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Predicting Ecologically Suitable Areas of Cotton Cultivation Using the MaxEnt Model in Xinjiang, China

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Abstract: Cultivating cotton and sustaining its productivity are challenging in temperate arid regions around the globe. Exploring suitable cotton cultivation areas to improve productivity in such climatic regions is essential. Thus, this study explores the ecologically suitable areas for cotton cultivation using the MaxEnt model, having 375 distribution points of long-staple cotton and various factors, including 19 climatic factors, 2 terrain factors, and 6 soil factors in Xinjiang. The area under the curve (AUC) of the predicted results was greater than 0.9, indicating that the model's predictions had fairly high accuracy. However, the main environmental factors that affected the cotton's growth were the lowest temperature in the coldest month, the hottest month, the precipitation in the driest season, and the monthly average temperature difference. Further, the temperature factors contributed 71%, while the contribution ratio of terrain and soil factors was only 22%. The research indicated that the current planting area was consistent with the predicted area in many areas of the study. Still, some areas, such as the Turpan region northwest of Bayingolin Mongol Autonomous Prefecture, are supposed to be suitable for planting cotton, but it is not planted. The current potential distribution area of long-staple cotton is mainly located in Aksu Prefecture and the northern part of the Kashgar Prefecture region. The climatic prediction shows that the growing area of long-staple cotton may expand to southern Altay, central Aksu, and Bortala Mongol Autonomous Prefecture. This study will be helpful for cotton cultivation suitability areas in Xinjiang and other regions with similar environments.

Keywords: Xinjiang; long-staple cotton; MaxEnt model; potential distribution area; distribution coordination

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Citation: Li, L.; Wu, H.; Gao, Y.; Zhang, S. Predicting Ecologically Suitable Areas of Cotton Cultivation Using the MaxEnt Model in Xinjiang, China. *Ecologies* **2023**, *4*, 654–670. https://doi.org/10.3390/ecologies4040043

Academic Editor: José Ramón Arévalo Sierra

Received: 18 August 2023
Revised: 26 September 2023
Accepted: 30 September 2023
Published: 5 October 2023

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1. Introduction

Long-staple cotton is hybrid cotton, the best quality cotton fiber varieties in the world [1,2], and the world's best tetraploid cultivated cotton [3–6]. Its quality is essential and prominent in industrial production applications due to its soft, long fibers and kidney bean shape.

In terms of structure, the fiber is 90% cellulose, having primary and secondary walls and a lumen. Moreover, the cuticle comprises wax, proteins, and pectin. Thus, these structural components profoundly impact the fiber's production, processing, and storage performance. Hence, this cotton can be very suitable for the clothing industry as a raw material and has significant advantages in terms of comfort and durability [7]. Long-staple cotton is in high demand in the global market, and China is a major country in the clothing manufacturing industry [7,8]. Thus, an urgent agenda includes improving cotton's quality and economic benefits and sustainably developing the cotton industry according to local conditions. As China's most important long-staple cotton-producing zone, Xinjiang dominates the primary market for Chinese cotton.

It even influences China's international position regarding the long-staple cotton market [9]. The cotton variety grown in Xinjiang is mostly long-staple cotton [10,11].

Reviewing the past, it has been cultivated successfully in Central Asia for 70 years, since 1953, among more than 70 varieties. Although the quality of Xinjiang long-staple cotton is currently in the forefront worldwide, its yield shows a continuous upward tendency. Most of China's long-staple cotton is planted in Xinjiang. According to statistics, its output accounts for more than 95% of the country's total output. Therefore, it is necessary to improve the quality and economic benefits of long-staple cotton and to continuously develop it according to the local conditions in Xinjiang.

In recent years, global warming has become a major concern. According to the United Nations Intergovernmental Panel on Climate Change [12], the global temperature is still rising at a certain rate. China is vulnerable to global climate change, particularly in northwest China, where global warming is more visible in some areas, and global warming may increase the frequency of extreme events [12,13]. Xinjiang, a region situated in northwest China, exhibits a high degree of vulnerability to the impacts of global climate change [13]. This susceptibility is manifest in the potential alteration of cultivated regions and the potential migration of suitable areas as a consequence of global warming [11]. Numerous crops in the region of Xinjiang have experienced adverse consequences attributable to the phenomenon of global warming, with cotton cultivation being among the affected agricultural activities. Furthermore, the long-staple cotton cultivation in Xinjiang has significant impacts, leading to notable alterations in its suitable geographic region. Hence, the phenomenon of climate change has the potential to induce alterations in the cultivation and yield of long-staple cotton. Simultaneously, cotton productivity has been influenced by irrigation, insect pests, and diseases. Numerous scholarly investigations have been conducted to assess the effects of climate change on the cultivation of cotton [14,15]. The cultivation conditions for long-staple cotton in Xinjiang have undergone alterations, resulting in certain planting regions experiencing an unsuitable climate environment for cultivating long-staple cotton crops [3]. Hence, it is imperative to undertake future research on the impact of climate change on the viability of cotton cultivation in order to inform strategic planning for the cultivation of cotton.

Many scholars have conducted similar studies in the early stage and found through the query of data [14,15] that the distribution of crop suitability has been studied using multiple models concerning the advantages of low cost, high efficiency, and ease of control. However, studying suitable geographical locations and the unique climatic characteristics with the help of the MaxEnt model and Species Distribution Modeling (SDM) tools has not been explored clearly. Therefore, this study utilized SDM [16] to simulate the species' geographical distribution based on known distribution data and influencing environmental factors [17–19], which can predict the species distribution range and shift to climate change in the present and future. Thus, we used the MaxEnt model (designed with the Java language) and the ArcGIS (version 10.8) tool for data classification processing and analysis [20] to examine the factors that affect cotton growth and analyze the suitable distribution areas for Xinjiang long-staple cotton as well as the potential distribution zone under various future climates [21].

Xinjiang has 95% of China's long-staple cotton production. The importance of Xinjiang long-staple cotton in China is self-evident; Xinjiang cotton has achieved satisfactory results due to the area's unique climate and environmental factors. But there are also some limiting factors, such as limited water resources, temperature, and rainfall, which affect the growth of cotton [5,22,23]. Low temperatures may cause long- and short-stape cotton's slow growth and development. Further, high temperatures may also affect the volume of cotton bolls and the number of cotton seeds. Similarly, water is another important factor affecting the long and short cotton. If water is insufficient, it may affect the photosynthesis and yield of long- and short-staple cotton. The topography of the planting area may affect the water absorption. The temperature and water demand of long- and short-staple cotton differ for different stages, requiring the selection of climate factors when comprehensively determining the influencing factors. Therefore, maintaining the unique and valuable industry of long-staple cotton, maximizing the regional advantages of Xinjiang, and ensuring the sustainable and stable development of cotton production are urgent problems that we need to solve. This study predicts the suitable planting area and future development trend of long-staple cotton through multiple models closely related to the quality and yield of long-staple cotton. First, we explored the influence of climate, topography, and soil factors on long-staple cotton in Xinjiang and determined the larger environmental factors affecting long-staple cotton in order to assess the extent to which the distribution of long-staple cotton in Xinjiang aligns with the optimal conditions for maximizing benefits and promoting its sustainable development. Finally, future climate data from the three scenarios were used to determine the expansion direction of a suitable habitat under future climate conditions and the average expansion distance of suitable areas for long-staple cotton in Xinjiang by 2070, which will help prepare for the changes in long-staple cotton.

