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Delineating the Area for Sustainable Cultivation of *Morinda officinalis* Based on the MaxEnt Model

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Abstract: *Morinda officinalis*, a traditional medicinal plant in southern China, has a well-established cultivation history in Zhaoqing and Yunfu City of the Guangdong Province, China, contributing significantly to the local economy. Inadequate cultivation practices of *Morinda officinalis* may heighten the risk of landslide occurrences due to its specific growth and harvesting characteristics. This issue presents a challenge to the sustainable advancement of agriculture and forestry in the area, underscoring the necessity for scholarly intervention to address and devise effective remedies. This research utilized the MaxEnt model to assess landslide susceptibility and habitat suitability for *Morinda officinalis*, aiming to delineate appropriate cultivation zones amidst changing climatic conditions. The findings indicate that the model demonstrated a high level of accuracy, achieving combined AUC values of 0.802 for landslide susceptibility and 0.861 for habitat suitability evaluations, meeting the criteria for classification as "highly accurate". Regions such as the Yun'an District, Luoding City, and the Xinxing District in Yunfu City were identified as having a low landslide risk and being highly conducive to *Morinda officinalis* cultivation under current climate conditions. Future projections indicate an anticipated expansion of the species' distribution area between 2021 and 2040 under different climate scenarios, with subsequent variations. Spatial analysis unveiled a notable trend in the research area, indicating greater suitability for cultivation in the southern region compared to the northern region. This suggests that Yunfu City holds promise for facilitating the cultivation of *Morinda officinalis* more effectively than Zhaoqing City. This research offers a practical approach for promoting the sustainable growth of the regional *Morinda officinalis* industry, while also serving as a valuable resource for other economic crops encountering comparable developmental obstacles.

Keywords: sustainable cultivation; *Morinda officinalis*; habitat suitability; landslide susceptibility; MaxEnt model; climate change

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1. Introduction

Morinda officinalis, a perennial vine plant belonging to the Morinda genus of the Rubiaceae family, is acknowledged as a traditional southern medicinal herb in China, renowned for its therapeutic attributes in enhancing kidney Yang and fortifying muscles and bones by harnessing the potency of its succulent roots [1]. In contemporary times, the escalating demand for *Morinda officinalis* has resulted in their excessive exploitation, consequently depleting the available raw materials. However, current research in the academic community on *Morinda officinalis* mainly focuses on its chemical composition [2–4], genetic diversity [5], etc. Only a small number of scholars have conducted research on its germplasm resource protection [6], and there is almost no related research on plant ecology.

The regions of Zhaoqing City and Yunfu City in the Guangdong Province offer conducive environmental conditions for the cultivation of *Morinda officinalis*. Deqing County and the Gaoyao District of Zhaoqing City are recognized as the principal cultivation regions for *Morinda officinalis*, boasting a cultivation legacy of more than 270 years [7]. The

expansion of the *Morinda officinalis* industry has had a substantial positive impact on the local economy, as evidenced by the example of Zhaoqing City where the cultivating area reached 40,900 hm^2 and the output value amounted to CNY 884 million by 2020 [7,8]. The development of the southern medicinal industry chain, spearheaded by *Morinda officinalis*, has yielded substantial economic gains and promising growth prospects, playing a crucial role in driving agricultural transformation, upgrading, and poverty alleviation among local farmers, thereby contributing to their prosperity.

However, based on our field investigations and discussions with native farmers, it has been noted that the development of the *Morinda officinalis* industry in the designated area has faced a period of stagnation in recent years. The local governments of the Fengkai County, Guangning County, and Yunan County have actively discouraged the growth of *Morinda officinalis* due to the potential hazards linked with unscientific cultivation methods, such as soil erosion and landslide incidents [9,10]. These practices can result in ecological harm and pose risks to human lives.

Due to its drought tolerance and susceptibility to waterlogging, *Morinda officinalis* is commonly cultivated by local farmers through a practice of continuous deforestation. This method involves uprooting trees with their roots from sunny slopes in the autumn, followed by deep soil excavation for subsequent cultivating. The deep-rooted characteristics of *Morinda officinalis* can result in substantial harm to surrounding vegetation during the harvesting process, consequently contributing to soil erosion on inclines and elevating the likelihood of landslides. Numerous regions within Zhaoqing City and Yunfu City exhibit susceptibility to moderate-to-high occurrences of geological disasters [11], underscoring the significance of implementing efficient measures for geological disaster prevention. The extensive and irregular cultivation of *Morinda officinalis* may heighten the susceptibility to landslide disasters. Therefore, the conflict arising from the economic advantages of cultivating *Morinda officinalis* and the environmental hazards linked to its cultivation requires urgent attention from the academic community to seek resolution.

The use of species distribution models (SDMs) to forecast suitable habitats for species has become an important tool for developing effective management and control strategies. SDMs use statistical techniques to link species distribution data with relevant environmental factors, helping to understand how a species' range is influenced by its environment and predict changes in distribution under different climate conditions [12,13]. One popular SDM, MaxEnt, is based on the maximum entropy theory and is known for its reliable performance, high accuracy, and low susceptibility to sampling biases [14]. As a result, the MaxEnt model has been increasingly adopted recently due to its easy-to-use interface and strong predictive abilities in ecology fields [14–18]. It is important to highlight that a number of researchers have recently begun employing the Maximum Entropy (MaxEnt) model for evaluating landslide susceptibility, yielding favorable outcomes in simulation studies [19–21].

Based on the above, the authors propose a solution to the challenges associated with the sustainable cultivation of *Morinda officinalis*, which entails the scientific selection of cultivating locations considering the probability of landslide occurrences and the plant's habitat suitability by applying the optimized MaxEnt model. We conducted two experiments to assess the habitat suitability and evaluate the landslide susceptibility of *Morinda officinalis* in Zhaoqing City and Yunfu City. By superimposing the outcomes of these experiments, the research aimed to assess the suitability of cultivating *Morinda officinalis* in Zhaoqing and Yunfu City, taking into consideration the impacts of climate change. The aim of the study was to identify cultivation areas characterized by a low landslide risk and high suitability for the growth of *Morinda officinalis*.

Through our investigation, we have identified the sustainable distribution range of *Morinda officinalis* within the study region, considering factors such as susceptibility to landslides and habitat suitability amidst the backdrop of climate change. This finding can be utilized by local *Morinda officinalis* cultivators and relevant authorities to enhance sustainable cultivation practices, aiding in the informed selection of planting sites and the

development of pertinent strategies to address existing challenges in the *Morinda officinalis* industry. Furthermore, the methodology employed in this study can be extrapolated to similar investigations concerning economic crops globally, particularly those grappling with the balance between ecological preservation and economic viability, with the aim of fostering the sustainable advancement of such crops.

2. Materials and Methods

2.1. Study Area Overview

The research area includes Zhaoqing City and Yunfu City in the Guangdong Province, located in the central and western regions along the middle reaches of the Xijiang River, with a total area of 22,676.16 km^2. The climate in this region is defined by mild winters and hot summers, accompanied by significant rainfall throughout the same seasons. The average annual temperature is 22.4 °C and the average annual precipitation is 1651.3 mm. This region is classified under the South Asian tropical monsoon climate category, characterized by ample sunlight, warmth, and water resources [22].

The main economic crops in the research area are mainly Chinese medicinal herbs, including *Morinda officinalis*, *Polygonum multiflorum*, *Citrus medica*, and *Cinnamomum cassia*. In addition, there are also specialty economic crops such as *Dendrobium officinale* and *Euryale ferox* [23].

The region's topography is primarily characterized by low mountains and hills, with a restricted and sporadic plain terrain. The study area is geologically situated within the South China fold system and is in close proximity to the Pacific Volcanic Seismic Belt. Numerous large and small northeast fault zones are prevalent in the region, resulting in relatively frequent geological occurrences like landslides and collapses [11,24].

