Article

Effects of Climate Change on Climate Suitability of Green Orange Planting in Hainan Island, China

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Abstract: Hainan Island is endowed with unique climatic and geographical conditions in China. Green orange is a characteristic fruit and plays an important role in local agricultural production of the island. However, few studies have been available regarding the climatic suitability index of green orange planting suitable regions in the island. Based on 30 years (1980 to 2019) of climatic data from 19 meteorological stations in the island, this study established spatial analysis models with topographical data, land use and GIS spatial analysis. Based on climate suitability function, this study established the climate suitability models of temperature, sunshine, precipitation, accumulated temperature and comprehensive suitability model for green orange planting. The Climate suitability index model for green orange planting suitable zoning areas was developed using a natural point segmentation method, and future climate change scenarios were adopted for evaluating the trends of climate suitable areas. The results revealed that the most suitable areas for planting green orange are mainly located at the eastern central region in the island. The climate suitability index ranged from 0.9 to 1.0 in the most suitable regions. The suitable area is mainly distributed in the eastern part, most of the central and western parts of the island, with the climate suitability index ranging from 0.7–0.9. However, the population density in the area is large, and the planting land is limited. The sub-suitable area is mainly located in the coastal areas of the western island, and the high-altitude areas in the central and western regions of the island, with the climate suitability index varying from 0.4 to 0.7. The unsuitable area is mainly distributed in the central mountainous area, with the climate suitability index being 0.0–0.4. The suitability of temperature showed decreasing trend, and the suitability of precipitation gradually moved from the east to the central region under future climate change scenarios. This study is helpful in promoting the development and utilization of agricultural resources and the fine zoning of green orange planting climate suitability in the island.

Keywords: Hainan Island; green orange; climate suitability; GIS; climate change

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1. Introduction

Green orange is one of the well-known typical fruits in Hainan Island, formerly known as Hongjiang Orange. After introduced into Hainan in the 1980s from Lianjiang in Guangdong province, green orange showed stronger adaptability than the original place, with early fruiting, better quality and yield [1]. Green orange has been certified as a pollution-free agricultural product and green food by the Ministry of Agriculture, and

is a high-quality brand-name product in Hainan [2]. The planting area of green orange accounts for 36.4% of the total planting areas of citrus, orange and grapefruit in the Island.

Climate warming is one of the main features of climate change. According to the sixth Assessment Report of IPCC, the global average surface temperature has risen by about 1 °C since 1850, and the temperature rise is expected to reach or exceed 1.5 °C in the next 20 years [3]. Climate is an important factor affecting crop growth, yield and quality. Therefore, crop climate suitability and its changing trend in the context of climate change are receiving increasing attention [4]. Previous studies on crop climate suitability have been carried out by using fuzzy mathematics, analytic hierarchy process, weighted index method, cluster analysis method, spatial analysis method, etc. [5,6].

Previous studies revealed the production, climate suitability for planting citrus, orange and pomelo fruit trees [7–10]. Some researchers drew the national citrus climate zoning map by using air temperature, accumulated temperature ≥ 10 °C, extreme minimum temperature and other temperature indicators [8]. Others studied the climate regionalization of ponkan by using fuzzy clustering method, and divided ponkan into four suitable planting areas [9], and the climate regionalization of sweet orange planting in Daying County, Sichuan Province [10]. Some scientists also considered meteorological disaster factors in the study of climate suitability of citrus production [11–14]. For example, the photothermal conditions were required for late ripening citrus in Sichuan Province, and the Delphi method was applied to superimpose winter and spring meteorological disaster factors on the basis of the original regionalization indexes to solve the problem of low winter and spring yield in late ripening citrus [12]. Previous studies on the climate suitability of major citrus production areas in China have been carried out according to the climatic requirements of citrus growth. However, few studies have been available on climate suitability of green orange planting in Hainan Island [15]. The time series of meteorological data used in previous studies was short and early, and the spatial accuracy of the data was low compared with the requirement of spatial difference of green orange planting, which is difficult to meet the requirements of fine zoning of green orange planting. In addition, with climate changing and the improvement of cultivation technology, the traditional climate suitability zoning has been unable to meet the requirements of high quality and stable yield of green orange. Hainan Island is located in the southernmost part of China, which has unique climatic and geographical conditions. Therefore, it is necessary to perform fine regionalization of planting green orange climate suitability, with an appropriate climate suitability index model and evaluation method.