2. Data and Methods

2.1. Study Area

Xinjiang (73°40′–96°18′ E, 34°25′–48°10′ N) is located on the northwest border of China and lies in the hinterland of Eurasia. It is surrounded by "three mountains (the northernmost part of Xinjiang is the Mount Altai, the southernmost part is the Kunlun Mountain, and the Tianshan Mountain lies across the middle part of Xinjiang, dividing Xinjiang into north and south parts) accompanied by two basins". Xinjiang has a typical temperate continental arid climate with sparse precipitation, high evaporation, extremely uneven spatiotemporal distribution of water resources, and an average annual sunshine time of 2300–3200 h [24]. Thus, the duration of sunlight and the daily temperature difference create unique conditions for the growth of long-staple cotton.

2.2. Data Collection

2.2.1. Species Distribution Data

We searched Xinjiang long-staple cotton data through the Web of Science (WOS), China National Knowledge Infrastructure (CNKI), Google Academic, and databases such as the Global Biodiversity Information Facility (GBIF). Then we obtained 1026 accurate point data for cotton locations and put them into ArcGIS software. To prevent model overfitting caused by sampling bias, which may even reduce the predictive ability later on, we used the SDMtoolbox 2.4 in ArcGIS (version 10.8) [16] for the deviation correction method of system resampling based on the attributes of environmental variables. This method means that only a limited number of sites are kept within a certain distance. Buffer analysis was conducted for cotton samples with a radius of 20 km, and only one distribution point within the overlapping buffer zone was kept in ArcGIS. Therefore, the model overfitting matter could be effectively reduced, and 375 distribution point data were obtained through screening (Figure 1) [16,25].

2.2.2. Climatic and Environmental Variable Data

Planting patterns of long-staple cotton including low height, high density, and early sowing are interdependent and, when worked together, produce high yields [26]. Among them, low height refers to dwarfing cultivation; through dwarfing plants, the angle distribution of branches and leaves is reasonable, and photosynthesis is increased. High density refers to rational close planting, which may fully utilize light and heat resources during growth. Early sowing means that the sowing time for long-staple cotton in southern Xinjiang is in mid-April, while in northern Xinjiang, it is in late April. Before sowing, methods such as sun drying and seed soaking are used to promote the early germination of seeds. During field observations, it is likely that mulch film is used primarily to increase the soil temperature, promote the growth of long-staple cotton seedlings, and increase the soil moisture content. Therefore, this study simulated the multi-dimensional factors that affect the classification of cotton's suitable zone through climate, terrain, and soil factors.

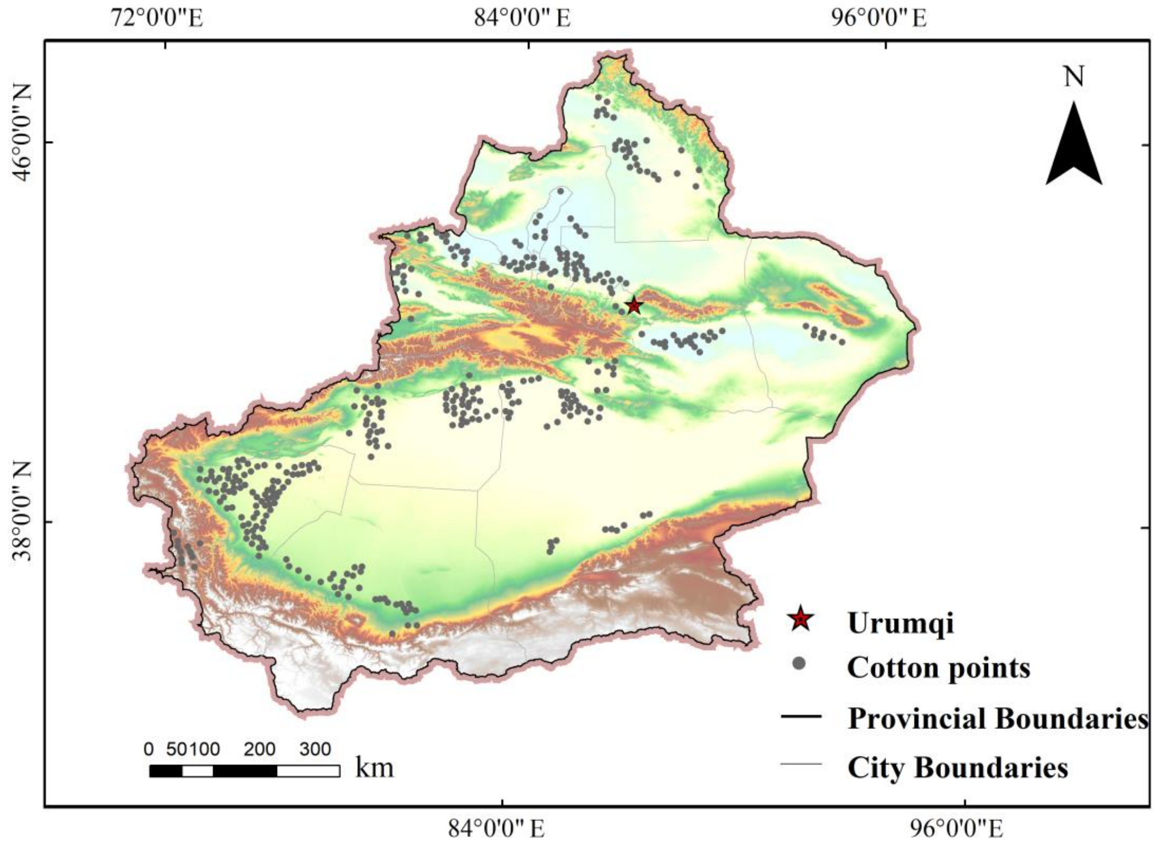

Figure 1. The study area. The study region and the distribution of long-staple cotton sample points (Points from GBIF, Web of Science, CNKI, and Google Scholar).