The soil composition in the area consists mainly of mountain yellow and red soil types, which are highly suitable for the cultivation of *Morinda officinalis* [7]. According to the description of the yellow and red soils in the study area in the Chinese Soil Database (http://vdb3.soil.csdb.cn/, accessed on 13 October 2023), the soil texture is sandy loam, acidic in nature, with parent material being weathered granite alluvium and residual material. The soil layer is deep, suitable for the growth of economic crops and trees such as evergreen coniferous and broad-leaved forests. However, the soil contains a lot of sand, and after vegetation destruction, it is prone to soil erosion.

2.2. Research Method and Study Area Overview

2.2.1. Scenarios Setting

In this study, a collection of seven unique climate scenarios have been utilized, incorporating three scenarios derived from the shared socio-economic pathways outlined by the 6th International Coupled Model Comparison Program (CMIP6) for future climate projections [25]. The scenarios are elaborated in Table 1. The atmospheric circulation model employed is the second-generation National Climate Center Medium-Resolution Climate System Model (BCC-CSM2-M2), recognized for its improved precision in reproducing temperature and precipitation distributions in China [26].

Table 1. Three kinds of shared socio-economic pathways.

Scenario	Description
SSP1-2.6	Sustainable Path Scenario updates the RCP2.6 scenario by setting the radiative forcing at 2.6 W/m^2 in 2100.
SSP2-4.5	Medium development path scenario involves updating the RCP4.5 scenario to achieve a radiative forcing of 4.5 W/m^2 by 2100.
SSP5-8.5	The conventional development path scenario, which updates the RCP8.5 scenario and sets the radiative forcing at 8.5 W/m^2 in 2100.

2.2.2. Model Parameter Setting and Optimization

The MaxEnt model was utilized to simulate the habitat suitability and landslide susceptibility of *Morinda officinalis* in Zhaoqing City and Yunfu City. The model configuration involved allocating 75% of distribution points to the training set, 25% to the test set, and

employing the Bootstrap method for validation [27]. Each process was repeated 40 times to assess the predictive accuracy of the model using the Receiver Operating Characteristic (ROC) curve. The significance of environmental variables was evaluated utilizing the Jackknife method, with the default settings being retained for the remaining parameters.

The distribution points were segmented into two groups utilizing the "Kuemn" package (Version 2019)in the R language. Then, 75% of the random sample data were assigned to the training set, while the remaining 25% were allocated to the test set. The regularization multiplier (RM) and feature combinations (FC) were evaluated using the MaxEnt software(Version 3.4.1). The parameters were optimized by adjusting the RM within the range of 0.1 to 4, with increments of 0.1. A comprehensive set of regularization frequency multipliers comprising 40 variations and 29 feature combinations were established, encompassing Linear (L), Quadratic (Q), Hinge (H), Product (P), and Threshold (T) modifications. The Kuemn language package was utilized to evaluate 1160 different parameter combinations. The model's performance was assessed by the minimum information criterion AICc value, which was utilized to evaluate the Area under the Receiver Operating Characteristic (ROC) curve. The AUC difference test was employed to assess the adequacy and intricacy of the model. The model exhibiting the lowest Akaike Information Criterion corrected (AICc) value (AICc = 0) was considered the most appropriate for the development of the MaxEnt model [28].

2.2.3. Variables' Collinearity Test

To address the challenge of overfitting in model simulations caused by autocorrelation among environmental variables, all environmental variables were initially included in the MaxEnt model for simulation. Variables that showed no significant impact on the model (as indicated by a contribution rate of 0) were subsequently removed from the simulation results. The residual environmental variables were subsequently imported into the SPSS software(Version 17)for further analysis. The presence of multicollinearity among variables was evaluated through the utilization of the Pearson correlation coefficient (r) [29]. In instances where sets of variables exhibited a strong correlation ($|r| > 0.8$), only the variable with the highest contribution rate was selected for inclusion in the final model implementation. Figure 1 shows the correlation analysis performed in the two subexperiments that constitute this study.



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

Figure 1. Experimental collinearity test of landslide susceptibility evaluation (**a**) and habitat suitability evaluation of *Morinda officinalis* (**b**).

2.2.4. Accuracy Evaluation Method

The Receiver Operating Characteristic (ROC) curve functions as a metric for assessing the accuracy of model predictions. The area enclosed by the Receiver Operating Characteristic (ROC) curve and the *x*-axis is commonly referred to as the Area Under the ROC Curve (AUC) value, which serves as a key indicator of the optimal model accuracy [30].

The Area Under the Curve (AUC) value is a scalar that ranges from 0 to 1. Values closer to 1 suggest higher predictive accuracy [31]. Typically, an AUC value ranging from 0.7 to 0.8 is classified as "relatively accurate", values between 0.8 and 0.9 are deemed "very accurate", and those surpassing 0.9 are denoted as "highly accurate" [32].

2.2.5. Technical Route

This study comprises two experiments: the analysis of landslide susceptibility in Zhaoqing City and Yunfu City in the Guangdong Province (Experiment 1), and the assessment of habitat suitability for *Morinda officinalis* (Experiment 2). In experiment 2, particular attention is given to considering the ecological differences present among different populations of *Morinda officinalis* in order to improve the scientific evaluation of the suitability of habitats for this species. The inclusion of distribution data for *Morinda officinalis* across China is utilized to evaluate the appropriateness of habitats. Subsequently, the masking extraction tool in ArcGIS is used to extract the results of the habitat suitability assessment based on the scope of the study area. Upon analyzing the results of both experiments, a superposition analysis was conducted to determine the geographic distribution of regions exhibiting high habitat suitability and low susceptibility to landslides for *Morinda officinalis*. The technical methodology utilized is depicted in Figure 2.

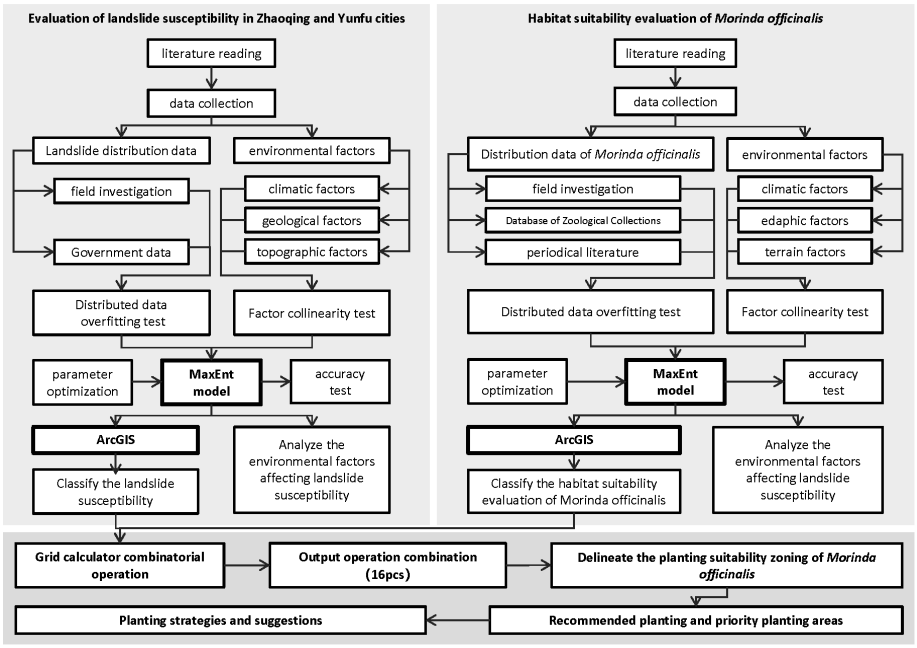


Figure 2. Technical route of this study.

