

Article

From Marginal Lands to Biofuel Bounty: Predicting the Distribution of Oilseed Crop *Idesia polycarpa* in Southern China's Karst Ecosystem

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Abstract: With the global energy crisis and the decline of fossil fuel resources, biofuels are gaining attention as alternative energy sources. China, as a major developing country, has long depended on coal and is now looking to biofuels to diversify its energy structure and ensure sustainable development. However, due to its large population and limited arable land, it cannot widely use corn or sugarcane as raw materials for bioenergy. Instead, the Chinese government encourages the planting of non-food crops on marginal lands to safeguard food security and support the biofuel sector. The Southern China Karst Region, with its typical karst landscape and fragile ecological environment, offers a wealth of potential marginal land resources that are suitable for planting non-food energy crops. This area is also one of the most impoverished rural regions in China, confronting a variety of challenges, such as harsh natural conditions, scarcity of land, and ecological deterioration. *Idesia polycarpa*, as a fast-growing tree species that is drought-tolerant and can thrive in poor soil, is well adapted to the karst region and has important value for ecological restoration and biodiesel production. By integrating 19 bioclimatic variables and karst landform data, our analysis reveals that the Maximum Entropy (MaxEnt) model surpasses the Random Forest (RF) model in predictive accuracy for *Idesia polycarpa*'s distribution. The karst areas of Sichuan, Chongqing, Hubei, Hunan, and Guizhou provinces are identified as highly suitable for the species, aligning with regions of ecological vulnerability and poverty. This research provides critical insights into the strategic cultivation of *Idesia polycarpa*, contributing to ecological restoration, local economic development, and the advancement of China's biofuel industry.

Keywords: species distribution models (SDMs); maximum entropy (MaxEnt); random forest (RF); contiguous poverty areas; crop simulation modeling

1. Introduction

Since the first oil crisis of the 1970s, the world, facing a severe energy crisis due to the intensification of energy depletion and environmental issues, is actively seeking biofuels as alternatives to traditional fossil fuels [1]. Particularly, Brazil and the United States, as pioneers in the field of biofuels, mainly utilize sugarcane and corn as raw materials [2]. At the same time, other regions and countries around the world are also accelerating the commercialization of bioenergy to replace fossil fuels [2,3]. Many countries have set voluntary or mandatory targets for biofuels to replace petroleum fuels to meet the needs of energy transition [3]. For developing countries, especially large developing countries like China, the importance of biofuels is on the rise. China, which has long relied on coal, faces the challenge of a single energy structure, and due to the depletion of fuel reserves and environmental impacts, the current energy supply model will not be sustainable in the near future [4]. Sufficient energy resources are fundamental for a country's progress [5]. Moreover, a country must ensure energy security for the present as well as for the future to continue to achieve significant growth and development [6].

However, unlike many other countries, China's large population and limited arable land resources restrict the use of corn or sugarcane as raw materials for bioenergy in China [7]. The Chinese government has clarified the guiding principles for the development of biofuels: "Non-food crops as raw materials, and the cultivation of these crops on marginal land" [8]. This principle aims to ensure the development of the biofuel industry without threatening food security and the rural economy [8,9]. Therefore, the production of biofuel raw materials is limited to marginal land to avoid competing with food crops for land resources, thereby safeguarding the country's food security. At the same time, this also contributes to the development of a sustainable bioenergy industry [9].

The Southern China Karst Region, one of the most typical and complex karst areas in the world with the richest types of karst landscapes, covers an area of over 550,000 km². It stands alongside Central America and Southeast Europe as one of the world's three major concentrated distribution areas of carbonate rocks [10]. The region accounts for more than 30% of China's potential usable marginal land area [11,12], providing relatively abundant land resources for the development of non-food energy crops. The Southern Karst Region is also the area with the largest scale and deepest degree of rural poverty in China and is one of the country's four major ecologically fragile areas. Its regional ecological and poverty issues are representative not only in China but also in the world [13,14]. The region faces multiple challenges, mainly including unfavorable natural conditions, such as insufficient natural endowment, harsh geographical environment, and the continuous deterioration of the ecological environment [15]. The mountainous karst terrain leads to a scarcity of arable land, which restricts economic development and, to some extent, exacerbates regional poverty issues. With the growth of the population, unreasonable land development and excessive cultivation have further deteriorated the land environment, resulting in a significant reduction in arable land area, as well as several serious ecological problems such as soil erosion and rocky desertification [16]. For the Southern Karst Region, which has scarce and barren land, relying on traditional food crop cultivation makes it difficult to effectively promote economic growth. Therefore, it is urgent to adopt new strategies and methods to adapt to local special conditions and promote sustainable economic development.

Idesia polycarpa, a deciduous tree species belonging to the Flacourtiaceae family, is known for its rapid growth and extensive root system. It is drought-tolerant and can thrive in poor soil conditions, effectively preventing soil erosion, and is commonly used as a pioneer plant in the ecological restoration of karst desertification areas [17]. Additionally, as a perennial woody non-edible oil crop, *Idesia polycarpa* is characterized by its high yield and quality, with potential outputs reaching 3000–4500 kg per hectare and a fruit production cycle that can last from 70 to 100 years [18]. Research indicates that the fruit flesh and seeds account for 62.3% and 37.6% of the fruit's weight, with oil contents of 37.22% and 24.29%, respectively [19]. Extracts from the fruit of *Idesia polycarpa* also have potential medicinal values, such as anti-obesity effects, and in the treatment and prevention of

hyperlipidemia and atherosclerosis [20]. Industrially, it can be used as a lubricant, emulsifier, drying agent, and material for biodiesel, showcasing significant ecological and multifaceted economic values [20,21]. The cultivation of *Idesia polycarpa* holds significant importance for mountainous areas where arable land is scarce, as it aids in transforming the structure of cultivation, developing characteristic industries, promoting new agricultural models, and achieving a virtuous cycle of economic development and ecological conservation. The planting of *Idesia polycarpa* not only supports regional development and karst desertification management but also plays a crucial role in ensuring national food and energy security. To better adapt to the needs of regional and industrial development, gaining an in-depth understanding of the distribution potential of *Idesia polycarpa* in these areas is valuable and necessary.

