Prediction of *Cossus Linnaeus* suitable growing area in China under Future Climate change based on optimized MaxEnt Model and Geographic detector

Hua Zhang*, Ming Li, Jinyue Song, and Wuhong Han

College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, China; 2019212355@nwnu.edu.cn; 2019212367@nwnu.edu.cn (J.S.); 2019212364@ nwnu.edu.cn (W.H.)

* Correspondence: zhanghua@nwnu.edu.cn (H.Z.).

Abstract: *CossusLinnaeus* is a kind of insect that causes great harm to forest trees in China, which has a great impact on the country's agriculture and forestry, and seriously affects the stability of the ecosystem, so it is very important to predict its distribution and contain it. Most researchers use the MaxEnt model with default parameters to build models to predict the potential geographical distribution of species. Recent studies have found that in the case of default parameters, the prediction results of MaxEnt model are not only inaccurate, but also sometimes difficult to explain. In this paper, ENMeval packets are used to adjust the optimal feature combination parameters of MaxEnt model, and then the MaxEnt model with optimal parameters is used to predict the potential geographical distribution of *CossusLinnaeus* under present and future climatic conditions. The simulation results show that the simulation effect of the MaxEnt model is good (the area under the ROC curve (AUC = 0.914), Cossus Linnaeus is mainly distributed in Liaoning Province, Hebei Province, Shandong Province, Henan Province, Shaanxi Province, Shanxi Province, Ningxia and Gansu Province, etc., which is consistent with the actual distribution results. Under future climatic conditions, the area of Cossus Linnaeus high suitable growth area will rise up 26.7% to 87.4% compared with the current one. Climate change affects the potential distribution of Cossus Linnaeus, and the top four environmental variables with contribution rate are normalized vegetation index (NDVI,40.3%), annual mean temperature (Bio1,24.1%), coldest monthly minimum temperature (Bio6,12.4%) and diurnal range of mean temperature (Bio2,9%). Under the condition of future climate change, the center of gravity of Cossus Linnaeus will move to high latitudes. This study will provide theoretical support for the prevention and control of Cossus Linnaeus and tree protection in China.

Keywords: MaxEnt model; Model optimization;Climate change; *Cossus Linnaeus*; Suitable growth zone.

Harmful species, including invasive species, pathogens and various pests, destroy ecosystems, biodiversity, agriculture and human health and cause important harm to biodiversity[1]. Among them, there are pest species that threaten the world's agriculture, forestry and animal husbandry, and even destroy the stability of ecosystems[2-4]. Global climate change is changing the global species distribution pattern through terrestrial ecosystems [5,6]. Climate is considered to be an important factor affecting the distribution of species on the earth [7]. Studies have shown that climate change will have a great impact on the decrease or increase of the distribution range, physical characteristics and number of species [8,9], and the most obvious manifestation is the shift of species distribution to high latitudes and high elevations [10,11]. Therefore, in the case of future climate change, it is of great significance to study the potential geographical distribution and changes of harmful species to control the number of pests and reduce damage.

The Species Distribution Model (Species distribution models, SDMs) combines known discovered species with local temperature data to predict the potential geographical distribution of species [12,13]. MaxEnt model based on maximum entropy theory is the most popular model to predict species distribution. This model simulates the use of current species distribution information and various environmental variables to predict the potential geographical distribution of species[14,15]. Most researchers use the MaxEnt model with default parameters to predict species distribution, but subsequent studies found that MaxEnt model is more sensitive to sampling errors and prone to over-fitting. This simulation is not only inaccurate, but also difficult to explain. In this study, the ENMeval data packet is used to adjust the optimal feature combination parameters of the MaxEnt model, and the MaxEnt model with the optimal parameters is used to model and predict the results with strong stability and high accuracy, which shows a good prediction result for the habitat suitability prediction of species [16-19]. Geographic detector model is a set of statistical methods to detect spatial differentiation and reveal the driving forces behind it [20]. Geographic detectors are widely used in the detection of influencing factors such as geological disasters [21], disease transmission [22,23], meteorological changes [24,25], and vegetation changes [26]. We can try to use the geographic detector model to analyze the impact of climate variables on species distribution, and determine the most appropriate characteristics of each environmental variable to promote species distribution. Therefore, the combination of optimized MaxEnt model and geographic detector model can not only test the results of species distribution simulated by MaxEnt model, but also make the suitable distribution range of species more accurate. Based on the optimized MaxEnt model, geographic detector model and ArcGis software, the potential geographical distribution of pest species is predicted, and the potential risk of climate change on the geographical distribution of pest species is predicted, so that scholars and decision makers can put forward corresponding strategies to deal with the impact of climate change on the geographical distribution of pest species [27].