This paper adopted the daily climatic data of 19 main meteorological stations in Hainan Island from 1980 to 2019, combined with multi-point data and topographic factors of the entire island, and constructed climate suitability index model using the mathematical regression statistical method combined with spatial analysis. The regionalization indexes were determined according to the climatic factors of green orange planting in the Island. On the basis of climate suitability function, the models of temperature, sunshine, precipitation, accumulated temperature and comprehensive suitability of green orange were established. Based on GIS technology and natural point segmentation method, the purposes of this study were to evaluate the climate suitability of green orange planting in complex terrain, and to provide production reference for optimizing spatial layout of green orange planting in Hainan Island.

2. Data and Methods

2.1. Overview of the Study Area

Hainan Island is the second largest island in China, with 33,900 square kilometers of land area and 18 counties and cities [16]. The Island is located in the zone of tropical monsoon climate, with an annual average temperature of 23.2–27.1 °C, annual total precipitation of 1009–2367.7 mm, and annual sunshine duration of 1776–2783 h. The spatial distribution of meteorological observation stations in Hainan Island is shown in Figure 1.

Figure 1. Meteorological stations spatial distribution map of Hainan Island.

2.2. Data Source

- (1) Daily meteorological data of 19 meteorological stations on the main island of Hainan Island from 1980 to 2019, were obtained from the National Meteorological Data Network, including daily mean temperature, daily maximum temperature, daily minimum temperature, average precipitation and sunshine.
- (2) DEM digital elevation model data in Hainan Island, including slope, aspect and elevation data were obtained by DEM data (30 m $\times$ 30 m, National Basic Geographic Information Center).
- (3) 1:250,000 vector layer of administrative division in Hainan Island, including boundary of Hainan Island, boundary of 18 cities and counties, etc. were provided by the Resource and Environmental Science and Data Center.
- (4) Future scenario meteorological data in Hainan Island, namely simulation data of CMIP5 model under RCP4.5 and RCP8.5 emission climate scenario, including temperature data and precipitation data from 2020 to 2049 were downloaded from the website of the CEDA (<http://data.ceda.ac.uk/>, accessed date: 3 November 2021).
- (5) Data on the planting and production of Citrus, Orange, pomelo and green Orange agricultural Products in Hainan Island were obtained from the Hainan Statistical Yearbook, 2020.

2.3. Methodology

2.3.1. Distribution of Climatic Resources in the Study Area

The green orange growing areas in Hainan Island are mainly distributed in the central and northeastern regions (Table 1). The average annual temperature in the growing areas is 24.2 °C, the average annual extreme minimum temperature is 7.8 °C, the average annual accumulated temperature ≥ 10 °C is 8851.1 °C, the average temperature in January is 18.1 °C, and the average temperature in July is 28.3 °C. The average annual precipitation is 2023.5 mm, relative humidity 85.3%, dryness 0.75. The precipitation is not evenly distributed in each season. The average annual precipitation is 90 mm in winter, 321 mm in spring, 721 mm in summer and 676.8 mm in autumn. The average annual total sunshine duration is 1964.8 h.

Table 1. Characteristics of meteorological elements in main cities and counties of green orange planting.