The administrative division map of Xinjiang came from the Resources and Environment Science and Data Center (http://www.resdc.cn/, 25 December 2022), and DEM data with 2.5 min resolution came from the geospatial data cloud (http://www.gscloud.cn/search, 25 December 2022). The data sets were merged, trimmed, processed (spatial analysis) in ArcGIS software to obtain the slope and aspect of this study area. This article's current and future climate data were downloaded from the WorldClim global climate database (https://www.worldclim.org, 25 December 2022). A total of 19 bioclimatic variables were included, with a selected spatial resolution of 1 KM and a coordinate system of GCS_WGS_1984 [27].

The data information about the "current" scenario mainly included data from 1950 to 2000, while the climate data for the "future" scenario was selected from data from 2061 to 2080 (around 2070s), using the Shared Socioeconomic Pathways (SSPs) including SSP126 data, SSP245 data, and SSP585 data provided by China's National Climate Center's BCC-CSM2-MR and CMIP 6 [27]. Among these data, SSP126 data represent the comprehensive impact of low radiative forcing, low vulnerability, and low mitigation pressure, and sustainable development is relatively slow, lower than the current trend. SSP245 data represent medium radiative forcing and medium social vulnerability, and global economic development maintains the current trend. The SSP585 data represent the future rapid growth of the global economy to energy-intensive labor and life and large-scale extraction of fossil fuels, which is higher than the current trend [28]. In addition, we also downloaded 11 soil factor data with a resolution of 2.5 min from the World Soil Database (https://www.fao.org/, 26 January 2023) (Table 1).

Table 1. Environmental Variables Selection.

	Variables	Description	Units
Climatic variables (19)	Bio1	Annual Mean temperature (°C)	°C
	Bio2	Mean Diurnal Range (Mean of monthly(Max temp–min temp)) (°C)	°C
	Bio3	Isothermality (Bio2/Bio7) (×100)	–
	Bio4	Temperature Seasonality (standard Deviation × 100) (Coefficient of Variation)	°C
	Bio5	Max Temperature of Warmest Month (°C)	°C
	Bio6	Min Temperature of Coldest Month (°C)	°C
	Bio7	Temperature Annual Range (Bio5–Bio6) (°C)	°C
	Bio8	Mean Temperature of Wettest Quarter (°C)	°C
	Bio9	Mean Temperature of Driest Quarter (°C)	°C
	Bio10	Mean Temperature of Warmest Quarter (°C)	°C
	Bio11	Mean Temperature of Coldest Quarter (°C)	°C
	Bio12	Annual Precipitation (mm)	mm
	Bio13	Precipitation of Wettest Month (mm)	mm
	Bio14	Precipitation of Driest Month (mm)	mm
	Bio15	Precipitation Seasonality (Coefficient of Variation)	–
	Bio16	Precipitation of Wettest Quarter (mm)	mm
	Bio17	Precipitation of Driest Quarter (mm)	mm
	Bio18	Precipitation of Warmest Quarter (mm)	mm
	Bio19	Precipitation of Coldest Quarter (mm)	mm
Terrain variables (2)	Asp	Aspect (°)	°
	Slo	Slope (%)	%
Soil variables (6)	T_PH	pH value	1
	T_OC	Organic carbon content (%)	%
	T_texture	Soil texture	code
	T_sand	Sand content (%wt.)	%wt.
	T_$CaCO_3$	Carbonate content (%wt.)	%
	T_ece_soil	Soil cation-exchange capacity (mmol/kg)	mmol/kg

2.3. Application and Evaluation of the MaxEnt Model

The MaxEnt model is an ecological niche model developed by Phillips, based on the maximum entropy principle and Java language, which is suitable for studying the known geographical distribution data and the potential distribution of species of environmental variables in the study area.

We loaded the processed species point, bioclimate, and terrain data into the MaxEnt model. Due to some correlation between environmental factors, we first imported all environmental factors into the MaxEnt model. Then during the calculation process, we set the training and testing dataset proportions to 75% and 25%, respectively, namely, a 3:1

ratio [29], with 10,000 iterations and 10 repetitions to eliminate randomness [30]. Moreover, jackknife resampling was used to measure the contribution of each influential factor toward the model, and a response curve characterized the relationship between variable factors and species suitability. Finally, results were output in the logistic format, operation results were consecutive values between 0 and 1, and the format for species distribution was ASCII. After that, a Pearson correlation analysis was performed on each environmental variable in order to effectively avoid factors with high correlation but low contribution [31–33]. Thus, the most relevant factors were chosen to compare their correlation and actual significance [34].

According to the model prediction results, the average AUC (area under the curve) value for the training set was 0.912 ± 0.002, while the AUC value for the test set was 0.900 ± 0.023 (Figure 2), which was significantly higher than the random prediction (0.5), indicating that the prediction accuracy was a good fit for the model [35].

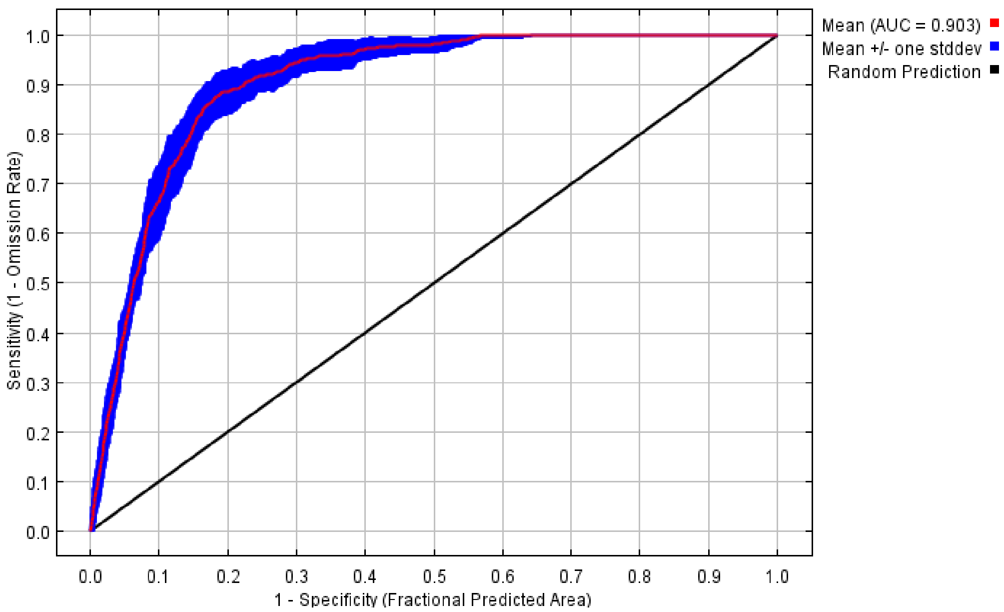

Figure 2. MaxEnt Results of the ROC curve accuracy test in the model.