2.3. Data Sources

2.3.1. Landslide Data and Morinda Officinalis Distribution Data

The landslide disaster data utilized in this study were obtained from the Zhaoqing Natural Resources Bureau and Yunfu Natural Resources Bureau of the Guangdong Province through official channels, comprising a total of 134 records. The data encompassed details such as the geographical coordinates of the landslide locations, their severity classification, and the count of individuals at risk. A dataset comprising 88 data points on the distribution of *Morinda officinalis* was compiled from diverse sources, which were collected from all over China. These sources included field surveys that documented GPS coordinates, literature reviews from databases like CNKI and Wanfang, as well as shared databases such as the Global Biodiversity Information Database (GBIF, http://www.gbif.org/, accessed on 13 October 2023), China Digital Herbarium (CVH: https://www.cvh.ac.cn/, accessed on 13 October 2023), and the National Specimen Sharing Platform (NSII: http://www.nsii.org.cn/, accessed on 17 October 2023). To address the potential issue of model overfitting due

to sampling biases and dense local data points, we utilized the ENMtools software(Version 1.3) package to perform an overfitting analysis and screening of both landslide disaster and *Morinda officinalis* distribution data points at a resolution of the environmental variables (30 arc s, ~1 km). This study collected a total of 127 data points on landslide disaster occurrences and 54 points on the distribution of *Morinda officinalis* (Figure 3). Among them, the habitat suitability experiment of *Morinda officinalis* was first conducted nationwide, and then the output results were processed into the study area by an ArcGIS 10.8 software mask.

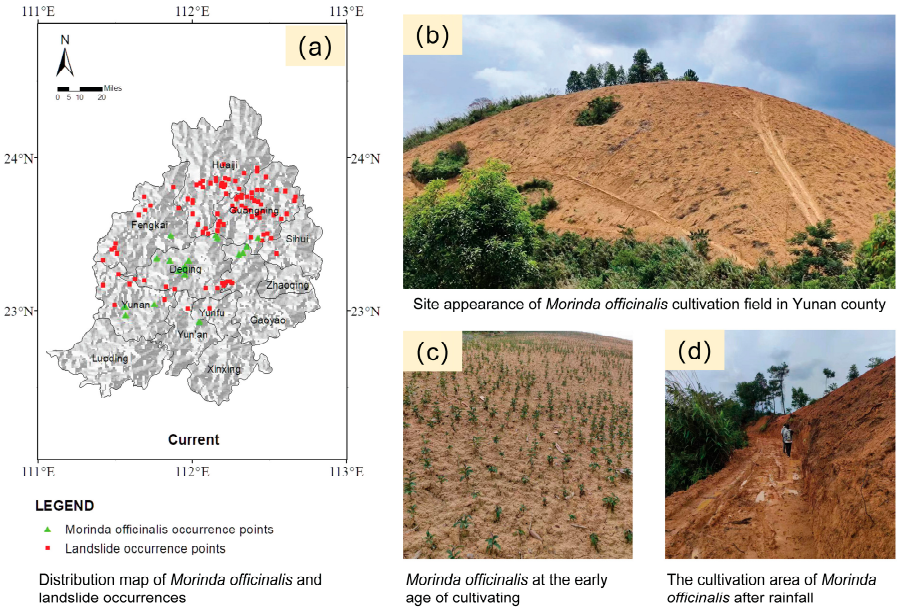


Figure 3. The occurrence points distribution of *Morinda officinalis* and landslide and the appearance of *Morinda officinalis* cultivation field. (**a**) Distribution map of *Morinda officinalis* and landslide occurrences. (**b**) Site appearance of *Morinda officinalis* cultivation field in Yunan county. (**c**) *Morinda officinalis* at the early age of cultivating. (**d**) The cultivation area of *Morinda officinalis* after rainfall.

2.3.2. Selection of Environmental Variables

This study comprises two sets of sub-experiments that differ in the selection of environmental impact variables (Table S1). In the experiment evaluating landslide susceptibility, climate, terrain, geology, and land cover were recognized as the principal variables based on prior studies of landslide occurrences in the Guangdong Province [33,34]. Climate variables were selected based on the prevalence of rainfall-triggered landslides in the area, particularly during the flood season spanning from March to September [35]. The precipitation data spanning from 2020 to 2022 (sourced from the Resources and Environmental Science and Date Center) [36] and future climate predictions covering the period from 2021 to 2060 (obtained from the World Climate Database) [37] were utilized. Topographic variables comprised elevation, slope, and aspect. The elevation data were obtained from the World Climate Database, while slope and aspect data were computed utilizing ArcGIS software. Geological variables, including lithology and distance from faults, were chosen according to regional conditions and previous studies [38–40], utilizing data sourced from the Geocloud Platform of China Geographical Survey (https://geocloud.cgs.gov.cn/, accessed on 23 May 2024). The distance from faults was assessed by importing fault lines into ArcGIS software and computing the Euclidean distance. Land cover involved utilizing vegetation cover data from 2019 [41] and land use data from 2020 [42], sourced from the Resource Environmental Science and Data Center.

At the same time, three primary criteria were established simultaneously to assess the suitability of habitats: climate, soil, and terrain variables. Data regarding climatic and topographic conditions were obtained from the World Climatic Database (http://www.worldclim.org, accessed on 23 May 2024) for both current (1970–2000) as well as future

periods (2021–2040 and 2041–2060). The climatic factor index consisted of 19 bioclimatic variables (bio1-bio19), whereas the topographic factor index replicated the one utilized in a prior landslide susceptibility investigation. Soil data were obtained from the Harmonized World Soil Database (HWSD) by utilizing the Chinese Soil Data Set (v1.1) available at http://vdb3.soil.csdb.cn/ (accessed on 23 May 2024). One soil type was chosen from a selection of 34 options for the purpose of this analysis. Consequently, a comprehensive evaluation of habitat suitability for *Morinda officinalis* involved the consideration of 56 environmental variables, as outlined in Table S2.

Before performing the MaxEnt model simulation, the raster data depicting different environmental variables were standardized in a resolution and geographic coordinate system. For this study, all environmental impact variables were standardized to a uniform resolution of 30 arc seconds and a cohesive geographic coordinate system of WGS1984.

3. Results and Analysis

3.1. Environmental Variables' Screening Results

Upon integrating the distribution points and environmental impact variables of the two experimental groups into the MaxEnt model for simulation, an evaluation of collinearity among the environmental impact variables was conducted following the guidelines detailed in Section 2.2.3 (Figure 2). The selected environmental impact variables for incorporation into the model are delineated in Tables 2 and 3.

Table 2. Environmental variables selected for landslide susceptibility evaluation experiment after collinearity test.

Primary Index	Secondary Index	Code	Percent Contribution	Permutation Importance
Climatic variables	Precipitation in April	prec4	8.1	7.4
	Precipitation in July	prec7	23.1	6.6
	Precipitation in August	prec8	29.2	44.9
Terrain variables	Elevation	elev	22.7	31.1
	Aspect	aspect	1.8	1.2
Geological variables	Lithology	lithology	7.1	6.4
	Distance from fault	dis_fault	8	2.5

Table 3. Environmental variables selected for habitat suitability evaluation experiment of *Morinda officinalis* after collinearity test.

Primary Index	Secondary Index	Code	Percent Contribution	Permutation Importance
Climatic variables	Monthly mean temperature	Bio2	21.4	27.1
	Annual temperature range	Bio7	34.2	39.8
	Wettest monthly precipitation	Bio13	7.8	8.5
Edaphic variables	Subsoil gravel volume percentage	S_gravel	3.5	1.5
	Sediment content in the subsoil	S_sand	2.9	3.4
	Subsoil texture classification	S_usda_tex	5.7	3.3
	Cation exchange capacity of the lower cohesive layer soil	S_cec_clay	0.1	0.2
	Cation exchange capacity of the subsoil	S_cec_soil	8.1	6.3
	The subsoil can exchange sodium salts	S_esp	2.4	2.7
	Cation exchange capacity of upper cohesive layer soils	T_cec_clay	0.2	0.5
Terrain variables	Aspect	Aspect	12.2	4.5
	Slope	Slope	1.5	2.2
	Aspect	Aspect	12.2	4.5
	Slope	Slope	1.5	2.2

3.2. Model Optimization Parameter Results and Accuracy Evaluation

Following the protocol delineated in Section 2.2.2, the optimization and validation of the landslide susceptibility assessment model were conducted. This process involved the utilization of seven environmental variables and 127 instances of landslide occurrences after a screening process. The optimized parameters for the landslide susceptibility assessment

model were determined as RM = 2.2 and FC was set equal to QT. Subsequently, the model underwent refinement and testing using 14 selected environmental variables and 54 data points associated with the distribution of *Morinda officinalis*. The optimized parameters for the habitat suitability assessment model of *Morinda officinalis* were identified as RM = 0.8 and FC was set equal to Q.