Station	Annual Mean Temperature (°C)	Annual Accumulation Temperature (°C)	January Mean Temperature (°C)	July Mean Temperature (°C)	Annual Precipitation (mm)	Sunshine Hours (h)	Altitude (m)	Dryness	Wind Speed (ms ^{−1})
Haikou	24.5	8939.3	18.0	28.8	1748.4	1959.5	63.5	0.82	2.60
Lingao	24.1	8800.7	17.6	28.6	1516.7	2038.8	31.7	0.93	2.33
Chengmai	24.2	8822.1	17.8	28.5	1882.0	1782.4	31.4	0.75	1.52
Danzhou	24.0	8749.3	17.8	28.0	1917.9	1970.5	169.0	0.73	1.96
Changjiang	25.1	9151.6	19.4	28.8	1729.9	2237.7	98.1	0.85	2.11
Baisha	23.5	8589.4	17.6	27.4	1949.1	2090.2	215.6	0.71	1.19
Qiongzong	23.2	8481.4	17.4	27.1	2367.8	1918.8	250.9	0.57	1.15
Dingan	24.4	8924.7	18.2	28.7	1992.1	1810.1	53.3	0.72	1.77
Tuanchang	24.1	8816.0	18.1	28.2	2126.7	1916.6	118.3	0.66	1.63
Wenchang	24.5	8934.8	18.5	28.5	1959.2	1909.5	21.7	0.73	1.90
Qiongshan	24.7	8979.2	18.0	28.9	1789.4	1986.7	9.9	0.80	2.62
Dongfang	25.4	9264.3	19.3	29.5	1009.0	2553.8	7.6	1.47	4.18
Qionghai	24.7	9025.7	18.8	28.6	2103.9	1956.9	24.0	0.69	2.16
Ledong	24.7	9026.2	20.0	27.6	1610.2	2005.0	155.0	0.90	1.38
Wuzhishan	23.2	8495.0	18.5	26.3	1865.0	1957.9	328.5	0.73	1.68
Baotin	24.9	9082.4	20.3	27.7	2139.6	1776.1	68.6	0.68	1.15
Sanya	25.3	9223.6	20.9	27.9	1494.5	2300.8	419.4	0.99	2.90
Wanning	25.0	9123.7	19.5	28.6	2164.2	2024.9	39.9	0.68	2.21
Lingshui	25.0	9250.2	19.5	28.6	1756.9	2231.6	35.2	0.84	2.17

2.3.2. Establishment of Spatial Analysis Model of Meteorological Data

Based on the daily meteorological data of temperature, precipitation, sunshine and relative humidity from 19 meteorological stations in the last 40 years (1980–2019), and the simulated meteorological and precipitation data of CMIP5 model in the next 30 years (2020–2049) under RCP4.5 emission climate scenario, a mathematical statistical method was used to construct a spatial analysis model. As climate is related to factors such as longitude and latitude, altitude and slope aspect, the multiple regression relationship model between regionalization indexes and geographical factors can be expressed as the following equation [17,18]:

$$Y = f(\phi, \lambda, h, \beta, \theta) + e \quad (1)$$

In the formula, Y is the climatic regionalization index factor; $\phi, \lambda, h, \beta, \theta$ are geographical factors such as latitude, longitude, altitude, slope aspect and slope, respectively; e is the residual term, which is called geographical residual.

2.3.3. Establishment of Climate Suitability Model

Based on previous studies and through analyzing the climate conditions required for the growth and development of green orange in Hainan Island, the main indexes affecting the growth and development of green orange were screened, including four meteorological factors including annual mean temperature, annual sunshine duration, annual precipitation and annual accumulated temperature ≥ 10 °C [1,15,19]. In order to quantitatively analyze the influence of climate conditions on the planting suitability of green orange, the green orange suitability models of temperature, sunshine duration, precipitation and accumulated temperature ≥ 10 °C were established, based on relevant literature and research.

Temperature Suitability Model

Temperature is a decisive factor affecting the growth, development and yield of green orange [15]. Through agricultural climate analysis, previous researcher proposed that the most suitable annual average temperature for the growth of green orange is 22–24 °C, and the effective temperature of physiological activity is 12.8–37 °C [1]. The nonlinear beta

function that matches the three base point temperature of crops is mostly used in crop temperature suitability models [20]. Temperature suitability model is listed as below [21,22]:

$$S_T = \frac{(t - t_l)(t_h - t)^B}{(t_0 - t_l)(t_h - t_0)^B} \quad (2)$$

$$B = \frac{t_h - t_0}{t_0 - t_l} \quad (3)$$

In Equation (2), S_T is crop temperature suitability, t is actual temperature ($^{\circ}\text{C}$), t_0 , t_l and t_h are the optimum, lower limit and upper limit temperature for crop growth, respectively ($^{\circ}\text{C}$).