Cossus Linnaeus belongs to Lepidoptera [28], Coccinellidae, and its hosts are Populus L, Salix, Sophora japonica L, Juglans and Malus pumila Mill. At present, it is mainly distributed in North, Northeast and Northwest China. The larvae eat into the xylem of the trunk and rhizome, causing mechanical damage to the trees, destroying the physiological functions of the trees, leading to the weakness and withering of the trees, and even causing the death of the trees. *Cossus Linnaeus* has not only caused great damage to the country's agriculture, forestry and animal husbandry, but also affected the species diversity and the stability of the ecosystem. The purpose of this study is to simulate the geographical distribution of *Cossus Linnaeus* under current and future climatic conditions in China, to create a prediction model based on the existing geographical distribution information, bioclimatic variables and topographic data of *Cossus Linnaeus* in China, and to use MaxEnt model and geographic detector model to predict the potential geographical distribution of *Cossus Linnaeus* (2030 and 2050) in China under SSP1-2.6,4.5 and SSP5-8.5emission scenarios. At the same time, the suitable growth range of *Cossus Linnaeus* was also studied. The significance of this study is as follows: (1) to establish a model of the influence of bioclimatic variables and topographic factors on the distribution pattern of *Cossus Linnaeus*; (2) to study the main climatic variables that limit the potential geographical distribution of *Cossus Linnaeus*; (3) the optimized MaxEnt model and geographic detector model are combined to predict the geographical distribution of species.; (4) to predict the geographical distribution of *Cossus Linnaeus* in China under future climate change; and (5) to study the suitable growth range of *Cossus Linnaeus*. Our results will provide a scientific basis for the prevention and treatment of *Cossus Linnaeus*.

1 Data and methods

1.1 Geographic distribution data of *Cossus Linnaeus*

The geographical distribution of *Cossus Linnaeus* is to obtain the distribution information of 536 species through a comprehensive search of the China National Pest Quarantine Information platform (http:// www.pestchina.com/SitePages/Home.aspx), the Global Biodiversity Information Network (https://www.gbif.org/) and the results of the National Forestry Pest Survey of China from 2014 to 2017, and to confirm and select the geographical coordinates of the samples. Remove the distribution records that are not specific enough and are not within the study area, and then in order to avoid clustering effect leading to over-fitting of MaxEnt model (overfitting), considering that the accuracy of climate data is 2.5', only one distribution point is retained in each 2.5'× 2.5 'grid, and finally 86 effective distribution points of Cossus Linnaeus in China are obtained. The geographical distribution map of *Cossus Linnaeus* in China (Fig 1) is obtained by substituting ArcGis10.5 software, and converted into csv format for MaxEnt model.