The Receiver Operating Characteristic (ROC) curves of the two cohorts, which were subjected to trials for assessing landslide susceptibility and evaluating the suitability of the *Morinda officinalis* habitat, were individually produced utilizing the refined MaxEnt model, as illustrated in Figure 4. In line with the precision assessment methodology outlined in Section 2.2.4, the Area Under the Curve (AUC) metric for the experiments assessing landslide susceptibility and *Morinda officinalis* habitat suitability was calculated to be 0.802. Moreover, the Area Under the Curve (AUC) value for the experiment assessing the habitat suitability of *Morinda officinalis* was determined to be 0.861. These results indicate that the predictive abilities of both experiments have reached a high level of accuracy.

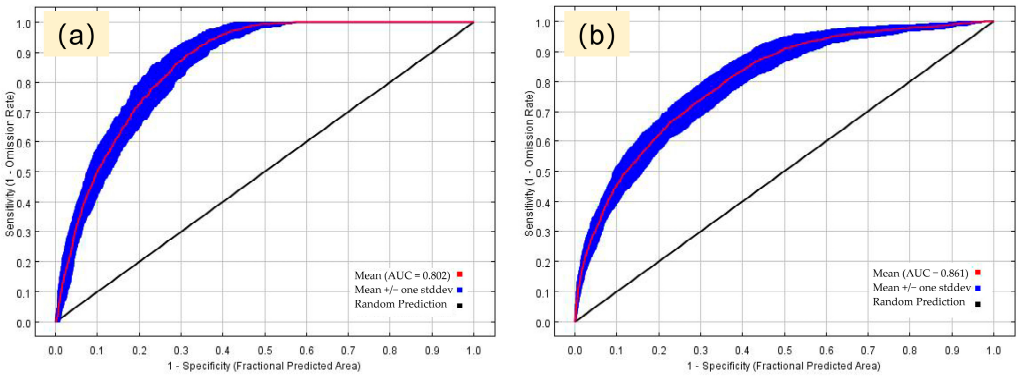


Figure 4. Average AUC of the Landslide susceptibility evaluation model (**a**) and Habitat suitability evaluation model for *Morinda officinalis* (**b**).

3.3. Evaluation of Landslide Susceptibility in Zhaoqing City and Yunfu City of Guangdong Province under Current and Future Climatic Conditions

The natural breakpoint method implemented in the ArcGIS software was employed to segment the outcomes of landslide susceptibility produced by MaxEnt (Figure 5). The landslide susceptibility zones in Zhaoqing City and Yunfu City, located in the Guangdong Province, have been categorized into four levels based on the landslide susceptibility index (P): Non-susceptibility area ($P < 0.14$), low-susceptibility area ($0.15 \leq P \leq 0.32$), medium-susceptibility area ($0.33 \leq P \leq 0.50$), and high-susceptibility area ($P > 0.51$). According to the data provided in Table 4, the current climate conditions suggest that the areas prone to high landslide susceptibility in Zhaoqing City and Yunfu City, located in the Guangdong Province, cover a total area of 4054 km^2. The aforementioned areas are primarily located in the western and north-central regions of the research area, encompassing a substantial portion of the Fengkai County, the southern area of the Huaiji County, the western sector of the Guangning County, the northern vicinity of Sihui City, the northeastern part of the Deqing County, and the northwestern part of Yunfu City. The medium-susceptibility area covers an estimated 5034 km^2, mainly concentrated in the central region of the study area, particularly surrounding the Deqing County, Gaoyao District, Huaiji County, Guangning County, and Fengkai County. Moreover, this geographical area encompasses the northwestern region of the Gaoyao District in Zhaoqing City, the eastern area of the Yunnan County in Yunfu City, the central zone of Luoding City, and the northern sector of the Yuncheng District. The areas of low susceptibility and non-susceptibility, totaling approximately 5306 km^2, are predominantly located in the northern and southern regions of the research area. These areas are particularly concentrated near the Yun'an District, Yuncheng District, Xinxing County, Gaoyao District, Duanzhou District, and Dinghu District of Zhaoqing City. The distribution of landslide susceptibility within the study area shows a spatial pattern

characterized by higher susceptibility in the northern region and lower susceptibility in the southern region. Yunfu City exhibits a lower level of landslide susceptibility in comparison to Zhaoqing.

In the context of climate change, the study area demonstrates diverse trends in landslide susceptibility across regions under distinct climate scenarios (Table 4). This study focuses on investigating the regional variations in areas characterized by low or no susceptibility to landslides. In scenarios SSP1-2.6 and SSP5-8.5, a decrease in the regions with low-to-no susceptibility to landslides is projected from 2021 to 2040 when compared to the current climate conditions. This decrease is especially significant in the northern, southwestern, and southeastern regions of the research area. During the period from 2041 to 2060, there will be an upward trend observed, leading to overall areas that are comparable to the current conditions. Conversely, in the SSP2-4.5 scenario, regions with low-to-no susceptibility to landslides show a consistent decline. Projections suggest a decrease to 3301.02 km^2 by 2041–2060, marking a 38% reduction compared to the present climate conditions. Notably, there has been a rise in the prevalence of areas exhibiting non-susceptibility and low susceptibility within the eastern and central regions of the study area.

Table 4. Statistical unit of landslide-prone zone area in different periods Unit: km^2.

Unit: km^2	Current	2021–2040			2041–2060		
		SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
Non-susceptibility area	5015.278	5946.528	3295.139	7519.444	2027.778	7608.333	2478.472
Low-susceptibility area	5806.944	6004.861	4314.583	5435.417	4234.722	6068.055	4597.917
Medium-susceptibility area	5034.028	5095.139	6127.778	5241.668	7215.972	4812.450	7345.833
High-susceptibility area	4054.861	2866.667	6175.694	1716.667	6434.722	1424.306	5490.972

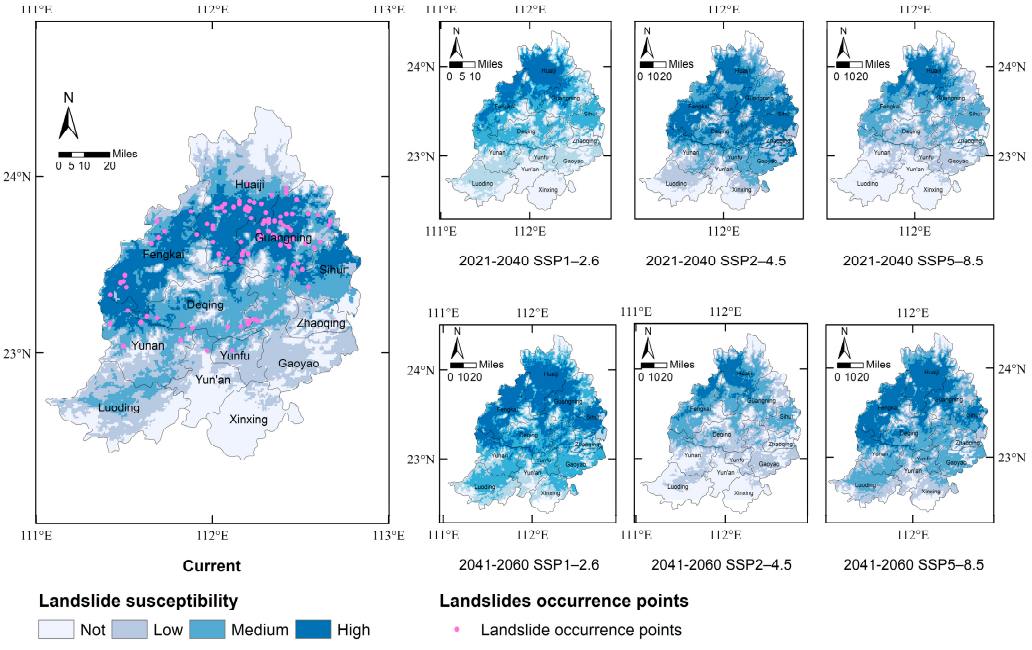


Figure 5. Landslide susceptibility zoning in Zhaoqing City and Yunfu City, Guangdong Province, under current and future climate conditions.