Sunshine Suitability Model

Sunshine affects fruit quality, color and quality, and sufficient sunshine can increase fruit quality and make fruits full and well-colored [23]. Too low or too high sunshine duration led to fruit dysplasia, especially in hot summer [24]. When the sunshine duration reaches 55% of the illuminable duration, crop response to light reaches the most appropriate state [25]. Sunshine suitability function model is as follows [20,21]:

$$S_S = \begin{cases} e^{-(S_0-S)/b} & S < S_0 \\ e^{-(S-S_0)/b} & S \geq S_0 \end{cases} \quad (4)$$

In Equation (4), S_S is crop sunshine suitability, S is actual sunshine duration (h), S_0 is available sunshine duration (h) in a specific area at a specific time, and b is a constant [26], the formula for S_0 is shown below:

$$\sin \frac{a}{2} = \sqrt{\frac{\sin\left(45^{\circ} - \frac{\Phi - \delta - \gamma}{2}\right) \sin\left(45^{\circ} + \frac{\Phi - \delta - \gamma}{2}\right)}{\cos \Phi \times \cos \delta}}$$

$$S_0 = \frac{2a}{15} \times 55\% \quad (5)$$

In Equation (5), Φ is geographic latitude, δ is declination, γ is gas coverage difference and a is time Angle.

Precipitation Suitability Model

Water affects the quality indexes of green orange fruit such as size, texture and flavor [27]. The optimal annual precipitation for green orange planting is 2000–2200 mm [19]. Crop precipitation suitability model is as follows [26,28,29]:

$$S_p = S_r + S_d/2 \quad (6)$$

In Equation (6), S_p is the suitability degree of crop precipitation, S_r is the suitability degree of the annual precipitation, S_d is the suitability degree of average precipitation days of the year.

$$S_r = \begin{cases} R/R_0 & R < R_0 \\ R_0/R & R_0 \leq R \end{cases} \quad (7)$$

In Equation (7), R is the actual precipitation (mm) and R_0 is the optimal precipitation for crop growth (mm).

$$S_d = \begin{cases} d/d_l & d \leq d_l \\ 1 & d_l < d < d_h \\ d_h/d & d_h \leq d \end{cases} \quad (8)$$

In Equation (8), d is the average precipitation days of the year (day), d_l and d_h are the lower limit and upper limit of suitable average precipitation days of the year for crop growth, respectively (day).

Accumulated Temperature Suitability Model

Heat is the main limiting factor affecting the growth of green orange. The annual accumulated temperature $\geq 10^\circ\text{C}$ reflects the influence of temperature on the growth of green orange, and the most suitable annual accumulated temperature $\geq 10^\circ\text{C}$ is $>8100^\circ\text{C}$ [1,12]. The model of crop accumulated temperature suitability is as follows:

$$S_D = \begin{cases} 1 & D > D_0 \\ D/D_0 & D < D_0 \end{cases} \quad (9)$$

In Equation (9), S_D is crop accumulated temperature suitability, D is annual accumulated temperature of actual temperature $\geq 10^\circ\text{C}$ ($^\circ\text{C}$) and D_0 is annual accumulated temperature of crop growth suitability $\geq 10^\circ\text{C}$ ($^\circ\text{C}$).

Comprehensive Suitability Model

Comprehensive climate suitability model was established by using equal weight summation method, geometric average method and unequal weight summation method, respectively [29,30], and calculate their mean values to obtain the comprehensive climate suitability of green orange in Hainan Island:

$$\text{Equal weight summation: } S = (S_T + S_S + S_p + S_D) / 4 \quad (10)$$

$$\text{Geometric method: } S = \sqrt[4]{S_T + S_S + S_p + S_D} \quad (11)$$

$$\text{Unequal weight summation: } S = S_T \times W_T + S_S \times W_S + S_p \times W_p + S_D \times W_D \quad (12)$$

In the above Equation (12), S is the comprehensive suitability of crops; and W_T , W_S , W_p , W_D are the suitability weights of crop's most suitable annual average temperature, annual actual sunshine duration, annual precipitation and annual accumulated temperature $\geq 10^\circ\text{C}$, respectively [22].