Aiming at improving the differentiation and practicality of habitat-suitable areas, we imported the ASC file (output by MaxEnt) into ArcGIS software. We used "vector to raster" and "reclassification" tools to classify species' potentially suitable distribution areas. Utilizing the natural break method, the threshold standard for a suitable area was $p \geq 0.7$, and an area meeting the standard meant a highly suitable area, an area fitting $0.3 \leq p < 0.7$ conditions referred to a medium suitable area, a zone with $0.1 \leq p < 0.3$ settings was viewed as a low suitable area, and the remaining area ($p < 0.1$) was an unsuitable area [34,36].

2.4. The Migration Trend of the Suitable Region's Centroids

If the current period were the base period, we could predict the planting range of long-staple cotton during the 2070s period (from 2061 to 2080). We used SSP126, SSP245, and SSP585 data from the Shared Socioeconomic Paths (SSPs) provided by CMIP6, representing low, medium, and high greenhouse gas emission scenarios, respectively [37,38]. Later, ArcGIS was used to project, resample, crop, and reclassify the spatial data, with ASCII output data for backup.

We only chose climate data for the model running and projected the model into current and three different future climate conditions to obtain suitable distribution maps for cotton growth under current and future climate conditions (SSP126, SSP245, SSP585). This time, the sum of the maximum sensitivity and specificity was selected as the optimal threshold, and then the reclassification tool was used to convert the four newly generated probability distribution maps into binary maps for long-staple cotton, where "0" represents the unsuitable area and “1” denotes the suitable area. After that, the con function in the raster calculator was used to calculate the suitable climate area in the future. Distribution maps with grid values of 0, 1, 2, and 3 indicate that “0” represents no future or present fitting this cotton planting; “1” represents that it is currently suitable and not suitable for planting in the future, namely, the shrinking area disappears in the future; “2” shows that it is not suitable for planting in the future, that is, the expansion area; and “3” represents that it is suitable for planting in both the future and present, that is, the stable area.

Next, we used the ArcGIS zonal tool to process the raster data of each suitable area and obtained the centroids of each suitable distribution area under different climate change scenarios in the current period and the 2070s. The spatial displacement of the centroids was used to represent the distribution changes in the entire range of suitable areas for long-staple cotton. We explored the migration and changes in centroids in suitable grades and suitable regions in long-staple cotton under three climate scenarios: RCP 2.6, RCP 4.5, and RCP 8.5.

3. Results and Analysis

3.1. Assessment of the Importance of Environmental Variables

The importance of environmental factors on the potentially suitable distribution of species was evaluated from the contribution rate, 10-fold cross-validation, and replacement rate in the output results from MaxEnt software. In the establishment of the model, the variables that had significant impacts on the simulation prediction results were the lowest temperature in the coldest month (Bio6), the highest temperature in the hottest month (Bio5), the average monthly temperature difference (Bio2), the driest season precipitation (Bio17), sand content (T_sand), the coldest season precipitation (Bio19), organic carbon content (T_OC), carbonate content (T_$CaCO_3$), isotherm (Bio3), and soil cation-exchange capacity (T_cec_soil), contributing 19.9%, 13.8%, 8.5%, 8.4%, 7.2%, 6.4%, 4.6%, 4.1%, 3.6%, and 3.4%, respectively, with a cumulative contribution rate of 78.9% (Table 2).

Table 2. Contribution rates of influencing factors.

Variables	Contribution Percent (%)	Permutation Importance (%)
Bio6	19.9	0.8
Bio5	13.8	14.1
Bio2	8.5	13.7
Bio17	8.4	0.1
T_sand	7.2	17.8
Bio19	6.4	8.3
T_OC	4.6	1.6
T_$CaCO_3$	4.1	6.7
Bio3	3.6	4.2
T_cec_soil	3.4	4.8

When environmental factors were used separately, the sequence (according to the AUC values in descending order, Figure 3c) was the hottest month’s highest temperature (Bio5), coldest month’s lowest temperature (Bio6), warmest season’s average temperature (Bio10), monthly temperature difference (Bio2), carbonate content (T_$CaCO_3$), coldest season precipitation (Bio19), soil cation-exchange capacity (T_cec_soil), sand content (T_sand), isotherm (Bio3), driest season precipitation (Bio17), and organic carbon content (T_OC). The AUC plot showed Bio5 and Bio6 (about temperature) were the most influential single variables while predicting almost 0.75 in the AUC. Similarly, these two factors were prominent among the variables in regularized training gain (Figure 3b) and test gain (Figure 3a). However, in Figure 3b, Bio19 (precipitation of the coldest quarter) is in the third position. At the same time, T_$CaCO_3$ (carbonate content) also ranked third. Based on these factors, the soil might be neglected according to the training results (Figure 3b); actually, they were competitive regarding variables of precipitation based on the test results (Figure 3a).

We found that climate factors were prominent among these variables after comprehensive analysis; for instance, the most significant ones were the highest temperature in the hottest month (Bio5), the lowest temperature in the coldest month (Bio6), the coldest season precipitation (Bio19), and the average monthly temperature difference (Bio2). As can be easily seen, the growth of long-staple cotton is mainly related to temperature and precipitation. Thus, the cotton distribution in Xinjiang is consistent with the spatial distribution pattern of these two-factor conditions, namely, on the north and south sides of the Tianshan Mountains, the northern foot of the Kunlun Mountains' west part, and the southern foot of Altai Mountains. In southern Xinjiang, it is mainly distributed around the marginal of the Taklamakan Desert, extending from the foot of the mountain to the desert along the river.

