
Nelson	0	0	25	450	2725	11,475	7300
Northland	1000	0	8150	167,925	357,500	182,825	119,450
Otago	0	725	20,625	120,125	1,720,600	143,375	176,700
Southland	0	0	7125	207,925	729,300	92,275	55,125
Taranaki	0	0	1650	215,275	147,550	28,775	58,250
Tasman	700	2250	6150	30,600	65,875	101,925	47,475
Waikato	825	150	18,300	602,850	592,975	308,200	133,925
Wellington	0	100	8225	35,950	302,050	76,450	127,450
West Coast	0	0	0	87,475	35,750	40,650	47,575
Outside RC boundaries	25	25	1050	3250	15,025	3550	12,800
Total	15,600	9425	447,450	2,098,200	8,152,825	2,002,075	1,743,000

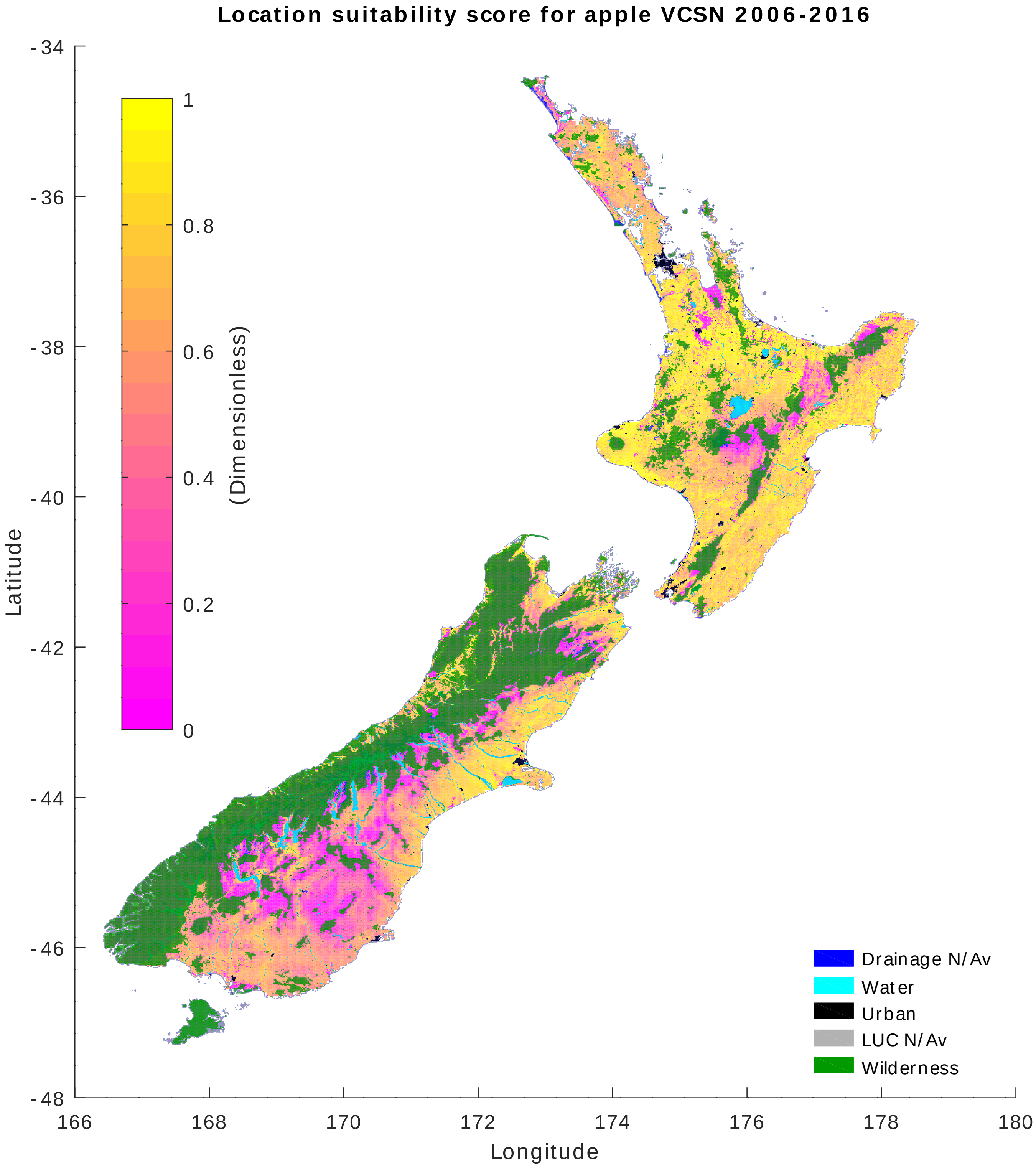

Figure 9. Location suitability scores for apple across New Zealand. N/av indicates data were not available. LUC is Land Use Capability classification. Wilderness areas encompass national parks, reserves, conservation areas and marginal strips.