Based on the meteorological data and geographical data of 19 meteorological stations in Hainan Island, and the requirements of green orange planting on temperature, sunshine, precipitation and accumulated temperature, the indexes of green orange suitability model were determined (Table 2).

Table 2. Optimum parameters' values of the comprehensive climatic suitability index model of green orange for optimum planting climate suitable zoning areas in Hainan Island.

Temperature ($^\circ\text{C}$)			Sunshine Hours (h)		Precipitation (mm)	Precipitation Days (day)		Temperature Accumulation ($^\circ\text{C}$)
t_0	t_l	t_h	S_0	b	R_0	d_l	d_h	D_0
23	18	28	4.9–5.5	5.1	2100	140	200	8100

3. Results

3.1. Spatial Analysis Model of Past and Future Meteorological Elements in Hainan Island

Regression analysis was performed with seven meteorological elements (i.e., the annual average temperature, annual total sunshine time, total annual precipitation, annual total precipitation days, annual accumulated temperature greater than 10°C , the future annual average temperature and the future annual total rainfall), and five geographic information factors (i.e., the longitude, latitude, altitude, slope direction and slope) to build the spatial analysis index model [31–33].

Table 3 indicated that, all models passed the significance test at 0.01 level. The annual mean temperature is negatively correlated with latitude, longitude, altitude, slope and aspect ($R = 0.760$). The annual total sunshine hours were negatively correlated with latitude, longitude, slope and aspect, but positively correlated with altitude ($R = 0.805$). The annual total precipitation was negatively correlated with latitude and altitude, and with longitude, slope and aspect ($R = 0.806$). The annual total precipitation days were positively correlated with latitude, longitude, altitude, slope and aspect ($R = 0.847$). Annual accumulated

temperature ≥ 10 °C is negatively correlated with latitude, longitude, altitude, slope and aspect ($R = 0.791$). The future annual mean temperature is negatively correlated with longitude, altitude, slope and aspect, and positively correlated with latitude ($R = 0.761$). The total precipitation in the future year is negatively correlated with latitude, altitude and slope direction, and negatively correlated with longitude and slope, ($R = 0.884$).

Table 3. Spatial analysis climatic suitability index model of green orange based on past and present climatic data sub-models and future climatic scenarios in Hainan Island.

Climatic Data Sub-Models	Model Equation	R
Annual mean temperature (°C)	$Y = -6.578\varphi - 3.214\lambda - 0.031h - 1.021\beta - 0.011\theta + 731.56$	0.760 **
Total annual sunshine hours (h)	$Y = -41.265\varphi - 254.591\lambda + 0.132h - 23.206\beta - 0.792\theta + 30,942.62$	0.805 **
Total annual precipitation (mm)	$Y = -147.341\varphi + 465.397\lambda + 0.027h + 47.797\beta + 0.978\theta - 46,680$	0.806 **
Total number of precipitation days per year (day)	$Y = 4.158\varphi + 34.013\lambda + 0.027h + 4.827\beta + 0.050\theta - 3690.948$	0.847 **
Annual ≥ 10 °C accumulated temperature (°C)	$Y = -272.017\varphi - 72.971\lambda - 1.188h - 35.345\beta - 0.326\theta + 22,444.36$	0.791 **
Future annual average temperature T_F (°C)	$Y = 0.085\varphi - 0.261\lambda - 0.002h - 0.217\beta - 0.001\theta + 52.821$	0.761 **
Total future annual precipitation R_F (mm)	$Y = -199.358\varphi + 35.019\lambda - 0.311h + 2.082\beta - 0.184\theta + 1983.950$	0.884 **

Note: ** is $p < 0.01$. φ is latitude coordinate value of kilometer network, λ is longitude coordinate value of kilometer network, h is Altitude (m), β is slope (°), θ is slope direction (°).