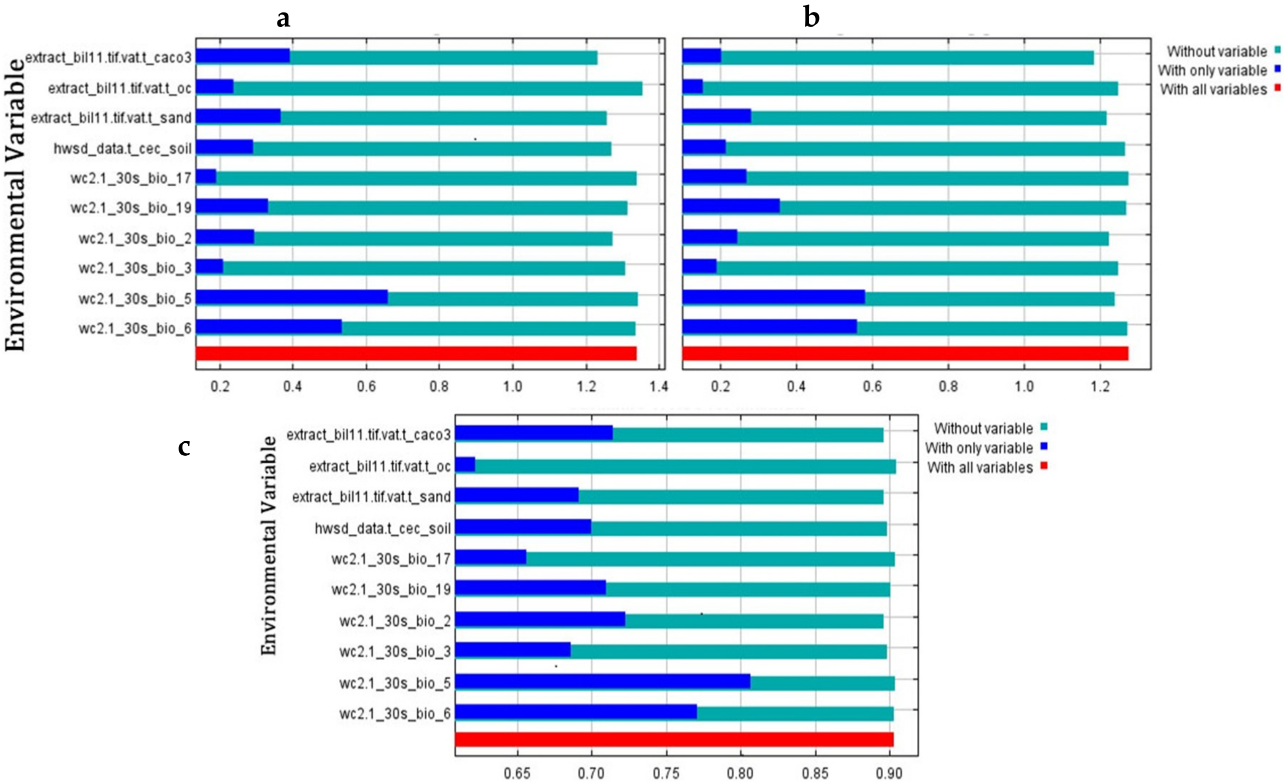

Figure 3. The jackknife plot for long-staple cotton. ((**a**) test gain, (**b**) regularized training gain, (**c**) AUC).

Four environmental factors that played a dominant role in potentially suitable distribution were selected in the study, and they had joint effects on each growth stage of cotton, ultimately reflecting the suitable growth of long-staple cotton in the study area (Figure 4).

When the monthly temperature difference (Bio 2) was lower than 9 °C, the probability of long-staple cotton was around 0.13; when the monthly temperature difference was greater than 9.6 °C and less than 15.7 °C, the probability was above 0.3 with a bimodal curve, first rising to 0.6 at 11 °C then decreasing to 0.3 at 12 °C. It next ascended again with a peak at 0.66, and after that the curve descended as the monthly temperature difference grew greater than 15 °C.

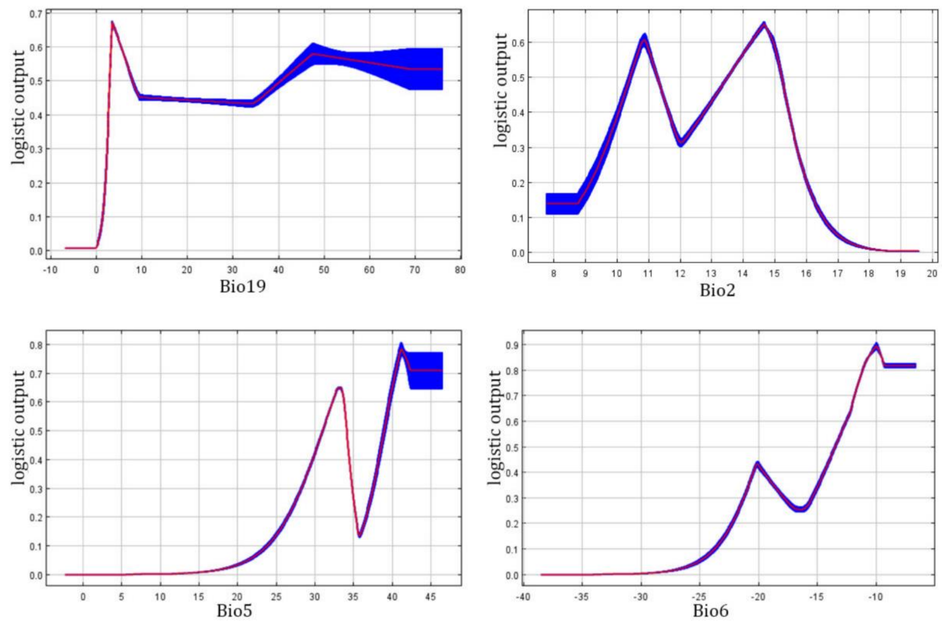

Figure 4. The response curves for variables Bio19, Bio2, Bio5, and Bio6. (The red line represents the curve trend, and the blue area represents the curve range).

When the lowest temperature in the coldest month (Bio 6) was less than −25 °C, the probability of existence was almost 0 and unsuitable for growth. When it was greater than −25 °C and less than −15 °C, the possibility of existence was slightly higher, under 0.5. The probability increased from 0.3 to 0.9 as the temperature rose from −15 °C to −10 °C; then, the probability of existence remained stable at 0.8 with a temperature higher than −10 °C. The same tendency also occurred for Bio5 (highest temperature in the hottest month); within a specific range, the probability rose as the variable value moved upwards. Then the probability dropped after a small peak but strongly reached another higher peak and remained still after.

If we emphasize the biological characteristics of long-staple cotton, we may find that it requires high temperatures during its growth. Moreover, long-staple cotton is a light-loving crop, and more than twelve hours of daily sunlight in specific periods is more conducive to its growth [14]. Luckily, the experimental results are in line with its physiological characteristics.

3.2. Potentially Suitable Distribution Areas under Current Climate Conditions

The prediction results of the MaxEnt model are shown in Figure 5, with a high suitability area of approximately 1.3×10^5 Km^2. In terms of southern Xinjiang, a highly suitable distribution area will be mainly on the edge of the Taklamakan Desert, and the northern part will be larger than the southern edge, corresponding to the administrative division, that is, north Kashgar, central and western Aksu Prefecture and central and eastern regions, northern Bayingolin Mongolian Autonomous Prefecture, central and western Hotan Prefecture. In addition, there are dotted distributions in Turpan and other places. Regarding Xinjiang north, areas will be concentrated at the northern foot of Tianshan Mountain, corresponding to the south of Tacheng Prefecture (part of Ili Kazakh Autonomous Prefecture), Yining City region, and the west of Changji Hui Autonomous Prefecture. The moderate suitable area will be approximately 1.9×10^5 Km^2, and the area of low-potential suitability will be about 0.4×10^5 Km^2, widely distributed in the Junggar Basin in the northern Xinjiang region. The southern Xinjiang region will remain around the edge of the Tarim Basin, located at the periphery of the high and moderate suitable areas.