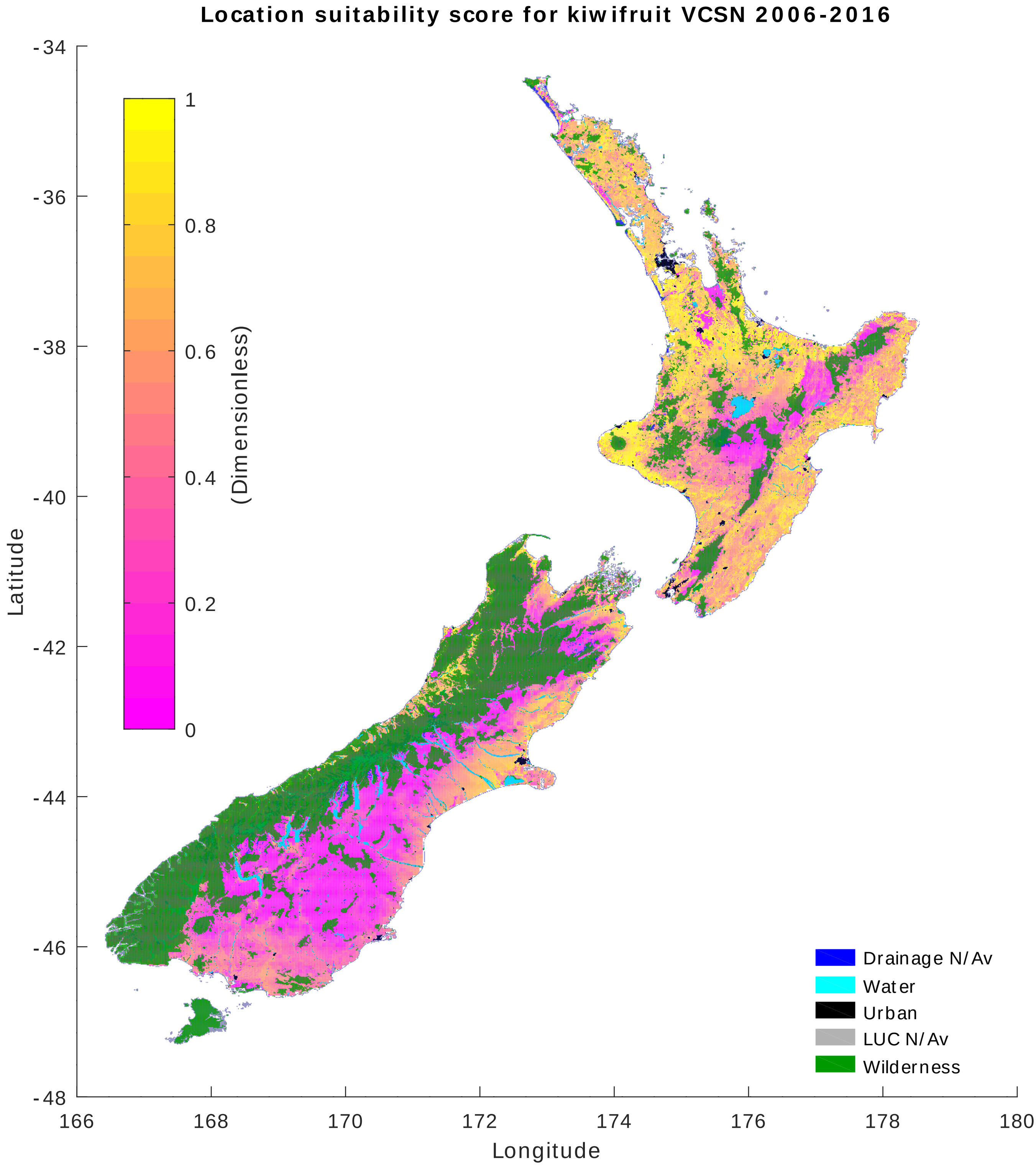

Figure 10. Location suitability scores for kiwifruit across New Zealand. N/av indicates data were not available. LUC is Land Use Capability classification. Wilderness areas encompass national parks, reserves, conservation areas and marginal strips.

3.5.2. Suitability Maps for Estimating an Econometric Model

The future projections that we report in Vetharaniam, Timar, Stanley, Müller, van den Dijssel and Clothier [17] used climate model projections based on datasets described by the New Zealand Ministry for the Environment [59]; these datasets had a hindcast period from

1972 to 2005, which serves as a reference for gauging future change. Thus suitability maps for the 1972–2005 period were developed from the calibrated suitability models [17], and used here for estimating relationships in an econometric model.

3.5.3. Land Use versus Location Suitability

For econometric projection of climate change effects on land use, the baseline land use is modelled as a function of suitability maps for the 1972–2005 period (and other variables). Thus, as a consistency check, the smoothed frequency distribution of the 1972–2005 kiwifruit and apple suitability scores by baseline land use were plotted in Figures 11 and 12, respectively. The mean score is also shown and labelled within each panel. The majority of kiwifruit land had high suitability scores for kiwifruit, and on average, kiwifruit suitability was highest on land currently used to grow kiwifruit compared with other land uses. Apple suitability was also highest on land currently used to grow apple compared with other land uses. The frequency distribution for apple was bi-modal, with one peak corresponding to very high suitability scores and another peak to moderate suitability scores. Dairy, forestry and (other) horticultural land also had relatively high average suitability for apple.