3.2. Green Orange Single Factor Climatic Suitability Zoning

3.2.1. Spatial Distribution of Single Factor Climate Suitability of Meteorological Elements

(1) Temperature suitability: The annual average temperature suitability index sub-model in Hainan Island is generally high in four areas and low in the middle. As shown in Figure 2a, the annual average temperature suitability ranges from -1 to 1 . The most suitable region for the growth of green orange is located in the central part of the Island, mainly in Qiongzong, Tunchang and some surrounding areas. The annual average temperature of this region is 22 – 24 °C. The average annual temperature is 24 – 25 °C in Haikou, Chengmai, Danzhou and Anding. The average annual temperature is 21 – 22 °C in Baisha, Changjiang and other areas. The temperature is not suitable for the region, some in the east and north, mainly in the east, Sanya, Ledong and other places, the annual average temperature of this region is higher than 25 °C, the other part in Changjiang, Wuzhishan, Baoting and other places, the annual average temperature is less than 21 °C, not suitable for green orange growth.

(2) Sunshine suitability: The annual sunshine suitability in Hainan Island generally presents a decreasing trend from west to east. As seen from Figure 2b, annual actual sunshine suitability index sub-model results range from 0.63 to 1.00 . The most suitable area for green orange growing sunshine duration is distributed in central and central and eastern regions, mainly in Chengmei, Dangan, Tunchang, Qiongzong and other cities and counties as well as surrounding areas. The annual sunshine duration in this area is 1800 – 2000 h. Some of the areas are located in the northeast, while others spread from the middle to the south and north, including Wenchang, Lingao, Danzhou and other counties. The annual sunshine hours are 1600 – 1800 h or 2000 – 2200 h. A small part of sunshine duration is located along the central river, and most are located in the west, including Dongfang, Ledong and other surrounding areas. The average annual sunshine duration in this area is more than 2200 h, not suitable for green orange growth.

(3) Precipitation suitability: The precipitation suitability in Hainan Island showed high in the east and low in the west. As indicated in Figure 2c, the annual precipitation suitability index sub-model results range from 0.45 to 1.00 . The most suitable area for green orange growth is located in the eastern and central parts of the region, mainly in Haikou, Wenchang, Dangan and other counties and cities, with annual precipitation of 2000 – 2200 mm. In the sub-suitable region, one part is located in the northern and central parts of the region, including Chengmai and Qiongzong, with an annual precipitation of 1800 – 2000 mm, and the other part is located in the scattered region of the central region with an annual precipitation of 2200 – 2400 mm. Some are located in the west and northwest,

mainly Danzhou, Changjiang, Dongfang, Ledong and other counties and their surrounding areas, with annual precipitation less than 1800 mm, and the other are located in the central part of the region, with annual precipitation more than 2400 mm.

Figure 2. The climate suitability of green orange total results of the main climatic sub-models showing the spatial distribution of: (a) annual average temperature suitability index sub-model results, (b) annual actual sunshine suitability index sub-model results, (c) annual precipitation suitability index sub-model results, (d) annual accumulated temperature ≥ 10 °C suitability index sub-model results.

(4) Accumulated temperature suitability: The accumulated temperature suitability in Hainan Island is low in the middle and high in the four sides. Figure 2d showed that, the annual accumulated temperature ≥ 10 °C suitability index sub-model results range from 0.63 to 1.00, and the most suitable annual accumulated temperature for green orange growth is higher than 8100 °C. Except for the central part (Baisha, Changjiang, Wuzhishan and other cities and counties and their surrounding areas), the annual accumulated temperature ≥ 10 °C in other areas is greater than 8100 °C, which meets the growth demand of green orange.