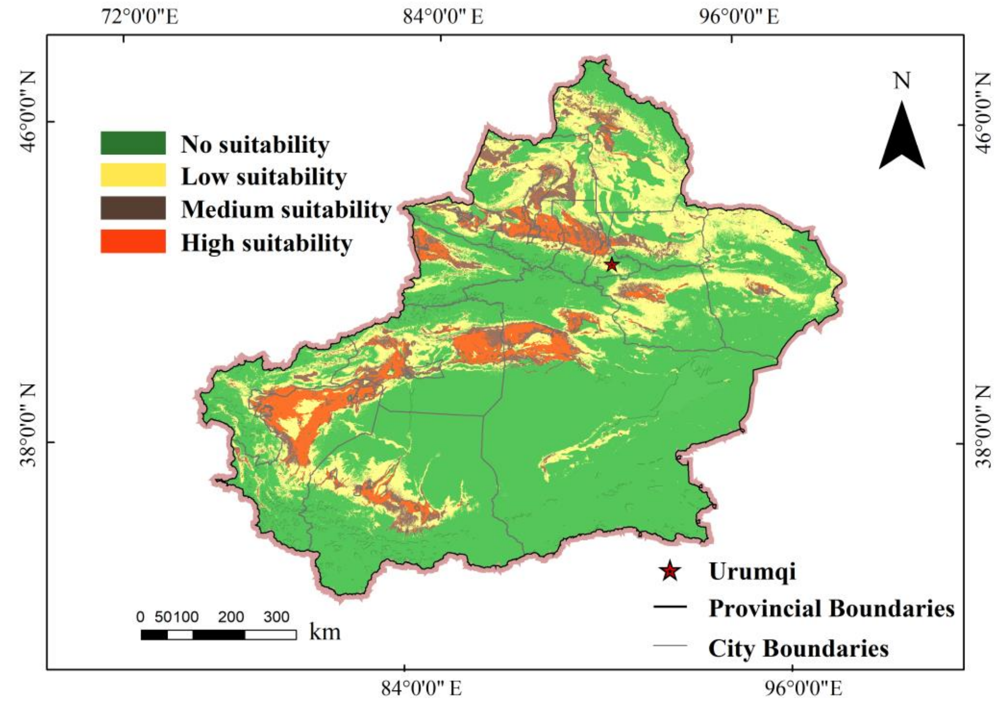

Figure 5. Distribution of suitable growth areas of long-staple cotton.

3.3. Suitable Distribution Areas and Changes in Future Climate Scenarios

According to the results in Figure 6, under the climate scenario of SSP126, the average temperature will increase by about 1.8 °C during the 2070s period, and the stable area of long-staple cotton will be 2.51×10^5 Km^2. This area is and will be suitable as a growing region, and the vanishing area will be about 0.38×10^5 Km^2, while the expansion area will reach 0.53×10^5 Km^2. In general, the suitable planting area of cotton is expanding, with the total area increasing by 5.8%.

Under the climate scenario of SSP245, during the 2070s period, the average temperature will increase by about 2.7 °C, and the stable area will be 2.51×10^5 Km^2, with an area of about 0.38×10^5 Km^2. The expansion area will reach 0.62×10^5 Km^2; thus, the suitable planting area is expanding, with the total area increasing by 9.4%.

Under the climate scenario of SSP585, the average temperature will increase by about 4.4 °C in the 2070s, and the stable area will be 2.45×10^5 Km^2, with an area of about 0.45×10^5 Km^2. In contrast, the expansion area will reach 0.63×10^5 Km^2, and the planting area of the suitable area is expanding, with the total area increasing by 7.3%.

The trend of suitable areas under the three climate scenarios simulation was consistent, with the expansion area significantly larger than the disappearing area, which is consistent with the biological characteristics of long-staple cotton. In the future, the average temperature will increase to some extent, and long-staple cotton is a species that likes light and warmth; thus, the temperature change can promote some areas previously limited by temperature to be newly suitable. For example, as shown in the three subplots b, c, and d of Figure 6, the central part of Altay Prefecture, the central part of Aksu Prefecture, Holtan Prefecture, and other local areas changed from the original unsuitable growing region to suitable areas.

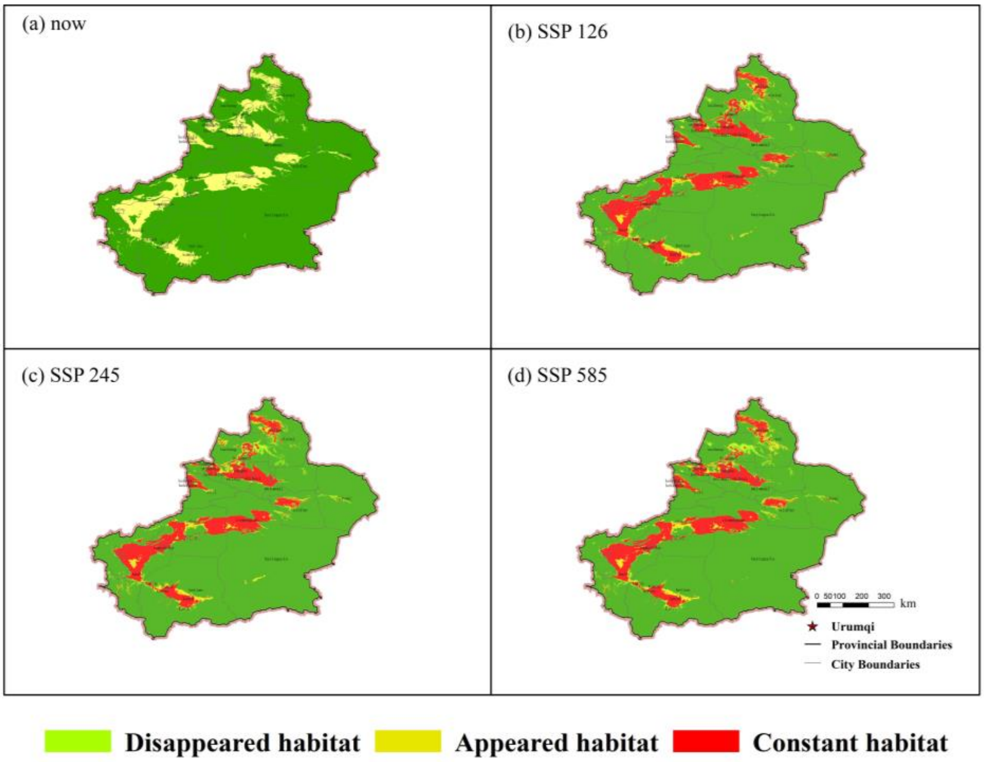

Figure 6. Transformation map of the 2070s under different climate scenarios. ((**a**) now, (**b**) SSP 126, (**c**) SSP 245 (**d**) SSP585).