Currently, numerous species distribution prediction models have been widely applied to predict the suitable growing areas for crops, such as the Distributions of Major Animal Groups in Nature (DOMAIN) [22], the Generalized Additive Model (GAM) [23], the Generalized Linear Model (GLM) [24], and the Biomapper [25]. Among these, regression models, including generalized linear models and generalized additive models [26,27], can sometimes be challenging to use for analyzing habitat suitability because there are no species absence point coordinate data [28]. However, when the relationship between species distribution and related environmental conditions is complex, machine learning models, such as the Random Forest (RF) and Maximum Entropy (MaxEnt) models, are more flexible [29,30]. The MaxEnt model uses species distribution information and environmental variables to analyze and predict the potential suitable distribution of species. It requires only a small number of presence points and has stability and scalability due to the model's ability to use both continuous and discrete data simultaneously [31]. The RF model can effectively form models with a limited number of training data samples and is not sensitive to training data that contain outliers [32]. It also minimizes overfitting [33]. Therefore, this paper selects the MaxEnt and RF models, along with 19 bioclimatic data and karst topography distribution data, to explore the potential distribution patterns of *Idesia polycarpa* in the region, as well as whether there are extensive high-suitability areas for planting *Idesia polycarpa* in karst and contiguous impoverished mountainous areas. This study aims to explore whether there are extensive high-suitability cultivation areas in the karst regions and contiguous poverty-stricken areas and to provide more precise guidance for the land use of *Idesia polycarpa* cultivation. This will not only help optimize the allocation of land resources and improve cultivation efficiency but also has significant implications for ensuring national food and energy security. Furthermore, the findings of this study will also support ecological restoration and economic diversification in the region, promoting the achievement of regional sustainable development goals.

2. Materials and Methods

2.1. Study Area

This article focuses on the Southern Karst Region of China (97°21'–117°19' E, 20°13'–34°19' N) as the study area, which includes Yunnan, Guizhou, Sichuan, Chongqing, Hubei, Hunan, Guangxi, and Guangdong, totaling eight provinces and municipalities, with a total area of 1.94 million km². The region spans the three major steps of China's topography, with the terrain being high in the west and low in the east, encompassing several first-level geomorphological units such as the Western Sichuan Plateau, Yunnan–Guizhou Plateau, Hengduan Mountains, Sichuan Basin, Dongting Lake Plain, and the hills of Guangdong and Guangxi, presenting complex geomorphological conditions [34]. The climatic characteristics of these areas are equally diverse, including features of low-latitude climate, monsoon climate, and plateau mountain climate. The annual mean temperature varies significantly, ranging from −1 to 25 °C, with annual sunshine duration ranging from 900 to 2600 h and annual precipitation ranging from 500 to 2500 mm. It is also the region with the largest distribution area and the most complete types among the world's three major concentrated karst areas [16]. At the same time, this area is also a concentrated distribution area of contiguous poverty zones in China, facing severe poverty and ecological issues, as well

as a series of ecological and environmental problems such as desertification, soil erosion, and environmental pollution. The national contiguous special poverty areas, including the Wuling Mountain Region (WLMR), Wumeng Mountain Region (WMMR), Yunnan–Guizhou–Guangxi Karst Desertification Region (YGGKDR), Western Yunnan Border Mountain Region (WYBMR), Qinba Mountain Region (QBMR), Four Provinces Tibetan Region (FPTR), Dabie Mountain Region (DBMR), and Luoxiao Mountain Region (LXMR), are concentrated in this region, among which seven contiguous poverty areas overlap with the karst area (Figure 1) presented below.

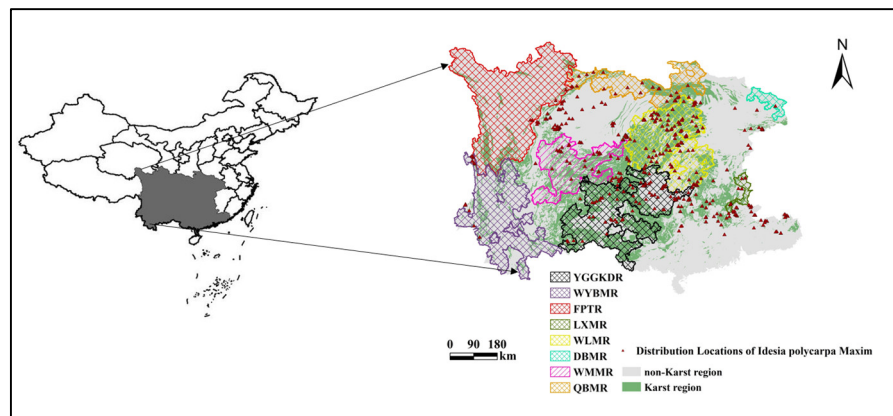


Figure 1. The study area of the Southern Karst Region of China. YGGKDR (Yunnan–Guizhou–Guangxi Karst Desertification Region), WYBMR (Western Yunnan Border Mountain Region), FPTR (Four Provinces Tibetan Region), LXMR (Luoxiao Mountain Region), WLMR (Wuling Mountain Region), DBMR (Dabie Mountain Region), WMMR (Wumeng Mountain Region), and QBMR (Qinba Mountain Region).