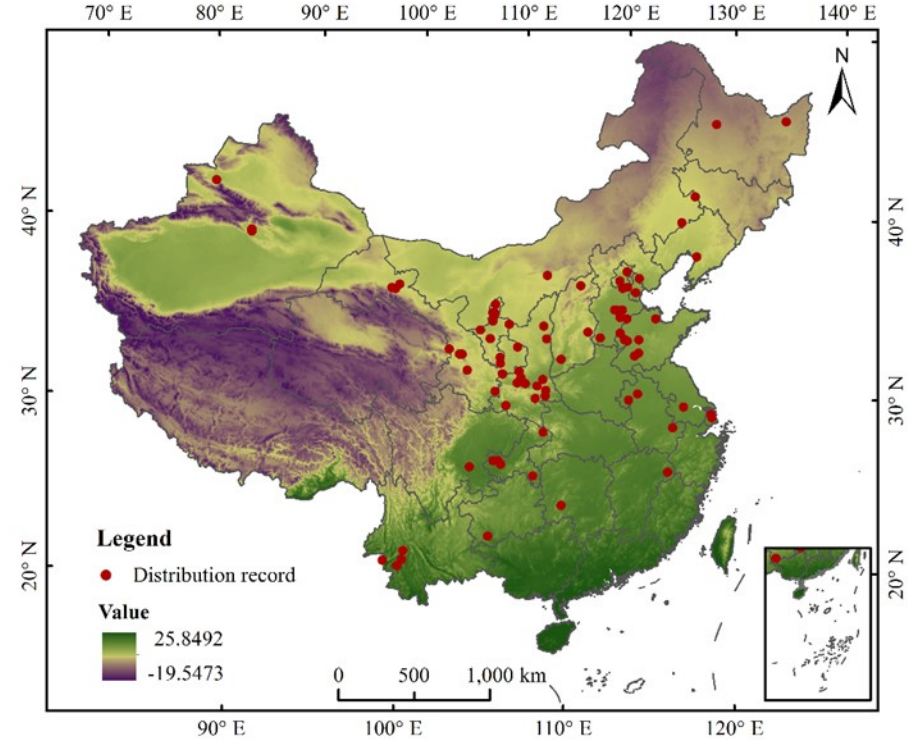


Figure1 Distribution records of *Cossus Linnaeus* in China with mean annual temperature.

1.2.1 Environmental factor screening and data processing

The modern climate data (1970-2000) and future climate data (2030 and 2050s) of study are all from the World Climate Database (http://www.worldclim.org/). The future climate data (2030 and 2050s) are based on the BCC-CSM2-MR climate system model developed by the National Climate Center and four shared socio-economic path (shared socio-economic pathways, SSPs) scenarios (Table1) in this model. Compared with the scenarios used in previous studies, the shared socio-economic path scenario is a major tool launched by the Intergovernmental Panel on Climate change (Intergovernmental Panel on Climate Change, IPCC) in 2010 to describe global socio-economic development scenarios. This scenario is based on the typical concentration path (Representative Concentration Pathways, RCPs) scenario and is used to quantitatively describe the relationship between climate change and socio-economic development path [29]. The spatial resolution is 2.5 seconds, and the data includes 23 bioclimatic factors (Table 2). The data have obvious biological significance and are usually used in species distribution and related ecological modeling. The topographic data includes three environmental factors: elevation, slope and aspect, which are derived from the world elevation data with a resolution of 2.5'in the World Climate Database (http://www.worldclim.org/). Three grid layers of elevation, slope and aspect in China are extracted and obtained by using the spatial analysis module in ArcGIS10.5.

Table1. Three emission scenarios.

Emission	Description
SSP1-2.6	SSP1 (Low forcing scenario) Upgrade to RCP2.6 scenario based on (Radiative forcing reaches 2.6 W/m2in 2100)
SSP2-4.5	SSP2 (Medium forcing scenario) Upgrade to RCP4.5 scenario based on (Radiative forcing reaches 4.5 W/m2in 2100)
SSP5-8.5	SSP5 (High Forcing Scenario) Upgrade to RCP8.5 scenario based on (SSP5 is the only SSP scenario that can achieve radiative forcing to 8.5 W/m2in 2100)