3.4. Habitat Suitability Evaluation of Morinda officinalis in Zhaoqing City and Yunfu City of Guangdong Province under Current and Future Climate Conditions

Similarly, the natural breakpoint method in the ArcGIS software was employed to divide the habitat suitability results of *Morinda officinalis* produced by MaxEnt (see Figure 6). The habitat suitability zoning for *Morinda officinalis* was categorized into four tiers, varying from low to high, according to the habitat suitability index (Q): non-prone area (Q < 0.28),

low-suitability area ($0.29 \leq Q \leq 0.42$), medium-suitability area ($0.43 \leq Q \leq 0.57$), and high-suitability area ($Q > 0.58$). The results revealed that the combined suitable area covered around 15,942 km^2 in Zhaoqing City and Yunfu City, with the majority consisting of the low-suitability area totaling 6695 km^2. The area classified as moderately suitable ranked second, encompassing approximately 37% of the total suitable area. The high-suitability region covers an area of 3336 km^2, primarily located in the western and southern sectors of the study area. The regions characterized by a distinct scale distribution predominantly encompassed the western and southern sectors of the Yunan District in Yunfu City, the eastern segment of the Yunan County, the eastern area of Luoding City, the western part of the Xinxing County, the eastern part of the Huaiji County in Zhaoqing City, the southern part of the Fengkai County, and the central part of the Deqing County, among other locations. The remaining regions were scattered. The high-suitability zones for *Morinda officinalis* in the study area exhibited a relatively dispersed distribution pattern. The suitability pattern was approximately described as being "high in the west and low in the east, high in the south and low in the north".

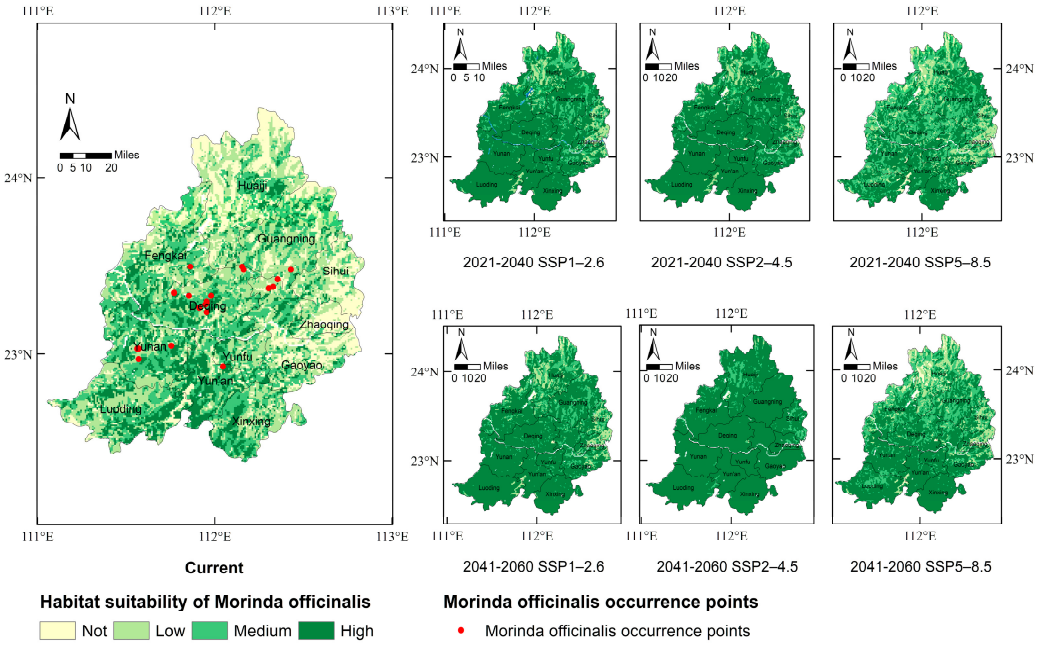


Figure 6. Suitability zoning of *Morinda officinalis* in Zhaoqing City and Yunfu City, Guangdong Province, under current and future climatic conditions.

In the context of climate change, the habitat suitability of *Morinda officinalis* within the research area has experienced substantial changes, as outlined in Table 5. Between the periods of 2021–2040 and 2041–2060, there was a marked increase in the area of highly suitable habitats for *Morinda officinalis*, with a growth pattern that initially showed rapid expansion before slowing down. Projections based on the SSP1-2.6 scenario indicate that the high-suitability habitat area for *Morinda officinalis* is expected to expand to 11,870 km^2 between 2021 and 2040. This represents a 256% increase compared to current climate conditions. This expansion is primarily characterized by a significant increase in the surrounding area with high suitability under the prevailing climate conditions. By the period of 2041–2060, it is anticipated that the area with high suitability will cover 15,336 km^2, indicating a 29% increase compared to the previous period of 2021–2040. Moreover, it is anticipated that the region with high suitability will exhibit increased contiguity. Under the SSP2-4.5 scenario, the high-suitability area of *Morinda officinalis* exhibited a significant increase of 387% from 2021 to 2040, expanding to 16,255 km^2. Subsequently, a more moderate rise was noted from 2041 to 2060, reaching 15,336 km^2. It is noteworthy that only a limited number of isolated regions within the study area were not classified as

high-suitability areas. In contrast, the expansion of the high-suitability area for *Morinda officinalis* was relatively smaller under the SSP5-8.5 scenario compared to the other two climate scenarios. An increase of 201% was observed between 2021 and 2040, leading to a total area of 11,982 km^2 by the period of 2041–2060. The expansion primarily focused on the southwestern and southern sectors.

Table 5. Statistical unit of habitat suitability area of *Morinda officinalis* in different periods. Unit: km^2.

Unit: km^2	Current	2021–2040			2041–2060		
		SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
Non-suitable area	3706.944	134.028	33.333	261.111	54.167	4.861	347.222
Low-suitability area	6695.139	2061.806	781.250	2377.778	1188.194	31.250	1981.250
Medium-suitability area	5911.111	5583.333	2579.167	6984.028	3070.139	968.056	5338.194
High-suitability area	3336.111	11,870.139	16,255.555	10,026.389	15,336.805	18,645.139	11,982.639

3.5. Under Current and Future Climate Conditions, the Cultivating Zones of Morinda Officinalis in Zhaoqing City and Yunfu City of Guangdong Province Were Determined

In alignment with the research objectives, the results of the landslide susceptibility and habitat suitability evaluations for Morinda officinaria in Zhaoqing city and Yunfu city, located in the Guangdong Province, were superimposed, yielding a total of 16 combinations. Subsequently, these combinations were stratified into different tiers of cultivating suitability zones for *Morinda officinalis* within the study area, encompassing a total of six levels (Figure 7). The cultivating regions were categorized into different levels of suitability based on a ranking system ranging from the least to most favorable. These categories included extremely unsuitable, unsuitable, low suitability, moderate suitability, high suitability, and optimal suitability. The delineations were visualized using ArcGIS software, and the results are illustrated in Figure 8.