In the contiguous poverty-stricken areas of this region, the Wuling Mountain Region boasts a rich abundance of woody oil resources such as *Camellia oleifera*, *Swida wilsoniana*, *Carya cathayensis*, *Eucommia ulmoides*, *Paeonia suffruticosa*, *Zanthoxylum bungeanum*, *Triadica sebifera*, *Hovenia acerba*, and *Sloanea hemsleyana* [35]. Additionally, there is extensive cultivation of herbaceous oil crops, including *Arachis hypogaea*, *Brassica rapa*, *Glycine max*, and *Helianthus annuus*. The cultivation area of *Juglans regia* in the Wuling Mountain Region has been expanding continuously and has surpassed 13,000 hm² [36]. The Qinba Mountain Region serves as a transitional zone between subtropical and warm temperate zones, harboring abundant oil crop resources such as *Juglans regia*, *Vernicia fordii*, *Toxicodendron vernicifluum*, *Pistacia chinensis*, *Trachycarpus fortunei*, and *Idesia polycarpa* [37]. Moreover, the Qinba Mountain Region is one of the main *Juglans regia* production bases in China, with the *Juglans regia* planting industry serving as the leading economic sector, directly impacting poverty alleviation efforts in the region [38]. In the Dabie Mountain Region, oil crops mainly include *Camellia oleifera*, *Carya cathayensis*, *Arachis hypogaea*, and *Triadica sebifera*. Additionally, the Dabie Mountain Region (Hubei Region) is one of the important planting areas for *Triadica sebifera* [39]. The local *Camellia oleifera* industry in the Dabie Mountain Region is one of the characteristic industries driving poverty alleviation efforts in concentrated contiguous areas of extreme poverty. In the Luoxiao Mountain, Wumeng Mountain, border areas of western Yunnan, rocky desertification areas of Yunnan–Guizhou–Guangxi, and Tibetan Areas in Four Provinces, which encompass five contiguous poverty-stricken areas, *Brassica rapa* and *Arachis hypogaea* are the main oil crops cultivated. These oil crops all have distinct regional characteristics, but they do not meet the potential demand for biofuel feedstock at the national level.

2.2. Compilation of Occurrence Data

In this study, 544 distribution data of the species of *Idesia polycarpa* were obtained from the Chinese Virtual Herbarium (CVH, <https://www.cvh.ac.cn> accessed on 1 June 2023), the China Specimen Sharing Platform (CSSP, <http://www.nsii.org.cn> accessed on 15

July 2023), and the Global Biodiversity Information Facility (GBIF, <https://www.gbif.org> accessed on 16 October 2023). Duplicate sample points were removed, and to better explore the species distribution patterns at the meso-scale geographical spatial scale, the spatially autocorrelated 10 km species distribution points were removed using a tool pack SDM 10.2 of ArcGIS 10.2. Ultimately, 239 species distribution data were obtained. Subsequently, these data were transformed into comma-separated values (CSV) files for modeling and analysis.

2.3. Selection and Preprocessing of Environmental Variables

Biological climate variables are crucial for determining the environmental and ecological niche of a species. In conjunction with this study's exploration of species distribution patterns at a medium geographical spatial scale, 19 bioclimatic data with a spatial resolution of approximately 1 km were selected from the WorldClim database (<https://worldclim.org> accessed on 15 September 2023) as environmental variables. Additionally, to explore whether karst areas are more suitable for the growth of *Idesia polycarpa*, karst distribution data were included as an environmental variable, obtained from the Institute of Geochemistry, Chinese Academy of Sciences (<http://www.karstdata.cn/index.aspx> accessed on 18 September 2020), totaling 20 environmental variables (Table 1). The study area's vector layers were obtained from the National Fundamental Geographic Information System database (<http://nfgis.nsdi.gov.cn> accessed on 13 September 2023), and the required range of environmental variable data were extracted using ArcGIS 10.2 with a mask. Since multicollinearity between variables can lead to overfitting in distribution prediction models, principal component analysis and Spearman correlation analysis were used. Principal component analysis and Spearman correlation analysis were conducted using R 4.3.1 software to determine the contribution rates and correlations (Figure 2) among environmental variables. Variables with a correlation less than 0.8 were directly retained, while for those with a correlation greater than 0.8, the variable with the greatest contribution rate was retained [40]. This approach aimed to simplify the model and reduce the impact of multicollinearity, preventing overfitting of the model. After testing for multicollinearity, 7 environmental variables were ultimately determined for model construction (Table 2). For model calculation convenience, karst distribution data are coded with 0 for no presence and 1 for presence.

Table 1. Environmental variables.