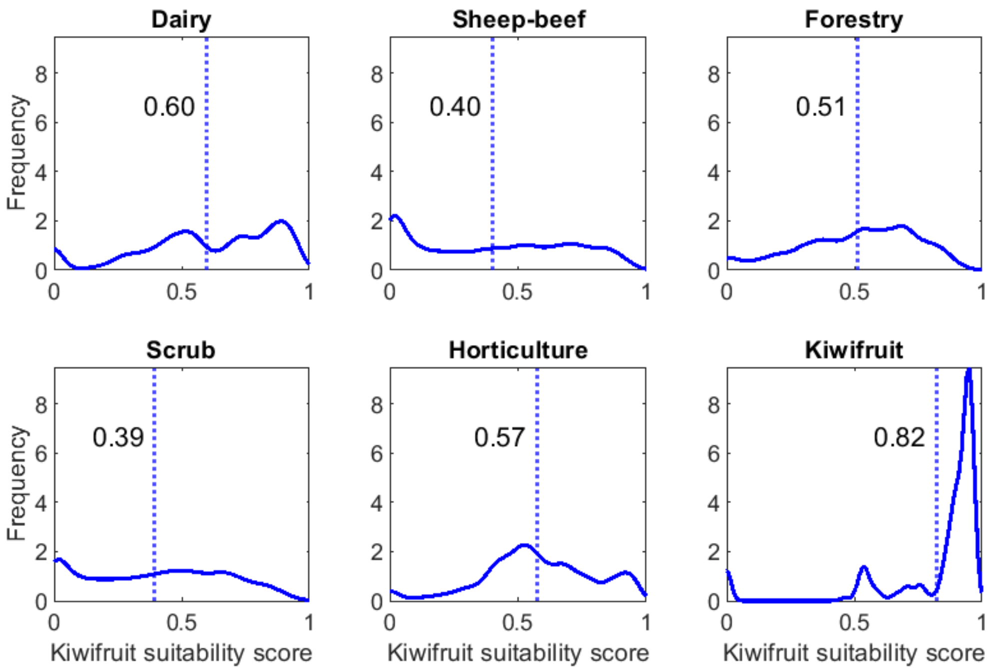

Figure 11. The frequency distribution (solid line) and mean (dotted line with value indicated) of kiwifruit suitability scores (using 1972–2005 climate model data) for different observed land uses. Horticulture indicates all horticultural industries other than kiwifruit and apple.

There was little difference between the climate-model-derived baseline maps and suitability maps derived from VCSN data for the same period because we performed aligning corrections to the climate model data [17].

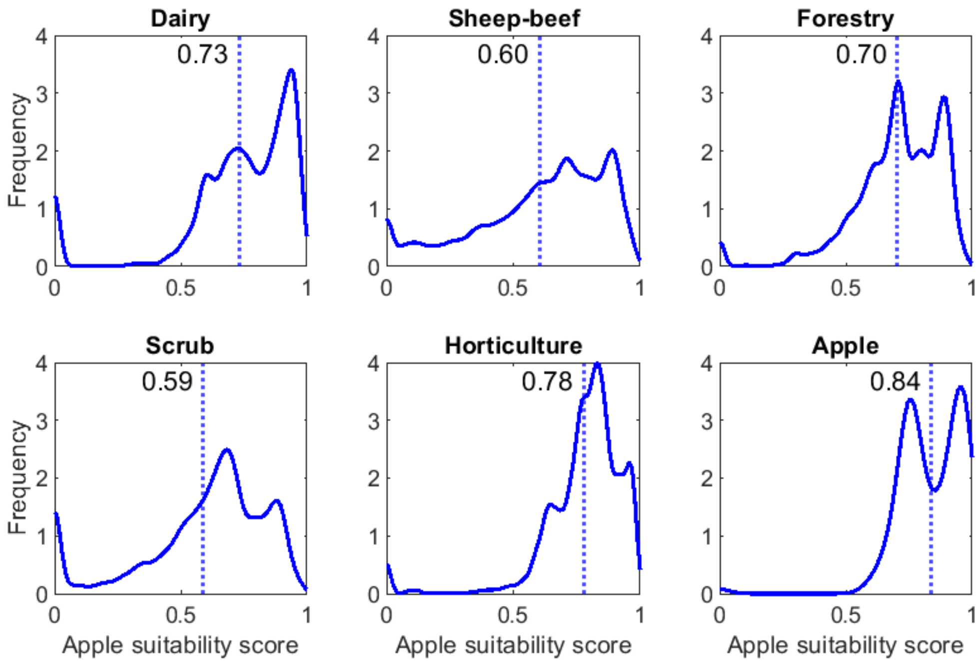

Figure 12. The frequency distribution (solid line) and mean (dotted line with value indicated) of apple suitability scores (using 1972–2005 climate model data) for different observed land uses. Horticulture indicates all horticultural industries other than kiwifruit and apple.

3.5.4. Estimation

The econometric model is a multinomial logit land-use choice model, similar to models that have previously been described [40,60,61]. The utility of land use choice j at grid cell i (U_{ij}) is specified as a linear combination of k independent variables (X_{ki}) associated with the grid cell, and parameters to be estimated (β_{0j}, β_{kj}) that vary over the land use alternatives:

$$U_{ij} = \beta_{0j} + \sum_{k} \beta_{kj} X_{ki} + \varepsilon_{ij} = V_{ij} + \varepsilon_{ij} \tag{6}$$

The distribution of the error term, ε_{ij}, is assumed to be type I extreme value, and represents all factors that matter in the land-use decision but are not captured by V_{ij}.