Table2 Environmental variables related to the distribution of *Cossus Linnaeus*

Variable	Description	Unit
Bio1	Annual mean temperature	°C
Bio2	Mean diurnal range (mean of monthly (max temp - min temp)	°C
Bio3	Isothermality (bio2/bio7) (*100)	—
Bio4	Temperature seasonality (standard deviation*100)	°C
Bio5	Max temperature of warmest month	°C
Bio6	Min temperature of coldest month	°C
Bio7	Temperature annual range (bio5-bio6)	°C
Bio8	Mean temperature of wettest quarter	°C
Bio9	Mean temperature of driest quarter	°C
Bio10	Mean temperature of warmest quarter	°C
Bio11	Mean temperature of coldest quarter	°C
Bio12	Annual precipitation	mm
Bio13	Precipitation of wettest month	mm
Bio14	Precipitation of driest month	mm
Bio15	Precipitation seasonality (coefficient of variation)	—
Bio16	Precipitation of wettest quarter	mm
Bio17	Precipitation of driest quarter	mm
Bio18	Precipitation of warmest quarter	mm
Bio19	Precipitation of coldest quarter	mm
Alt	DEM	m
Slope	Slope	°
Aspect	Aspect	°
2018NDVI	Normalized Difference Vegetation Index	—

1.2.2 Geographic detector model

Geographic detectors are a set of statistical methods for detecting spatial differences and revealing the driving forces behind them [30]. Its core idea is based on the assumption that if an independent variable has an important influence on a dependent variable, then the spatial distribution of the independent variable and the dependent variable should be similar.

Spatial differentiation is one of the basic characteristics of geographical phenomena. Geographic detector is a tool to detect and make use of spatial differentiation.

(1) The main results are as follows: Spatial differentiation and factor detection: to detect the spatial differentiation of the *Cossus Linnaeus*, and to what extent the environmental variables affect the spatial differentiation of the *Cossus Linnaeus*. Measured by q value, the expression is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h s_h^2}{N s^2} = 1 - \frac{SSW}{SST} \tag{1}$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2, SST = N\sigma^2 \tag{2}$$

In the formula: The delamination of variable Y or factor X is called L, which is the delamination of variable Y or factor X; N_h and N are the number of units in the layer h and the whole region, respectively; σ_h^2 and σ^2 are the variance of Y value of layer h and the entire area, respectively. SSW and SST are the sum of the intra-layer variance and the total variance of the entire area, respectively. The influence of q value as an environmental variable on the distribution of *Cossus Linnaeus*, the value range is [0,1]. The higher the value, the stronger the influence on the distribution of *Cossus Linnaeus*, and vice versa.

1.3 Environmental variables and preprocessing

As there is a certain correlation between environmental factors, in order to avoid over-fitting of MaxEnt model, this study combines the cutter method of MaxEnt model with geographic detector model to eliminate the environmental variables that have little impact on the prediction results of MaxEnt model. The specific processing steps are as follows: the geographical distribution points of *Cossus Linnaeus* and 23 environmental variables are converted into grid form in ArcGis10.5, and the quantitative relationship between *Cossus Linnaeus* and 23 environmental variables is obtained by generating random sampling points. The influence of 23 environmental variables on the distribution of *Cossus Linnaeus* in China is obtained by substituting 23 environmental variables into the geographic detector model, and 13 environmental variables whose contribution is greater than 0.1 are selected [31]. Combined with the results of the knife-cutting method in the MaxEnt model, eight important environmental variables were selected to predict the suitable growing area of *Cossus Linnaeus* in China (Table 3).

Table3 Environmental factor variables involved in prediction.

Variable	Description
NDVI	Normalized Difference Vegetation Index Vegetation Index
Bio1	Annual mean temperature
Bio6	Min temperature of coldest month
Bio2	Mean diurnal range (mean of monthly (max temp – min temp)

Bio11	Mean temperature of coldest quarter
Bio7	Temperature annual range (bio5-bio6)
Bio3	Isothermality (bio2/bio7) (*100)
Bio18	Precipitation of warmest quarter

1.4 Basic map data and model sources.

The administrative map of China's national and provincial boundaries (1VR 16 million) derives from the National basic Geographic Information Center (http://www.). Version 3.4.1 of ngcc.cn/ngcc/), MaxEnt comes from the website (http://biodiversityinformatics.amnh.org), and the geo-detector model is downloaded from the website (http://www.geodetector.org/). The ArcGis version used in this study is version 10.5.