Variable	Description	Unit
bio1	Annual mean temperature	°C
bio2	Mean diurnal range (mean of monthly (max – min temp))	°C
bio3	Isothermality (Bio2/Bio7) (×100)	-
bio4	Temperature seasonality (standard deviation ×100)	-
bio5	Maximum temperature of the warmest month	°C
bio6	Minimum temperature of the coldest month	°C
bio7	Temperature annual range (Bio5–Bio6)	°C
bio8	Mean temperature of the wettest quarter	°C
bio9	Mean temperature of the driest quarter	°C
bio10	Mean temperature of the warmest quarter	°C
bio11	Mean temperature of the coldest quarter	°C
bio12	Annual precipitation	mm
bio13	Precipitation of the wettest month	mm
bio14	Precipitation of the driest month	mm
bio15	Precipitation seasonality (coefficient of variation)	-
bio16	Precipitation of the wettest quarter	mm
bio17	Precipitation of the driest quarter	mm
bio18	Precipitation of the warmest quarter	mm
bio19	Precipitation of the coldest quarter	mm
karst	Karst distribution	-

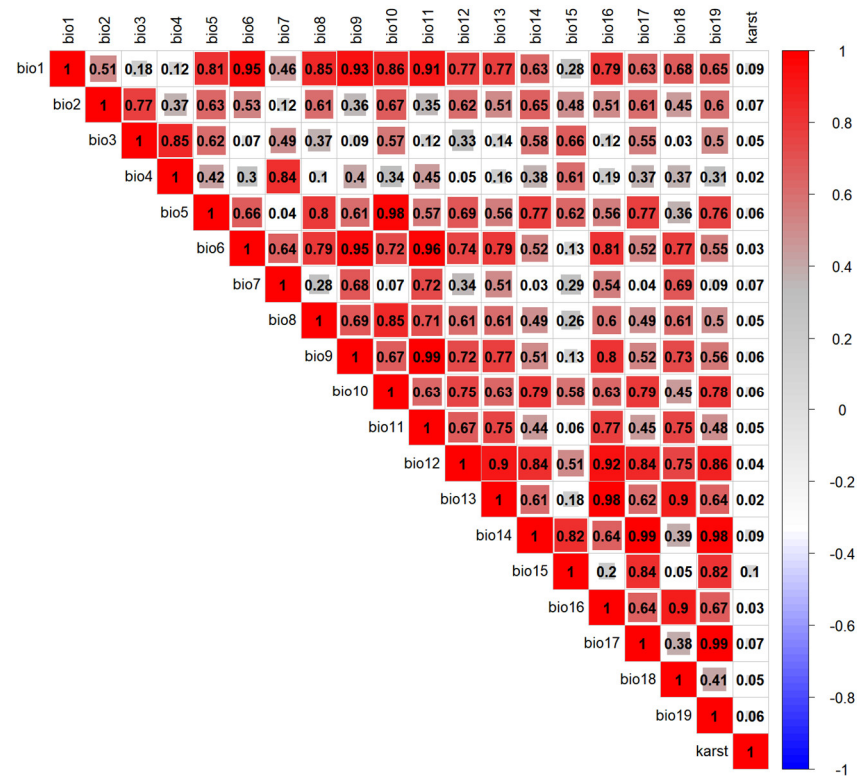


Figure 2. Heatmap of the correlation analysis between environmental variables.

Table 2. Environmental variable multicollinearity test.

	karst	bio15	bio18	bio2	bio3	bio5
bio15	0.10					
bio18	0.05	0.05				
bio2	0.07	0.48	0.45			
bio3	0.05	0.66	0.03	0.77		
bio5	0.06	0.62	0.36	0.63	0.62	
bio8	0.05	0.26	0.61	0.61	0.37	0.80

2.4. Establishment of Models

First, the CSV file of the distribution data for *Idesia polycarpa* and the ASCII files of the 8 pre-selected environmental variables were imported into the MaxEnt software (version 3.4.1). The software was set to randomly select 75% of the points for model building and 25% for model validation, with a maximum number of iterations set to 1000 [41,42]. To reduce the uncertainty of the MaxEnt model, 10 repeated cross-validation runs were conducted to build the model, and the average of the 10 repetitions was selected as the final predictive outcome [43].

In this study, the obtained species distribution data were retained, and pseudo-absence data were created, as the RF model requires both presence and absence data. However, the number and method of creating pseudo-absence data greatly affect the accuracy of the RF model [44]. Therefore, a geographical distance method was used to create 1000 pseudo-absence data, employing the “dismo” package in R [45]. We constructed the RF model using a 10-fold cross-validation method, setting the number of trees to 500, the number of variables at each split to 3 ($p = 3$, where p is the number of variables), and the minimum size of terminal nodes to 5 [43,45]. The dataset was randomly divided into ten equal subsets, with the model trained on nine subsets and validated on the remaining subset. We created 10 RF models and obtained the final results by averaging the models.

2.5. Model Accuracy Assessment

The area under the Receiver Operating Characteristic (ROC) curve, known as the Area Under the Curve (AUC), serves as an indicator of the predictive performance of species distribution models. The AUC values obtained from the training and evaluation datasets are referred to as training AUC and testing AUC, respectively. There are five levels of model evaluation indices: when $0.50 \leq \text{AUC} < 0.60$, the prediction is considered a “failure”; when $0.60 \leq \text{AUC} < 0.70$, it is “poor”; when $0.70 \leq \text{AUC} < 0.80$, it is “fair”; when $0.80 \leq \text{AUC} < 0.90$, it is “good”; and when $0.90 \leq \text{AUC} < 1.00$, it is “excellent” [40].