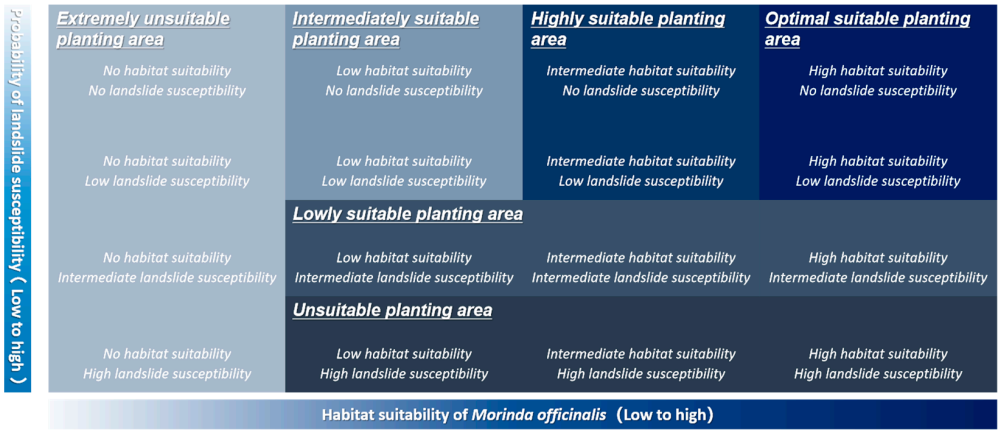


Figure 7. Cultivating zoning of *Morinda officinalis* in Zhaoqing City and Yunfu City, Guangdong Province, China.

The results revealed that under the prevailing climatic conditions, the low-suitability cultivation area for *Morinda officinalis* in the study area accounted for the highest percentage at 22%, covering a landmass of 4239 km^2 (Table 6). Conversely, the cultivation region with the optimal suitability represented only 10% of the total, primarily located in diverse areas such as the Yun'an District of Yunfu City, the southeastern region of Luoding City, and the western and southern parts of the Xinxing County, and sporadically found in the Yuncheng District of Yunfu City, the central and northern Huaiji County of Zhaoqing City, the southwest of the Gaoyao District, and other dispersed sites. The cultivation land area of 2953 km^2 is highly suitable, with a primary concentration in the most favorable cultivation region. The least suitable cultivation area covered 4239 km^2, ranking second in size after

the area with low-suitability cultivation conditions. This area was primarily located in the northern part of the Huaiji County, as well as in the central and eastern areas of Sihui City and Zhaoqing City. The cultivation suitability of *Morinda officinalis* in the study area demonstrated a spatial pattern characterized by higher suitability in the southern regions and lower suitability in the northern areas. This pattern exhibited a negative correlation with the distribution of landslide susceptibility.

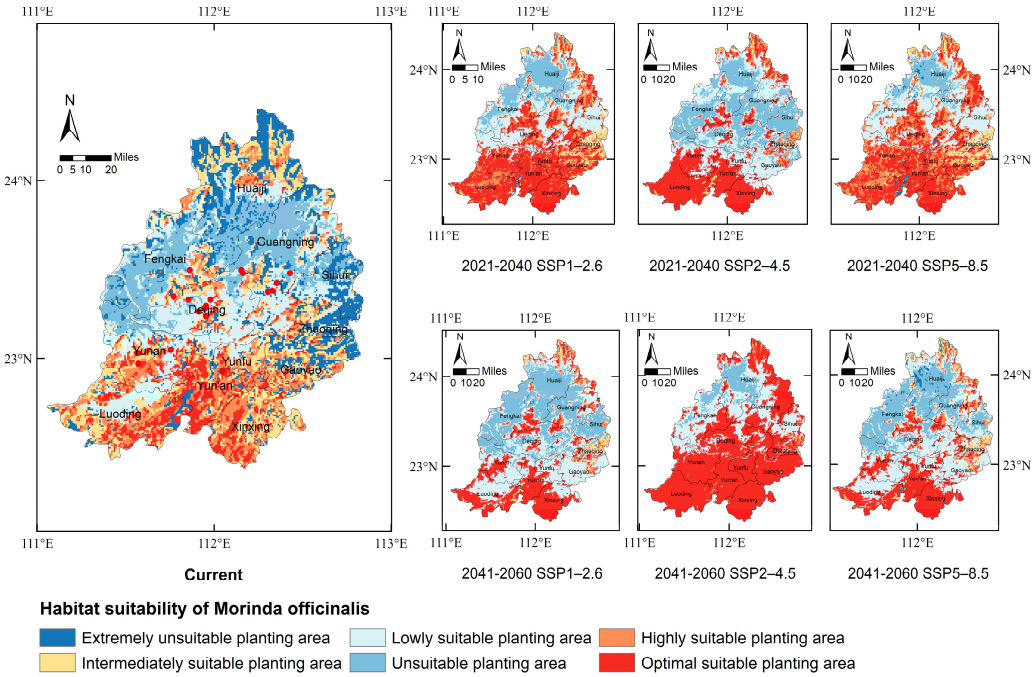


Figure 8. Cultivating suitability zoning of *Morinda officinalis* in Zhaoqing City and Yunfu City of Guangdong Province under current and future climate conditions.

In the context of climate change, the suitability of cultivating areas for *Morinda officinalis* has exhibited variability across various climate scenarios. This study focused on analyzing the changing trends in the highly suitable and optimal cultivating areas for *Morinda officinalis*, as illustrated in Figure 9. Firstly, focusing on the SSP1-2.6 and SSP5-8.5 scenarios, a consistent trend was identified in the alterations to the highly suitable and optimal cultivating areas for *Morinda officinalis*. The projections suggest a notable rise in these regions between 2021 and 2040 in comparison to the prevailing climate conditions. In the SSP1-2.6 scenario, there was an expansion of around 5870 km^2, which equated to a 120% increase. The spatial distribution demonstrated a continuous expansion in urban areas, including Yunfu City, the Yunnan County, Luoding City, the Yun'an District, and the Xinxing County. In the SSP5-8.5 scenario, there was a 133% increase in the area exhibiting a spatial distribution similar to that of the SSP1-2.6 scenario. During the period from 2041 to 2060, the optimal and most favorable cultivating regions for *Morinda officinalis* are anticipated to diminish in comparison to the preceding timeframe (2021–2040). In the SSP1-2.6 scenario, a reduction of approximately 47% is projected, whereas in the SSP5-8.5 scenario, a decrease of around 46% is anticipated, with spatial distributions remaining consistent across both scenarios. Conversely, the SSP2-4.5 scenario exhibited a clear pattern in the alterations of the highly suitable and most suitable cultivating regions for *Morinda officinalis*, demonstrating a consistent upward trend. Between 2021 and 2040, the anticipated expansion of the area is forecasted to grow from around 4868 km^2 under existing climate conditions to approximately 7273 km^2, representing a 49% increase. The anticipated expansion is expected to occur in areas such as Luoding City, the Yun'an District, and the Xinxing County. Moving forward to the period of 2041–2060, the projected expansion of the area is expected to increase by approximately 6218 km^2 in comparison to the preceding

period, reaching an estimated 13,491 km^2. Spatially, this expansion covers the entire area of Yunfu City, along with the Gaoyao District in Zhaoqing City, the Deqing County, and the neighboring regions, creating a vast and interconnected distribution.

Table 6. Statistical unit of cultivating area of *Morinda officinalis* in different periods. Unit: km^2.