A decision maker is assumed to maximise utility by choosing land use from a choice set of seven alternatives: kiwifruit, apple, other horticulture, dairy farming, sheep and beef farming, plantation forestry, and scrub (or unproductive). The independent variables X_{ki} include factors characterising land quality (slope and LUC class), accessibility to markets (distances to nearest port and to nearest town) and land tenure (general land or Māori freehold). In addition, for kiwifruit and apple, we included their respective suitability scores as predictors. Although slope and LUC are used in the calculation of apple and kiwifruit suitability scores, they are included as independent predictors in the econometric model because of their importance in influencing the different land-use choices considered. The estimation was performed by maximum likelihood methods in Stata 16 (StataCorp LLC) on 555,224 observations, each corresponding to a 25-hectare grid cell.

Table 5 contains parameter estimates and standard errors from the multinomial logit. A negative parameter estimate in the table indicates that an increase in the value of the variable decreases the log odds (ratio of probabilities) of the given land use versus scrub. Holding all other variables in the model constant, a one degree increase in slope would, for instance, be expected to decrease the multinomial log-odds for apple relative to scrub by 0.471. Our discussion below focuses on the estimates for apple and kiwifruit. Other results are similar to those presented in Timar [40].

Table 5. Multinomial logit estimation results. Standard errors are shown in parentheses. Asterisks indicate statistical significance at the 1% (**) and at the 5% (*) level.

Variable	Kiwifruit	Apple	Other Horticulture	Dairy	Sheep-Beef	Forestry
LUC class	−0.736 **	−1.179 **	−0.923 **	−0.563 **	−0.409 **	−0.029 **
	(0.035)	(0.060)	(0.010)	(0.006)	(0.005)	(0.006)
Slope	−0.134 **	−0.471 **	−0.407 **	−0.202 **	−0.055 **	−0.065 **
	(0.016)	(0.057)	(0.006)	(0.001)	(0.001)	(0.001)
Distance to nearest port	−0.216 **	−0.378 **	−0.100 **	−0.024 **	0.012 **	−0.049 **
	(0.011)	(0.019)	(0.002)	(0.001)	(0.001)	(0.001)
Distance to nearest town	−0.851 **	−1.412 **	−0.279 **	−0.231 **	0.017 **	0.013 **
	(0.058)	(0.110)	(0.008)	(0.003)	(0.001)	(0.002)
Maori freehold	−1.323 **	−1.798 **	−1.435 **	−1.623 **	−1.621 **	−0.713 **
	(0.195)	(0.388)	(0.056)	(0.028)	(0.016)	(0.018)
Kiwifruit score	5.285 **	-	-	-	-	-
	(0.271)					
Apple score	-	2.226 **	-	-	-	-
		(0.380)				
Constant	0.006	4.346 **	6.335 **	5.759 **	4.541 **	1.893 **
	(0.275)	(0.382)	(0.040)	(0.030)	(0.028)	(0.032)

LUC = land use class.

Results in Table 5 indicate that the included variables matter for kiwifruit and apple land uses. Lower land quality (as reflected in higher LUC class and higher slope), higher cost of market access (increased distance to ports and towns) and Māori freehold tenure are all associated with a decreasing relative probability of both kiwifruit and apple land use. As expected, higher kiwifruit suitability increases the probability of kiwifruit land use, and higher apple suitability increases the probability of apple land use. We note that LUC class and slope also contribute to location suitability for kiwifruit and apple, so the estimates for kiwifruit score and apple score could capture some of the effect of these variables on land-use decisions.

The model predicts choice probabilities for each land use type j at each grid cell i, given the characteristics associated with the cell. Choice probabilities can be derived by the formula:

$$\text{Prob}_{ij} = \frac{\exp(V_{ij})}{\sum_k \exp(V_{ik})} \tag{7}$$

3.5.5. Projected Land-Use Change

The predicted choice probabilities from the multinomial logit model can be aggregated into predicted land-use areas. At observed values of all explanatory variables, the model's aggregate predictions exactly match observed land-use areas in the estimation sample. By substituting future values of suitability into the equation, one can use the estimation results to project future land-use change for kiwifruit and apple under a given climate-change pathway (assuming no change in other variables).