2.6. Suitable Area Classification

We converted the ASCII files of species’ predicted distribution probabilities into raster format files and successfully imported them into ArcGIS 10.2 software. Using the natural breaks method, the potential suitable distribution of *Idesia polycarpa* was divided into four levels based on the percentage: unsuitable areas (0~5%), low-suitability areas (5~33%), medium-suitability areas (33~67%), and high-suitability areas (67~100%) [46]. Then, using ArcGIS 10.2, the overall potential suitability distribution of *Idesia polycarpa* in the Southern Karst Region of China, as well as in impoverished mountainous areas and karst regions, was calculated.

3. Results

3.1. Model Accuracy

The MaxEnt model has an average AUC of 0.82 (Figure 3a). In contrast, the RF model has an average AUC of 0.76 (Figure 3b). According to the evaluation criteria, the overall predictive accuracy of the MaxEnt model has reached a good level, while the predictive accuracy of the Random Forest algorithm is fair. Therefore, we choose the results of the MaxEnt model for further analysis.

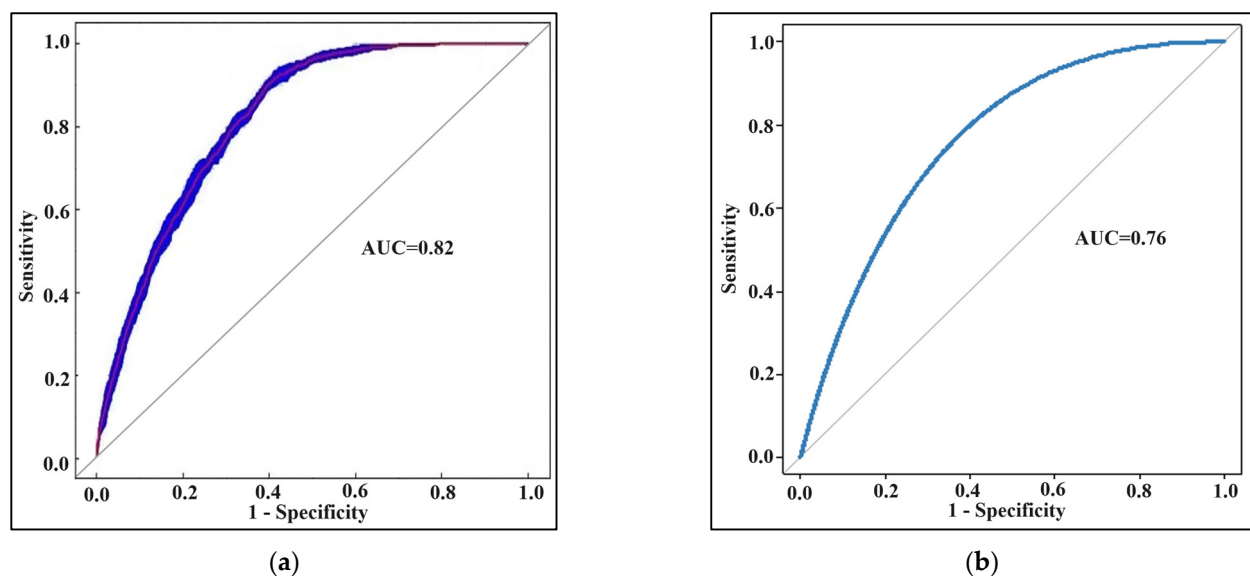


Figure 3. Accuracy of species distribution model forecasts: (a) Maximum Entropy model; (b) Random Forest model.

3.2. Distribution Patterns of Suitable Areas in the Karst Region of Southern China

This study reveals significant spatial differences in the potential suitable area distribution of *Idesia polycarpa* in the karst region of Southern China. The unsuitable areas for *Idesia polycarpa* are mainly distributed in the western part of Sichuan Province, the southern coastal areas of Guangdong Province, and some central parts of Yunnan Province; the low-suitability areas mainly include most parts of Yunnan Province, the central part of Sichuan Province, the southern part of Guangxi Province, the central part of Guangdong,

and some central and eastern parts of Hubei and Hunan Provinces; the medium-suitability areas are mainly distributed in most parts of Guizhou Province, the eastern part of Sichuan Province, the central part of Guangdong Province, and some parts of Yunnan and Guangxi, as well as some parts of Hunan and Hubei Provinces; the high-suitability areas are mainly distributed in the eastern part of Chongqing City, the western parts of Hubei and Hunan Provinces, and also include some parts of the northern Guangdong and Guangxi, and the central part of Sichuan Province (Figure 4a). Among them, the unsuitable area accounts for the largest proportion in Sichuan Province, 43.6% of the total area of the province, followed by Guangdong, Yunnan, and Guangxi Provinces, with other provinces having less distribution. The low-suitability area accounts for the largest proportion in Yunnan Province, 69.8% of the total distribution area of the province, followed by Guangxi, Hubei, and Hunan Provinces at 49.5%, 39.0%, and 34.8%, respectively, with other provinces having a smaller proportion. The medium-suitability area accounts for the largest proportion in Guizhou Province at 69.7%, followed by Chongqing City and Hunan Province at 41.9% and 32.4%, respectively, while Hubei, Guangxi, and Guangdong account for about 20%, and the other two provinces account for less. The high-suitability area accounts for the largest proportion in Chongqing and Guizhou, Hubei, and Hunan Provinces, with 38.9% of the total area of Chongqing City being high-suitability areas, followed by Hunan and Guizhou with high-suitability area proportions of 32.9% and 25.1%, respectively, and other provinces all account for less than 25% (Figure 4b). In addition, by subdividing the karst and non-karst areas and calculating the proportion of suitable areas at all levels, it was found that the proportion of medium and high-suitability areas in the karst area is higher than that in the non-karst area, especially the proportion of high-suitability areas, which exceeds 10%; while the proportion of unsuitable areas in the non-karst area is much greater than that in the karst area, with an area of 107,502.31 km² (Figure 5).