3.2.2. Temporal and Spatial Distribution of Climate Resources in the Study Area

(1) Spatial and temporal distribution of heat resources: The average annual temperature is low in the middle and generally high in the surrounding areas, while the temperature in southwestern areas is the highest in Hainan Island. According to the average annual temperature in the past 40 years from 1980 to 2019 (Figure 3A), the average annual temperature in the central region was lower than 21 °C, while the average annual temperature in the western and northern regions was higher than 25 °C. According to the average annual temperature in the future 30 years (2020–2049) under the scenario of RCP 4.5 (Figure 3B), the area with average annual temperature below 21 °C in the central region is wider than that in the past 40 years, with an area increase of about 23%. In addition, the average annual temperature in most coastal areas around the region is above 25 °C, with an area increase of about 25% compared with that in Figure 3A. In general, compared with the past 40 years, the mean temperature of Hainan Island will increase in different degrees

in the next 30 years, but the opposite trend in the higher altitude areas, and the low temperature areas also have an expanding trend. Since the average annual temperature of green orange is 22–24 °C, the suitable temperature area for planting green orange shows decreasing trend.

Figure 3. (a) Spatial distribution of average temperature from 1980 to 2019, (b) Spatial distribution of average temperature in 2020–2049 under RCP4.5 scenarios (annual average temperature represented by T in the figure.).

(2) Spatial and temporal distribution of precipitation resources: the precipitation intensity is high in the east and low in the west, and gradually increases from the surrounding to the middle in Hainan Island. According to the average annual precipitation in the past 40-year period from 1980 to 2019 (Figure 4A), the average annual precipitation in some parts of central region was >2400 mm, and in western coastal areas was <1800 mm. Based on the average situation in the future 30 years from 2020 to 2049 under the RCP4.5 scenario (Figure 4B), the area with annual total precipitation >2400 mm will expand from part of central region to most of central region compared with the past 40 years, with an area increase of about 14%. The annual precipitation in most parts of eastern region is more than 2200 mm. In general, the average annual precipitation in the next 30 years will increase to varying degrees compared with the past 40 years, and the area with annual precipitation <1800 mm will decrease in Hainan Island. Since the average annual total precipitation for green orange is about 2000–2200 mm, the suitable precipitation for planting green orange will gradually move from the east to the central region.

Figure 4. (a) Spatial distribution of average total precipitation from 1980 to 2019, (b) Spatial distribution of average total precipitation from 2020 to 2049 under rcp4.5 scenarios (annual precipitation represented by P in the figure).

3.2.3. Comprehensive Climate Suitability Zoning

According to the above single-factor climate suitability zoning results, the summation method of equal weight, geometric average method and unequal weight summation method were used to establish the comprehensive climate suitability and calculate their mean values to obtain the comprehensive climate suitability of green orange in Hainan Island. Then, based on inputs from climatic data sub-models, topographic factors and land use types of the entire island, the natural point segmentation method was used for zoning [21] to obtain climatic suitability index model of green orange results classified in four suitability classes as: (1st) the most suitable regions, (2nd) suitable regions, (3rd) sub-suitable regions and (4th) unsuitable regions (see Figure 5).

Figure 5. Climatic suitability zoning map for green orange in Hainan Island.

3.3. Zoning Assessment

3.3.1. The Most Suitable Region

This region is mainly distributed in the central part in Hainan Island, including Haikou city, southern Chengmai, the south of Dingan, the northeast Wenchang, the northwest of Qionghai, most of Tunchang, the south of Danzhou, Wanning, Qiongzong, Baisha, and part of Wuzhishan, with total area of about 8700 km². The average annual temperature is 22.8–24.7 °C, the average annual accumulated temperature ≥ 10 °C is higher than 8100 °C, the average annual sunshine duration is 1782–2064 h, and the average annual precipitation is 1784–2367 mm. The region has suitable temperature, low terrain, small slope, and sufficient water, which meets most conditions for the growth of green orange. However, due to the rapid urbanization of Haikou, Qionghai and other places, the actual area is less for planting green orange.

3.3.2. Suitable Region

This region is mainly distributed in the eastern part and most of the northern part in Hainan Island, including the central part of Haikou, the central part of Wenchang and most of the eastern coastal areas, the central part of Dingan county, the central and eastern coastal areas of Qionghai, western and central Chengmai, Lingao county, most of Danzhou, northern Baisha, with an area of about 17,300 km². The average annual temperature is 21.3–25.6 °C, the average annual accumulated temperature ≥ 10 °C is >7600 °C, the average annual sunshine duration is 1624–2271 h, and the average annual precipitation is 1309–2465 mm.