According to the calculation results of ArcGIS's zonal tool, it was found that the centroids of the suitable areas did move to some extent under the three climate models. In the 2070s, the center point of the suitable area for long-staple cotton will migrate to the northeast at a straight distance of 147 km, while the center point of the suitable area will find its way to the southwest at a straight distance of 48 km. The center point of the low suitable area will migrate to the northwest at a straight distance of 29 km. The center point of the unsuitable area will move in the northwest direction by nearly 294 km (Figure 7).

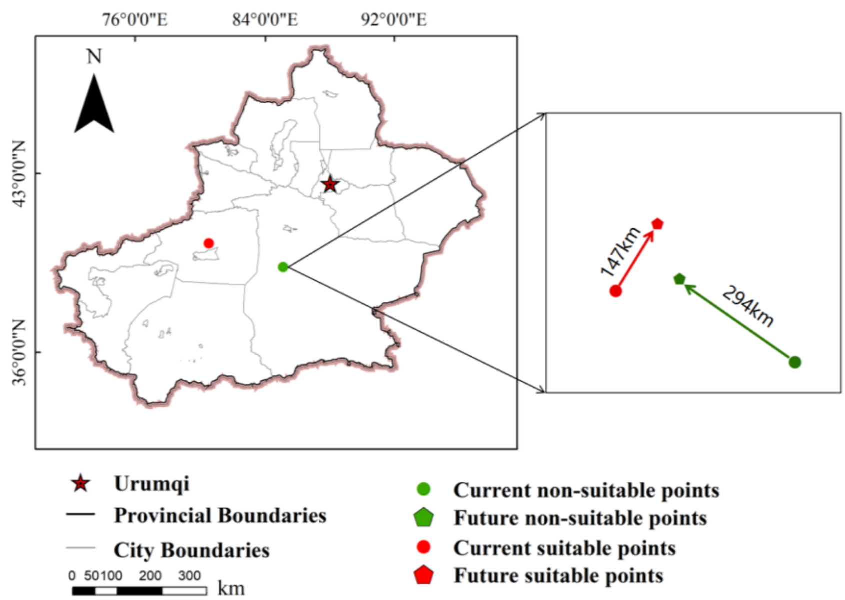

Figure 7. Centroid shift between the 2070s climate scenario and the present.

3.4. Coordination of Ecologically Suitable Areas

It can be seen from Figure 8 below that the growing region of Xinjiang long-staple cotton is mainly distributed on the western and northern edges of the Tarim Basin, the northern foot of Tianshan Mountain, and other places that are consistent with the predicted suitable areas. Still, some areas such as the Turpan region and the northwest of Bayingolin Mongol Autonomous Prefecture are theoretically suitable for planting long-staple cotton; however, they have not been developed yet [39].

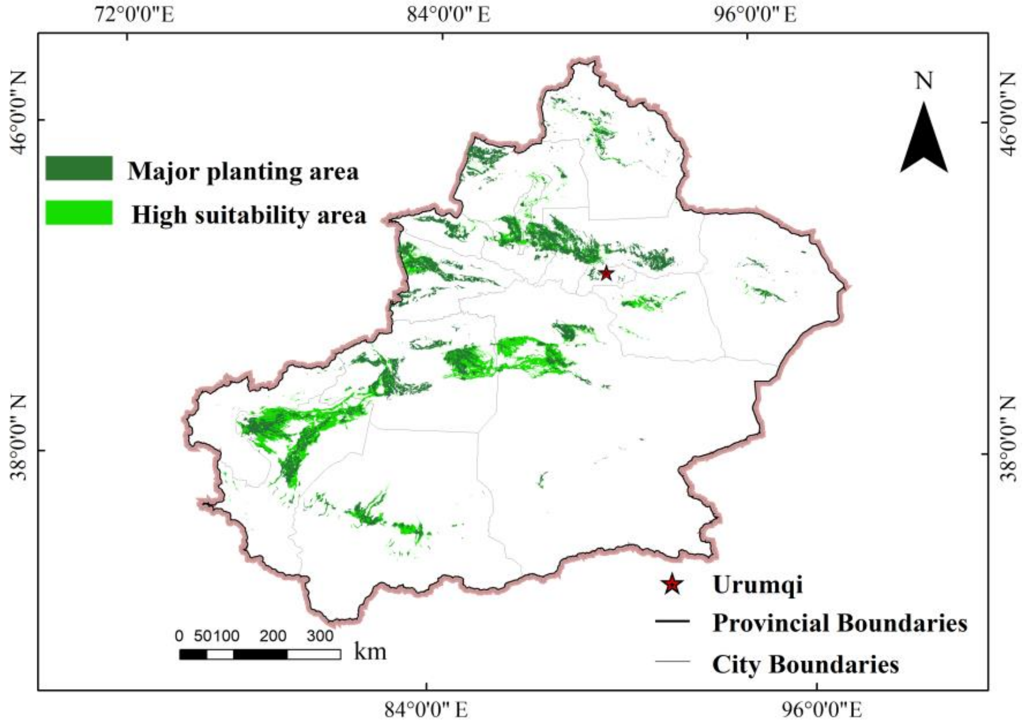

Figure 8. Overlap between long-staple cotton growing areas and climate-suitable areas.

4. Discussion

4.1. Evaluation of Model Accuracy

The average AUC value of the model's training set was 0.912, and the AUC value for the test set was 0.900, both of which are greater than 0.9, indicating that the model prediction accuracy is good. The predicted results are highly consistent with record points of long-staple cotton and previous research results, indicating that this study's results have good accuracy and credibility [40].

4.2. Main Environmental Factors That Affect the Distribution

Among the 27 influencing factors (including climate, topography, and soil), the prediction results indicated that temperature and precipitation were the main factors affecting plant growth. The main factors included the highest temperature, the coldest month, the lowest temperature, precipitation in the coldest season, and monthly mean temperature difference. The results showed that the effect of temperature on cotton exceeds the precipitation factors in Xinjiang. The above conclusions are slightly different from those of other scholars [39,41]. In their study, precipitation and temperature are almost equally as important. The main reason for the difference is the regional differences in Xinjiang. There is generally less precipitation in Xinjiang, and the growth of long-staple cotton mainly depends on artificial irrigation [39,41]. Therefore, humans can properly compensate for the limitations of precipitation factors, resulting in the insignificant effect of precipitation factors on long-staple cotton in Xinjiang. From the results of the MaxEnt model operation, it was not difficult to determine that the suitable core area of 1.3×10^5 Km^2 is mainly distributed in the edge of the Taklimakan Desert, and the north is greater than the southern edge. The climate characteristics of these areas, especially the temperature, fully meet the above analysis, which also verifies the correctness of our conclusion. Next, we will elaborate on the effects of the three classes of influence factors on long-staple cotton in combination with the prediction data.