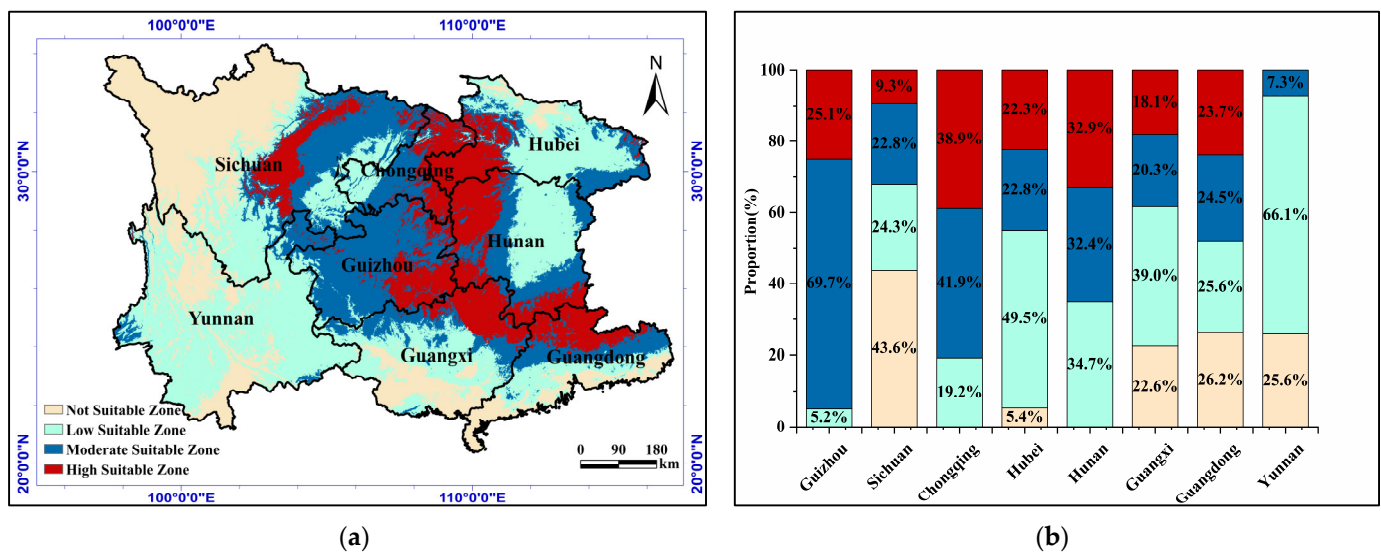


Figure 4. Spatial distribution and provincial proportion of suitable areas for *Idesia polycarpa* in the Southern China Karst Region: (a) spatial distribution of suitable areas for *Idesia polycarpa* in the Southern China Karst Region; (b) proportion of suitable areas for *Idesia polycarpa* in each province of the Southern China Karst Region.

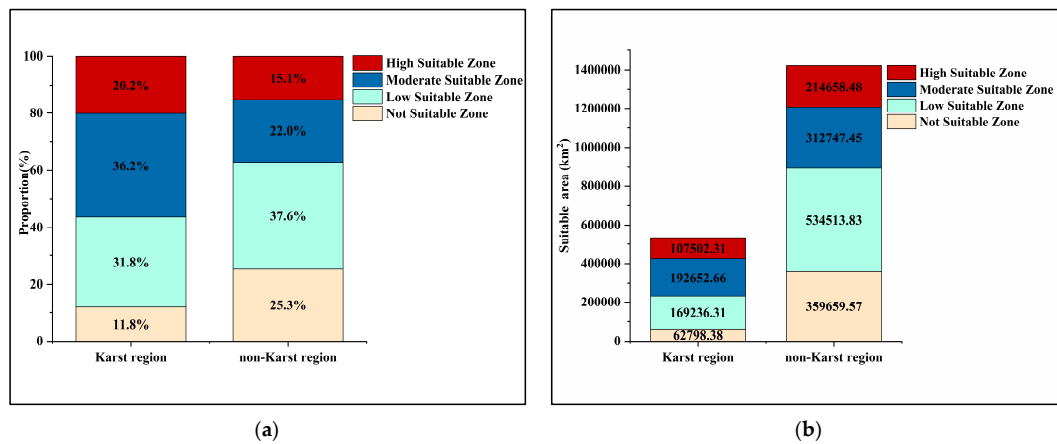


Figure 5. The proportion and area of suitable areas of karst and non-karst in karst areas of Southern China: (a) proportion of suitable areas of karst and non-karst at all levels; (b) karst and non-karst suitable area of each grade.

3.3. Proportion of Suitable Areas in Impoverished Regions

Of the eight contiguous impoverished areas of the region, four have a large proportion of high-suitability areas for *Idesia polycarpa* (Figure 6a). Among them, the Wuling Mountain area has the largest proportion of high-suitability areas, reaching 59.7%, followed by the Luoxiao Mountain area (Hunan section) with a significant proportion of high-suitability areas at 50.7%; in the Qinba Mountain area (Shaanxi, Chongqing section), high-suitability areas are mainly distributed in the central region, accounting for 30.3%; the high-suitability areas in the Yunnan–Guizhou–Guangxi Rock Desertification area are distributed in its northern part, accounting for 21.4%, while the other contiguous impoverished areas have a relatively smaller proportion of high-suitability areas. The medium-suitability areas have the largest distribution proportion in the Wumeng Mountain area, the Dabie Mountain area, and the Qinba Mountain area, accounting for 53.9%, 51.3%, and 48.8%, respectively. The low-suitability areas and unsuitable areas have a larger distribution proportion in the Western Yunnan Border Mountain area and the Four Provinces Tibetan area, at 64.2% and 83.2%, respectively (Figure 6b).