3.3.3. Sub-Suitable Region

This region is mainly distributed in the west coast and the midwest high altitude area in Hainan Island, including the west coast of Dongfang, the coastal and southern parts of Ledong, central Wuzhishan, with covering an area of about 10,100 km². The average annual temperature is 19.8–26.7 °C, the average annual accumulated temperature ≥ 10 °C is unstable, the average annual sunshine duration is 1394–2542 h, and the precipitation is less than that of the suitable area, the average annual precipitation is 1494–1757 mm. The precipitation in this region is less, the average temperature is low and the sunshine is insufficient in some areas. However, with comprehensive consideration, green orange can be planted under proper management.

3.3.4. Unsuitable Region

This region is mainly distributed in high altitude area in central Hainan Island, including the south of Changjiang, the east and the west of Qiongzong, northern Lingshui, central Wuzhishan etc., with covering an area of about 1700 km². The altitude in the region is higher than 400 m, with complicated terrain, the average annual temperature being less than 21 °C, and high precipitation, which is not suitable for the growth of green orange.

4. Discussion or Conclusions

The most suitable region for planting green orange is mainly located in the central part of Hainan Island, with climate suitability index ranging from 0.9 to 0.1. The suitable region is mainly located in the eastern and northern parts of the Island, with the climate suitability index ranging from 0.9 to 0.7. The sub-suitable region is mainly distributed in the coastal areas of western part and the high-altitude areas of central part of the Island, with the climate suitability index being between 0.4 and 0.7. The unsuitability region is mainly located in the high-altitude area of central part, with the climate suitability index being between 0 and 0.4. Under the future climate change scenario (RCP 4.5), the temperature and precipitation will greatly change from 2020 to 2049. The area of suitable temperature will gradually shrink from the surrounding to the central part, while the area of suitable precipitation will gradually move from the east to the central part in the Island.

The key of regionalizing crop's climate suitability is to select proper regionalization indexes [34]. However, the unified standard indexes are still unavailable for regionalizing green orange climate unsuitability. For instance, some indexes including temperature, accumulated temperature ≥ 10 °C, extreme minimum temperature and other temperature indexes, were used to study the climatic regionalization of citrus planting in China [7]. Some researchers used the annual average temperature, annual total radiation, air relative humidity and annual sunshine hours to investigate the planting zoning of different citrus varieties [11]. Others used temperature, precipitation and sunshine suitability model to analyze the climatic regionalization of citrus suitability in the past and future 30 years [21]. In this study, based on the climate suitability function, the suitability models of green orange were constructed with temperature, sunshine, precipitation and accumulated temperature, to perform fine zoning of climate suitability for green orange in Hainan Island. This study also combined the weighted summation method, the geometric average method and weighted summation method to establish the comprehensive climate suitability index model for optimum green orange planting areas. Using the natural break point method, the new climate suitability index model classified the evaluation area in four suitability classes as: (1st) the most suitable regions, (2nd) suitable regions, (3rd) sub-suitable regions and (4th) unsuitable regions.

At present, the green orange planting areas are mainly distributed in Qiongzong, Baisha, Chengmai, Danzhou, Lingao, and Haikou in Hainan Island, all of which are in the suitable region to the most suitable region. This study also suggests some potential suitable areas for planting green orange, such as the northern part of Wanning, most parts of Dingan, the central Qionghai and the eastern coastal areas. The above potential areas can properly develop green orange planting, based on the local development of economic

society and requirement of fruit tree production. Agricultural climate suitability zoning only provides the guidance and suggestions for planting green orange. Due to the complex topography of the Island, it is also necessary to comprehensively consider the local actual production, carry out small-scale introduction tests and then perform the large-scale green orange planting.

In this study, climate and geographical factors were considered in the regionalization of climate suitability for green orange planting areas in Hainan Island, but meteorological disasters, crop varieties adopted to climate change, soil types and other factors were not involved. Therefore, further studies are needed to investigate climate suitability of green orange planting areas in combination with meteorological disasters, crop varieties adopted to climate change and various soil types, in order to provide scientific reference for agricultural sustainable development.

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