In the climatic factors affecting the potential distribution of long-staple cotton, the forecast results indicate that the average monthly temperature is 11–15 °C, the highest temperature in the hottest month range is 20–35 °C, the lowest temperature in the lowest month is −15~−10 °C, and the coldest season precipitation of 50–70 mm is the best. Overall, long- and short-staple cotton require a large amount of heat throughout the growing period, consistent with the results because calorie conditions are an important factor affecting cotton growth [42]. A careful observation of the prediction data shows that the most suitable temperature in the seedling stage is 25–30 °C, which is consistent with the conclusion of previous scholars [22]. This is because the lower temperature will lead to a slow emergence or even seed decay, and the higher temperature will greatly reduce the emergence rate. Adequate heat is the most important condition for the normal growth of long-staple cotton. Our prediction results show that the monthly average temperature difference will be at least 14 °C, and the temperature in the coldest month will not be less than −15 °C, so that long-staple cotton can store enough heat and finally achieve a higher yield, which is consistent with the results of Shkolnik.

In the soil factors affecting the potential distribution of long-staple cotton, sand content has the greatest influence on long- and short-staple cotton. This result is consistent with the findings of other scholars [43], as soils with a certain amount of sand content may have better water and air permeability. In addition, due to the low precipitation in Xinjiang, most of the long-staple cotton cultivation needs irrigation. Therefore, the soil with high sand content has more water to reach the cotton root and the water is replenished in time. However, previous scholars have reached different conclusions [44]. They believe that soil factors affect the growth of long-staple cotton, including soil PH value, because the soil PH value varies with the annual average temperature in Xinjiang; however, we did not conclude this in our study in Xinjiang. We found that soil PH changes were small in the study area, and small differences in long-staple cotton growth did not reflect that influence. Therefore, we considered that soil pH did not significantly affect the growth of long-staple cotton.

In the topographic factors affecting the potential distribution of long-staple cotton, the effect of various factors seemed to be insignificant on cotton growth. This is because most of the cultivated land in Xinjiang is flat and wide; under these conditions, the slope has little influence on the growth of long-staple cotton.

4.3. Migration and Prospect for Future Distribution

We combined future climate data with the maximum entropy model and predicted that in RCP 2.6, RCP 4.5, and RCP 8.5, climate warming [39] will lead to a significant increase in heat resources, the suitable distribution area of cotton flowers will also increase to varying degrees, and the expansion area generally includes high latitude areas. Compared with the current planting area of long-staple cotton, in 2070 the expanded area will increase by 3.8×10^4 km^2 in both the SSP126 and SSP245 scenarios, and the expanded area will increase by 4.5×10^4 km^2 in the SSP585 scenario. Meanwhile, the center of mass in the suitable area of long-staple cotton will migrate 147 km to the northeast. This is consistent with other findings [45], as future climate change may significantly improve thermal resources at higher latitudes, and the planting area of warm crops will also move north, consistent with other scholars' conclusions [24,46]. In the planting process of long-staple cotton in the future, we can adjust its planting area appropriately, and the planting center will gradually move closer to the northeast. Compared with the current potential suitable area, the main factor in the future potential suitable area migration is global temperature warming, including a 4×10^4 km^2 expansion mostly from the medium suitable area. It also shows that temperature is an important factor affecting the suitability of long-staple cotton, verifying the rationality of the MaxEnt model and excellent simulation effect [47].

Finally, the results of the predicted and the actual planting comparison indicated that most areas of Xinjiang are consistent with the forecast results; the actual planting area and suitable distribution area coincidence degree reached 83%, but there still exist some differences between the best planting area and actual distribution, such as Turpan area, Bayingolin Mongolian Autonomous Prefecture, with some suitable for planting long-staple cotton but not planting short-staple cotton. This result shows that there is a lot of room for adjustment of the cotton planting strategy, and the advantages of the Xinjiang region have not been fully exploited. We advocate that the government and relevant departments take the necessary measures to adjust the future planting strategies for long- and short-staple cotton in Xinjiang to achieve the best results and realize the sustainability of long-staple cotton planting in Xinjiang.

4.4. Shortcomings of the Model

For a particular species, many factors affect its growth status, such as climate, topography, and human activity. However, our study only used climate, terrain, and soil factors, ignoring potential human activity factors. Human activity is a significant factor, and people can reduce diseases and pests by using large amounts of fertilizers, pesticides, and herbicides. These behaviors may lead to some differences between the predicted results of this study and the actual results.

In terms of the influencing factors of human activities, they mainly increase the planting of suitable areas of long-staple cotton by changing the environmental factors. However, based on the results of this study, the slopes and aspects of topographical factors may have little effect on the appropriate distribution area, i.e., we can ignore the influence of human activities on topographical factors. In terms of pests and diseases, we should include this in the impact factor, and in our future study, the impact of human activities on the study area and its content needs to be fully considered.

5. Conclusions

In this study, the MaxEnt model and ArcGIS (version 10.8) were used to explore the potential distribution factors of long-staple cotton based in Xinjiang using 375 growth points of long-staple cotton and 27 environmental factors (climate, terrain, and soil levels). According to the analysis results, we found that in the Xinjiang region, because of its unique climatic conditions, there are more farmlands suitable for planting long-staple cotton; among them, the suitable area reached 3.2×10^5 Km^2. The suitable habitat of long-staple cotton is mainly located at the edge of Tarim Basin and Junggar Basin, that is, in the northern part of the Kunlun Mountains, foothills, and plains. In particular, among the Aksu region, northeastern Kashgar, northern Bagol Mongolian Autonomous Prefecture, western Changji Hui Autonomous Prefecture, western and southern Yili Kazak Autonomous Prefecture, the comparison of the prediction results and the actual planting area reached 83% agreement, indicating that the cultivation of long-staple cotton in the Xinjiang area is more reasonable.

In the study, it was found that one of the environmental factors affecting the largest potential distribution was the temperature, including the lowest temperature of the coldest month, the highest temperature of the hottest month, and the average temperature of the hottest season, and the precipitation of the coldest season also strongly influenced the precipitation factors, which affected up to 70% in Xinjiang. In the context of future climate change, the suitable area for long-staple cotton will increase to the northeast, while the northwest region will gradually shrink. Under all climate scenarios, the expanded area is greater than the disappeared area, which indicates that the planting of long-staple cotton in Xinjiang will be considerable in the future.

Author Contributions: L.L.: method, scheme design, data management, resources, first draft, review, verification, investigation, visualization, software, formal analysis, method; S.Z.: resources, formal analysis, writing; Y.G.: conceptualization, method, supervision, resources, review, verification, editing; H.W.: supervision, investigation, resources, review, editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the technical innovation guidance special fund of Shaanxi province (Grant No. "2020QFY07-03").

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All the data used for several analyses are freely available and resources are mentioned within the paper.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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