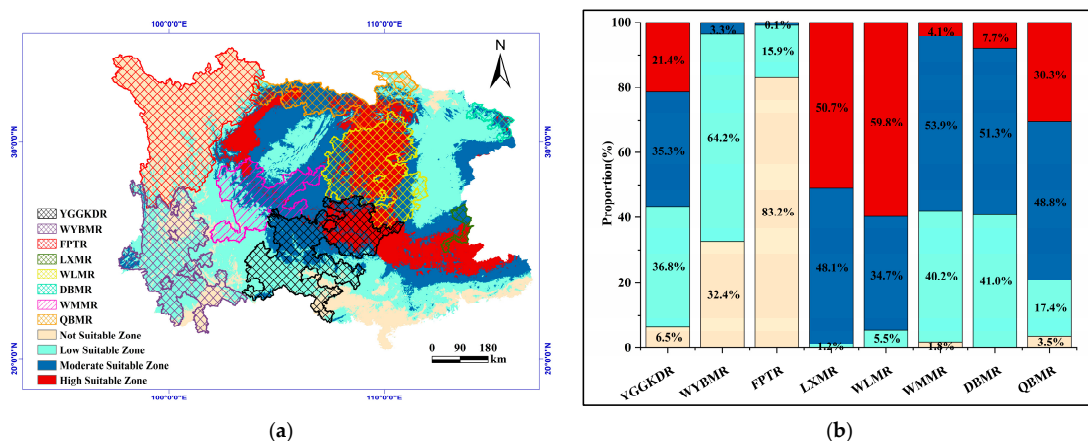


Figure 6. The distribution and proportion of suitable areas of each grade in contiguous poverty-stricken areas: (a) distribution of suitable areas of each grade in contiguous poverty-stricken areas; (b) proportion of suitable areas of each grade in contiguous poverty-stricken areas. YGGKDR (Yunnan–Guizhou–Guangxi Karst Desertification Region), WYBMR (Western Yunnan Border Mountain Region), FPTR (Four Provinces Tibetan Region), LXMR (Luoxiao Mountain Region), WLMR (Wuling Mountain Region), DBMR (Dabie Mountain Region), WMMR (Wumeng Mountain Region), and QBMR (Qinba Mountain Region).

4. Discussion

4.1. Spatial Distribution of *Idesia polycarpa* Suitability in Southern China's Karst Region

This study reveals that the potential suitable areas for *Idesia polycarpa* exhibit significant spatial differences in the Southern Karst Region, with high-suitability areas mainly distributed in the Sichuan Basin, Dabashan, Wuling Mountains, Miao Mountains, and the mountainous areas east of the Yunnan–Guizhou Plateau. In contrast, the unsuitable areas are primarily located in the eastern plateau and mountainous climate zones of Sichuan Province, as well as the southern regions of Guangdong, Guangxi, and Yunnan provinces (Figure 4). This distribution is largely consistent with the range of wild *Idesia polycarpa*, which is mainly found in subtropical climates at altitudes of 500 to 2000 m [17]. Temperature is extremely important for the distribution of *Idesia polycarpa*, as it has poor cold resistance, with the extreme minimum temperature for overwintering being between -8 to 10 °C, the most suitable extreme minimum temperature for overwintering being between -3 to 8 °C, and the suitable extreme maximum temperature for summer being 34 °C [47]. The high-altitude and high-temperature regions such as the eastern plateau and mountainous climate zone of Sichuan Province, the southern tropical monsoon climate zone of Yunnan Province, and the southern coastal areas of Guangdong and Guangxi are not conducive to the growth of *Idesia polycarpa*.

Furthermore, this study further explored the spatial differences in the potentially suitable areas of *Idesia polycarpa* between karst and non-karst areas, as well as contiguous poverty-stricken areas, finding that karst areas have a higher proportion of high-suitability areas compared to non-karst areas (Figure 5). This is because *Idesia polycarpa* grows well in slightly acidic, neutral, and slightly alkaline soils with a pH of 6.5 to 7.5 [17]. In contrast, the non-karst areas have more acidic soils, such as red soil, yellow soil, and brown soil. Moreover, the four contiguous poverty-stricken areas within this region, such as the Wuling Mountain area and the Wumeng Mountain area, contain a large number of highly suitable areas (Figure 6b).

4.2. Sustainable Development through *Idesia polycarpa*: Enhancing China's Food and Energy Security

The utilization of marginal land has garnered widespread global interest in enhancing food security and supporting the potential for bioenergy production [48,49]. This is a promising option for China, which faces a shortage of arable land and has a large population, to use marginal agricultural land for cultivating energy crops for biofuels, meeting biofuel demands without causing further shortages in food or environmental issues [50]. It plays an increasingly vital role in the improvement of the national energy structure.