Unit: km^2	Current	2021–2040			2041–2060		
		SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
Extremely unsuitable cultivating area	3706.945	134.028	33.335	261.112	54.167	4.862	347.223
Unsuitable cultivating area	3431.945	2812.500	6011.806	1629.167	6298.611	1400.000	5203.472
Low-suitability cultivating area	4239.584	4984.028	6045.833	5082.639	7096.528	4731.945	7176.389
Intermediately suitable cultivating area	3402.084	979.167	285.417	1290.972	472.222	21.528	737.500
Highly suitable cultivating area	2953.472	2745.834	847.222	3968.055	825.694	364.583	1221.528
Optimal suitability cultivating area	1915.278	7993.750	6425.694	7417.361	4902.084	13,126.389	4963.195

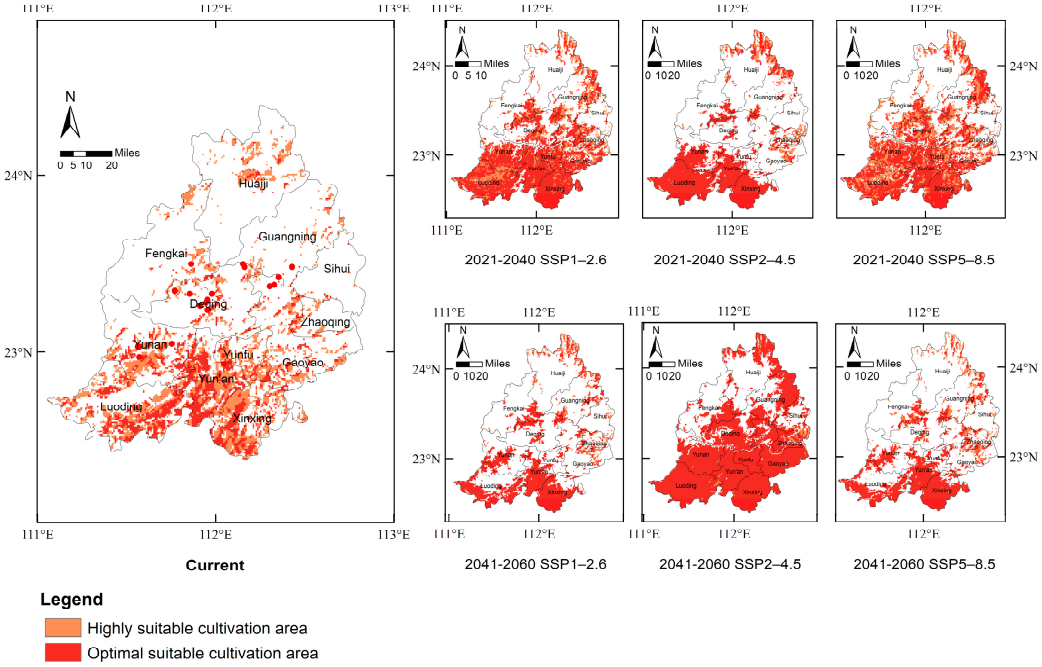


Figure 9. Distribution of the highly and optimally suitable cultivating areas of *Morinda officinalis* in Zhaoqing and Yunfu cities of Guangdong Province under current and future climate conditions.

4. Discussion

4.1. Analysis on the Cause of Relatively Low AUC Value of Two Sub-Experimental Models

In the study area, two sub-experiments were conducted utilizing the MaxEnt model to evaluate landslide susceptibility and assess the habitat suitability of Morbinaria officinalis. The aggregated AUC values for the two experimental models were 0.802 and 0.861, respectively, satisfying the requirements for a "highly accurate" model assessment. However, these values were relatively lower compared to the typical outcomes obtained in conventional assessments of the species' potential distribution utilizing the MaxEnt model [43–48]. Consequently, the following paragraphs will examine the variables contributing to this inconsistency and evaluate the dependability of the research model's output findings from different perspectives.

(1) The difference in sampling distribution points may contribute to the relatively lower observed AUC value in the model. A fundamental principle of Maximum Entropy (MaxEnt) modeling entails the deliberate and/or random selection of distribution points across the study area [49]. A greater quantity of precisely located distribution points for research subjects typically improves the accuracy of the MaxEnt model simulation [50]. Nevertheless, obstacles such as limitations in resources including personnel, equipment,

and expenses impede the achievement of impartial and thorough sampling, rendering the practical execution challenging. The data acquisition methods utilized in the subexperiments of this study closely resemble the common techniques of "field investigation + network data capture" that are prevalent in current relevant studies. The distribution data for *Morinda officinalis* were primarily obtained through a combination of "literature search + specimen data retrieval", supplemented by field sampling. The data on landslide distribution were obtained from geological locations surveyed by the Bureau of Natural Resources in Zhaoqing City and Yunfu City over multiple years. Thus, the experimental data were considered highly reliable and obtained from relatively comprehensive sources. However, limitations such as the research duration, costs, and the inherent uncertainties surrounding landslide occurrences may render it impractical to conduct a comprehensive survey of the study area with absolute precision. This constraint has the potential to result in a slight decrease in the AUC value of the model. Moreover, the choice of a sampling bias correction technique could potentially impact the model's comparatively reduced AUC value. Previous research conducted by Yackulic et al. [51] has brought attention to the significant issue of sampling bias in MaxEnt model studies, emphasizing the need for researchers to address and correct the biased data points sampled. Kong Weiyao et al. [52] delineated 13 distinct correction techniques for addressing sampling bias, which encompass spatial screening. Fourcade et al. [53] conducted a comparative evaluation of different correction methods, determining that spatial screening exhibited slightly superior efficacy compared to other approaches. Currently, there is a lack of standardized protocol for addressing sampling bias. Spatial screening is the primary approach employed to correct bias in the distribution of data points in species distribution studies utilizing the MaxEnt model, a method also utilized in the present study. Notably, this approach involves modifying distribution point data by considering the characteristics of environmental impact variables. This process may lead to the alteration or loss of original data, consequently contributing to a partial decrease in the model's AUC value [53].

(2) Further validation and examination are necessary to assess the suitability of using the MaxEnt model for evaluating landslide susceptibility. The evaluation of landslide susceptibility has been a continuous process since the mid-1970s, with a variety of assessment methods evolving over time. Nonetheless, an optimal model for the effective evaluation of landslide susceptibility is still lacking. In recent years, the MaxEnt model, a machine learning technique that operates analogously to the process of regionalizing landslide susceptibility, has been integrated into studies focusing on landslide susceptibility [54–58]. For example, Felicisimo et al. [20] performed a comparative study of four models, namely MLR, MARS, CART, and MAXENT, to evaluate the susceptibility of landslides in the Deba Valley, Spain. The predictive accuracy of these models was assessed using the Area Under the Curve (AUC) metric, revealing that the MaxEnt model produced the most favorable simulation outcomes. Subsequently, Chen et al. [21] employed three distinct machine learning models, namely MaxEnt, SVM, and ANN, both individually and collectively, to assess the susceptibility of landslides in Wanyuan City, the Sichuan Province, China. The results of the study revealed that the MaxEnt model exhibited the lowest AUC value. Furthermore, Mai Jianfeng et al. [38] evaluated the susceptibility of rain-induced landslides in the Guangdong Province by employing the MaxEnt model. Their analysis yielded an AUC value of 0.820, showing a slight disparity compared to the AUC value documented in our study. The application of the MaxEnt model in the landslide susceptibility assessment appears to be in the experimental stage, indicating a need for further deliberation on its suitability. This factor could potentially be a contributing factor to the comparatively lower AUC values noted in these studies.

In summary, the model's relatively low AUC value can be attributed to various variables. This phenomenon may be attributed to differences in sampling distribution points, corrections for sampling deviations, model optimization, and other relevant variables. The AUC values obtained from the two model experiments in this study were relatively lower in comparison to conventional research on species' potential distribution. However, they

still met the criteria for the "very accurate" category according to the AUC assessment framework. Moreover, the two sub-experiments in this study were optimized by sampling distribution points and performing collinearity evaluations of environmental variables. The optimization of model parameters was conducted utilizing the R programming language package. Consequently, despite the potential decrease in the AUC value of the model [59], it is more reliable in mitigating model overfitting and maintaining model precision, thereby ensuring scientifically sound outcomes [60,61]. Subsequently, the research team intends to conduct a comprehensive and precise field survey in the study area utilizing the landslide susceptibility distribution map and the habitat suitability distribution map of *Morinda officinalis* developed in this study. This will validate this study's findings and lay the groundwork for future research advancements.