4. Discussion and Conclusions

Crop growth is a biological process and the relationships between crop development and temperature, or in fact any other environmental parameter, are subject to natural variation. The uncertainty associated with this is magnified by differences between cultivars, and by spatial variation not captured in databases. The sliding-scale approach provides the flexibility to account for such uncertainties.

The model outputs not only highlight regions with optimal growing conditions for a certain crop, but also delineate and rank other regions with lesser suitability. The scores for the individual suitability criteria can then help to identify which measures, or management practices, would be required for viable crop production in regions with lesser suitability.

By combining suitability criteria scores on a yearly basis, we obtain a better reflection of the production loss that could be incurred over a period, rather than by combining the average criteria scores for the period. The latter approach will not distinguish between two criteria having poor suitability in the same years or different years. For example, if a location incurred heavy production losses due to severe frost in two out of ten years, and heavy production losses due to poor winter chill in two out of ten years, the frequency of poor production years could range from two to four out of ten, depending on whether losses from the two criteria occurred in the same years or not.

Through consultation with industry and experts we found that opinions on the relative importance of individual suitability criteria were quite diverse. In our modelling, we represented a "consensus" view of importance by taking a weighted combination of the individual climate-related and land-related suitability criteria to form a final suitability score, with criteria believed to be more important having a larger weight. The criteria weights can readily be changed to accommodate different views and changes in growing systems and cultivars.

The fact that the majority of land identified as kiwifruit blocks or apple blocks during the LURNZ baselining had high suitability scores for kiwifruit and apple indicates consistency between the baselining methodology and the suitability models; it also indicates that the majority of kiwifruit and apple orchards were established with appropriate site selection, although some orchard locations have low suitability which suggests they may be on poorly selected sites; however, it may be that these orchards are located in favourable microclimates of an otherwise unfavourable grid cell (a spatial resolution issue), that they have mitigation strategies to reduce the negative effects (e.g., low chill cultivars, frost protection) or that they are willing to have reduced returns or losses in some years. Our finding that land used for dairy, horticulture other than kiwifruit and apple, dry stock, or forestry (or in scrub) tended to have low suitability for kiwifruit cultivation indicates limited potential for a conversion of these land uses to kiwifruit under current environmental conditions; however, these same land uses included significant areas of land with high suitability for apple and thus have potential for conversion to apple orchards if financial returns were considered to be rewarding.

The extension of the logit model to include the apple and kiwifruit industries together with the inclusion of the location suitability scores provides the capacity for a phenology-driven model of land use for apple and kiwifruit. Continuous suitability scores provide more nuance in the econometric model than discrete suitability categories could, and allow the impact of small differences in suitability to be modelled when performing econometric investigations of land-use decisions; this has particular relevance to climate change, and the modelling capability that we have developed in this paper is used in our companion paper [17] to project the spatial footprints of apple and kiwifruit under different climate change pathways, to enable policy planning.

The concept of location suitability for crops relates to crop biology and its biophysical interaction with soil, terrain and climate. While issues such as social acceptability or biodiversity considerations are important, they do not affect location suitability. Thus they were not included in our suitability models. Furthermore, these issues are concerned with social benefits and costs and therefore they tend to be outside the scope of private actors making land-use decisions [62]; however, we note that, to the extent that such social benefits and costs do affect private land-use decisions, our land-use modelling will actually reflect these because it employs an econometric model estimated on observed land use outcomes (as opposed to an optimisation model). For instance, if kiwifruit were to have low social acceptability due to biodiversity (or other) issues and this low acceptability systematically affected land-use decisions, then the data we used to parameterise our model would reflect this. Hence, our simulations of future land use would also reflect the effect, but, of course, would be unable to account for any changes in social acceptability over time.

Climate change can result in an altered frequency and/or severity of extreme climatic events such as storms, floods and hail that have adverse effects on crops. We currently do not have a means to project extreme climatic events with the RCP weather data for NZ, and this is a limitation of a study which identifies potentially valuable future research.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data on soil and land properties are available from the URLs in the data section. To protect IP and privacy rights, we cannot share the VCSN datasets, orchard locations or other confidential industry data. Code for equations presented will be made available on request.

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