Planting *Idesia polycarpa* on karst marginal land will first yield a direct outcome by providing raw materials for edible oil. Edible oil security is a significant component of China's food security; however, China's reliance on imported edible oil is alarmingly high at 67.7%, and for high-end edible oils, it reaches 95%, posing a severe threat to China's grain and oil safety [51]. As a novel woody oil-bearing tree species, *Idesia polycarpa* plays a crucial role in safeguarding national grain and oil security [52]. Compared to other woody oil crops, the processing cost of *Idesia polycarpa* edible oil is lower, and it offers competitive advantages in terms of price and quality as a bulk oil, potentially addressing China's over 60% dependency on imported edible oils [53]. Moreover, cultivating *Idesia polycarpa* on marginal land for the production of biodiesel not only provides a source of biofuel but also reduces the need for arable land, thereby indirectly ensuring food security. Planting non-food energy crops for energy purposes on marginal land offers a compromise to the competitive demands of traditional grain production on agricultural land [54], further aiding in the diversification of China's energy structure, decreasing reliance on energy imports, and securing the nation's energy supply. This study concludes that there are numerous medium to high-suitability areas for *Idesia polycarpa* cultivation in the southern karst regions of China, predominantly located in karst areas within each

province, confirming the feasibility of utilizing marginal land for *Idesia polycarpa* cultivation in this region (Figures 4 and 5b).

4.3. Ecological and Economic Synergies in the Southern Karst Region: The Role of *Idesia polycarpa* Cultivation

The ecological and economic conditions of the karst regions in Southern China are significantly affected by the fragility of their underlying environment, resulting in ecosystems with low resistance to disturbances and stability [55,56]. Coupled with a large population and scarce arable land, people have frequently resorted to deforestation and land reclamation to increase the amount of cultivable land. These activities not only continuously disrupt and damage the fragile karst ecosystem but also exacerbate ecological vulnerability, leading to a decline in land productivity [10]. These factors, when combined, severely restrict the coordinated development of population, resources, and the environmental economy in the region [55]. Moreover, a mutually reinforcing and constraining relationship has formed between regional environmental degradation and poverty. Poverty intensifies ecological deterioration, and in turn, ecological deterioration deepens poverty, creating a vicious cycle [54]. As a result, the region faces dual pressures of ecological restoration and economic development [57].

How to break the vicious cycle of poverty and ecological degradation has become a widely discussed and highly concerned issue [58]. In recent years, with the joint efforts of ecologists, geographers, and local people, and with the support of governments at all levels, a series of measures have been taken to prevent further degradation of the fragile karst environment [59]. These measures include selecting appropriate tree species for afforestation and developing suitable models to control desertification while also promoting the development of the local economy. However, the industrial structure in ecologically fragile areas has not yet been able to effectively reverse the trend of ecological deterioration, which poses a serious threat to sustainable development [58]. In the special karst environment, only crops with biological characteristics such as drought resistance and calcium preference, such as *Idesia polycarpa*, can grow healthily [60]. As a shallow-rooted plant, *Idesia polycarpa* has a strong adaptability to arid and barren karst soil and is often chosen as a pioneer tree species for desertification control [17]. It not only has multiple economic values but also a high ecological value, making it a suitable economic crop. This study further confirms that *Idesia polycarpa* has strong suitability in karst areas and contiguous poverty-stricken areas, as well as a wide range of highly suitable areas (Figure 5b).

This is of great significance for the Southern Karst Region, which is scarce in arable land resources, constrained by land, has a weak industrial base, and insufficient internal development momentum [61]. Planting *Idesia polycarpa* helps to develop efficient industries in mountainous areas, accelerate the adjustment of rural industrial structures, guide the transformation of traditional agriculture to economic fruit trees and animal husbandry, cultivate characteristic advantageous industries, and thus enhance the region's internal development momentum [28]. In addition, planting *Idesia polycarpa* also helps to promote comprehensive development in mountainous areas, coordinate the relationship between ecological construction and economic development, and promote the industrialization of industries and the industrialization of ecology. This can not only consolidate and expand the achievements of poverty alleviation but also establish a long-term mechanism for solving relative poverty, achieving a “win-win” goal of ecological optimization in desertified mountainous areas and helping rural areas to break away from relative poverty [14].

5. Conclusions

This study delineates the high-suitability zones for *Idesia polycarpa* cultivation within the karst regions of China's southern provinces, particularly highlighting areas that coincide with contiguous poverty-stricken zones. The identified areas present a substantial potential for cultivation that surpasses current production zones, indicating a broader scope for the expansion of *Idesia polycarpa* as a non-food energy crop.

Idesia polycarpa demonstrates robust adaptability and resilience in harsh conditions, thriving in arid and infertile soils typical of karst landscapes. Its preference for slightly acidic to slightly alkaline soils aligns well with the environmental conditions of the targeted regions. The species' tolerance to a wide range of climatic conditions further underscores its suitability for cultivation in the karst areas.

The cultivation of *Idesia polycarpa* is not only ecologically beneficial for restoring the fragile karst ecosystem but also economically advantageous for local communities. It fosters the development of efficient industries in mountainous regions, accelerates the transformation of rural economies, and supports the transition from traditional agriculture to more lucrative economic fruit tree cultivation and animal husbandry. This shift aids in establishing a sustainable cycle of economic development and ecological conservation.

Moreover, the expansion of *Idesia polycarpa* cultivation in marginal lands can contribute significantly to China's biofuel industry, offering a sustainable alternative to traditional energy sources. It aligns with the national strategy for energy diversification and rural revitalization, thereby supporting the country's food and energy security while promoting regional sustainable development.

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