4.2. Specific Distribution of the Highest and Most Suitable Cultivating Areas of Morinda Officinalis in the Study Area under Climate Change

Global warming significantly impacts the distribution patterns of plants and the frequency of meteorological disasters. The research indicates that the average surface temperature is projected to increase by 2.6–4.8 °C by the conclusion of the 21st century [62]. The anticipated increase in temperature is projected to modify the habitat suitability and distribution of landslide susceptibility for *Morinda officinalis*. Therefore, climate change should be regarded as a pivotal factor. The ongoing progress of the *Morinda officinalis* cultivation sector in the study region is facing obstacles, highlighting the need for the establishment of a scientifically grounded cultivation zoning map with tangible applications. In consideration of the results outlined in Section 3.5 of this research and given the pressing nature of the issue, the focus is on identifying optimal cultivating locations for the current period and the time span from 2021 to 2040 for further examination. A superposition diagram was generated using ArcGIS software (Figure 10) to depict the spatial distribution of *Morinda officinalis* and identify the optimal cultivating area in the study region under both current climate conditions and projected conditions for the period 2021–2040. In the diagram, the green color block represents the distribution area of *Morinda officinalis* and the optimally suitable cultivating area under the prevailing climate conditions. The red color block delineates the stable distribution area of *Morinda officinalis* at high altitudes and the optimally suitable cultivating area under both current conditions and projected conditions for the period 2021–2040. The yellow color block delineates the newly incorporated region of *Morinda officinalis'* highly and optimally suitable cultivating area under different climate models for the timeframe spanning from 2021 to 2040.

Based on the analysis of satellite remote sensing data, the spatial distribution of *Morinda officinalis*, focusing on areas identified as highly conducive for cultivation and optimal cultivating locations, exhibits a consistent pattern across three different climate models covering the period from 2021 to 2040 in comparison to present climatic conditions. The aforementioned regions demonstrate a continuous geographical spread, encompassing the Yun'an District, Luoding City, and the Xinxing District of Yunfu City. Particularly, notable clusters are identified in Gaocun Town, Shicheng Town, Baishi Town, Nansheng Town, and Fulin Town within the Yun'an District, Yunfu City. The Yuncheng District includes Yaogu Town and Gao Feng Street, among other areas. The Yunan County comprises Dafang Town, Qianguan Town, Li Dong Town, and other regions. Luoding City consists of Luoping Town, Jinyinhe Forest Farm, Longyong Forest Farm, and other areas. The Xinxing County features Bougainzhu Town, Hetou Town, Dajiang Town, and other regions. Additionally, Liantang Town, Live Road Town, the Gaoyao District, and Zhaoqing City are part of this geographical area. Moreover, the analysis reveals a pattern of growth in the areas deemed highly suitable and optimal for cultivating between 2021 and 2040 in contrast to the present climate conditions. This expansion varies in magnitude across the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. The expansion is notably more pronounced in the SSP1-2.6 and SSP5-8.5 models, while relatively smaller in the SSP2-4.5 model. The results derived from Sections 3.3 and 3.4 of this research indicate a possible association

between the heightened vulnerability to landslides in the research site and the results identified within the SSP2-4.5 model.

The impact of climate change on the habitat's suitability and vulnerability to landslides for *Morinda officinalis* in the study area is a crucial factor that requires careful consideration. This factor significantly influences the trajectory of future research efforts. Subsequently, the upcoming phase of the research will entail analyzing the response curve of environmental variables, specifically concentrating on comprehending the variables influencing changes in habitat suitability and landslide susceptibility of *Morinda officinalis*. Furthermore, the study will integrate more accurate and detailed remote sensing imagery and geographic information, taking into account practical variables such as slope restrictions for growing profitable crops, local agricultural and forestry policies, and on-the-ground conditions. By embracing this methodology, the objective is to augment the scientific and practical significance of defining the study area, consequently boosting its relevance and effectiveness.

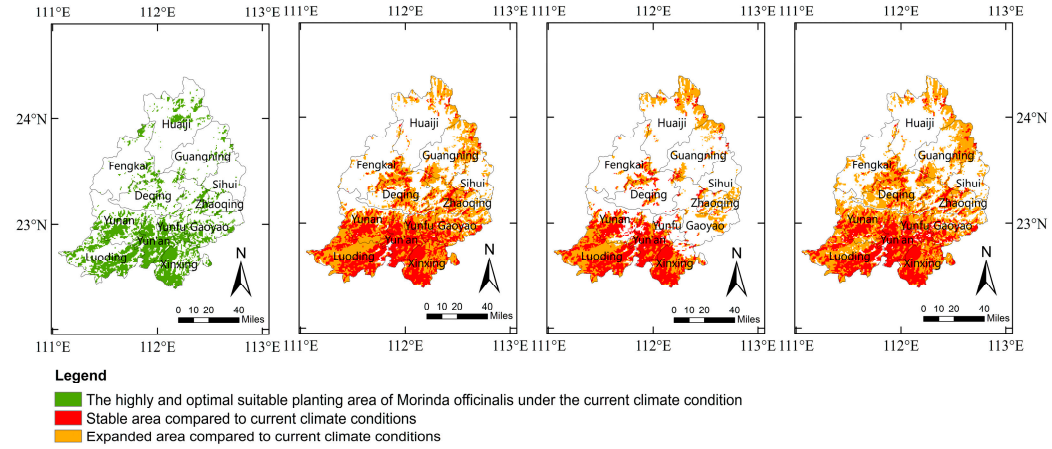


Figure 10. Superimposed spatial distribution map of the highly and optimally suitable cultivating area of *Morinda officinalis* in the study area under current and 2021–2040 climate conditions.

5. Conclusions

This study employed an optimized Maxent model to evaluate the habitat suitability and landslide susceptibility of *Morinda officinalis* in Zhaoqing City and Yunfu City. Through a superposition analysis, the Yun'an District in Luoding City and Xinxing District in Yunfu City have been identified as potential cultivation areas with a low risk of landslides and high suitability for *Morinda officinalis* cultivation. This study also investigated the influence of climate change on the geographical distribution of *Morinda officinalis* across various climate scenarios. The findings reveal a growing pattern in the distribution of *Morinda officinalis* from 2021 to 2040, especially under the SSP5-8.5 scenario, showing a significant rise of 133%. During the period from 2041 to 2060, the suitable cultivating area for *Morinda officinalis* experienced a decline in both high and optimal conditions under the SSP1-2.6 and SSP5-8.5 scenarios. In contrast, there was a notable increase in the cultivating area under the SSP2-4.5 scenario, with the area expanding to around 13,491 km^2. Spatially, the cultivating suitability of *Morinda officinalis* in the study area exhibited a pattern characterized by higher suitability in the southern regions and lower suitability in the northern regions across different climate scenarios and temporal periods. This implies that Yunfu City might be more conducive to the scientific cultivation of *Morinda officinalis* in comparison to Zhaoqing City, taking into account both landslide susceptibility and habitat suitability. The economic ramifications of *Morinda officinalis* and the environmental effects of landslides caused by inappropriate cultivating methods are recognized to influence local industrial advancement. This discovery can be used by *Morinda officinalis* growers and authorities at the local level to improve sustainable cultivation methods. It can help in choosing suitable planting locations and creating strategies to overcome current challenges in the *Morinda officinalis* industry. Additionally, the research methods used in this study can be applied to other studies

on economic crops worldwide, especially those facing challenges in balancing ecological conservation and economic profitability. This can contribute to the sustainable progress of these crops.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14061134/s1, Table S1. Environmental variables affecting the occurrence of landslide disasters. Table S2. Environmental variables affecting the habitat suitability of *Morinda officinalis*.

Author Contributions: J.L.: Investigation, Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing-original draft. G.T.: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Funding acquisition. X.Q.: Data curation, Funding acquisition, Investigation, Supervision, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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