1.5 MaxEnt Model Construction and Evaluation

Eight environment variables are brought into ArcGis10.5 and converted into csv format. *Cossus Linnaeus* geographical distribution points and eight environment variables are substituted into MaxEnt model for modeling and operation.Because the AUC value is not affected by the judgment threshold, the evaluation is more objective and accurate, so it has become the best index to measure the prediction accuracy of the model. The higher the AUC value (0 Mel 1), the farther away from the random distribution, indicating that the difference between the undistributed region and the distributed region of *Cossus Linnaeus*, the higher the value, the better the effect. The evaluation criteria are as follows: the AUC value of 0.7mur0.8 is more accurate, 0.8mur0.9 is very accurate, and 0.9mur1.0 is extremely accurate [32]. However, although we use AUC, which is probably the most popular method to evaluate the accuracy of prediction distribution models [33,34], to evaluate the performance of parameter configuration, considering the controversy among scientists about its reliability, we choose to use ENMeval packets to optimize the model of parameter configuration.

Finally, the Rm of this study is set to 3, and the feature combination is set as LQH, model parameters: 75% distribution data is selected as the training set (training data), remaining 25% as the test set (test data), adopts cross-validation method (Cross validate, randomly divides the species distribution data into 10 parts randomly, one of them is randomly selected as the test set each time, and the remaining 9 are used as the training set, repeated 10 times, with high data utilization). By default, the maximum number of background attractions is 10000, and the maximum number of iterations is 500. the knife-cutting method (Jackknife) is used to test the weight, and the subject working characteristic curve (ROC) is set.

The results are substituted into the Arcgis10.5 software. Based on the Reclassify function of the spatial analysis tool (Spatial analyst tools), the geographical distribution of *Cossus Linnaeus* in China is divided into four suitable zones by using the method of natural segment classification (Jenks' natural breaks)). They are: unsuitable zone (< 0.10) and low adaptive zone (0.10-0.30). The potential geographical distribution of Cossus Linnaeus in different grades of suitable growth in China was obtained by means of moderate and high suitable growth areas (0.30-0.60) and high suitable growth areas (0.60-1.00).

1.6 Importance assessment of environmental variables

The contribution rate and knife-cut test obtained from the operation of the optimized MaxEnt model are used to evaluate the importance of environmental factors that limit the potential geographical distribution of *Cossus Linnaeus* in China. The MaxEnt model can track the environmental factors with high contribution rate, increase the gain value through the gradual modification of a single factor, and then assign the gain value to the environmental factor on which the factor depends, and output the results in the form of a percentage. The decrease of AUC value indicates the dependence of the factor on the model. The knife-cutting test creates the model by using and excluding a certain environmental factor in turn and using all environmental factors. The importance of environmental factors is measured by providing three test results of regularized training gain, test gain and AUC value.

2 Results and analysis

2.1 Environmental variables affecting the potential geographical distribution of the *Cossus Linnaeus*

When the MaxEnt model is in the default parameters, the Feature run by RM=1, has H, L, LQ and LQH, and based on the AICc rule, when the MaxEnt model parameter is RM=3 and the running Feature is LQH, the AICC value is the lowest (Fig2). The AUC.diff and OR10 values based on the optimization model are significantly lower than those of the Maxent model under the default parameters, indicating that the optimized model significantly reduces the over-fitting of local distribution data. In the response curve, the Maxent model based on the default parameters shows obvious tortuosity, indicating that the Maxent model has the phenomenon of over-fitting to the species distribution data in the model construction area. On the contrary, when using the optimal model parameters, the response curve becomes relatively smooth, which also shows that the optimized model reduces the over-fitting of Maxent model to local distribution data, which is closer to the physiological response of *Cossus Linnaeus* to environmental factors.

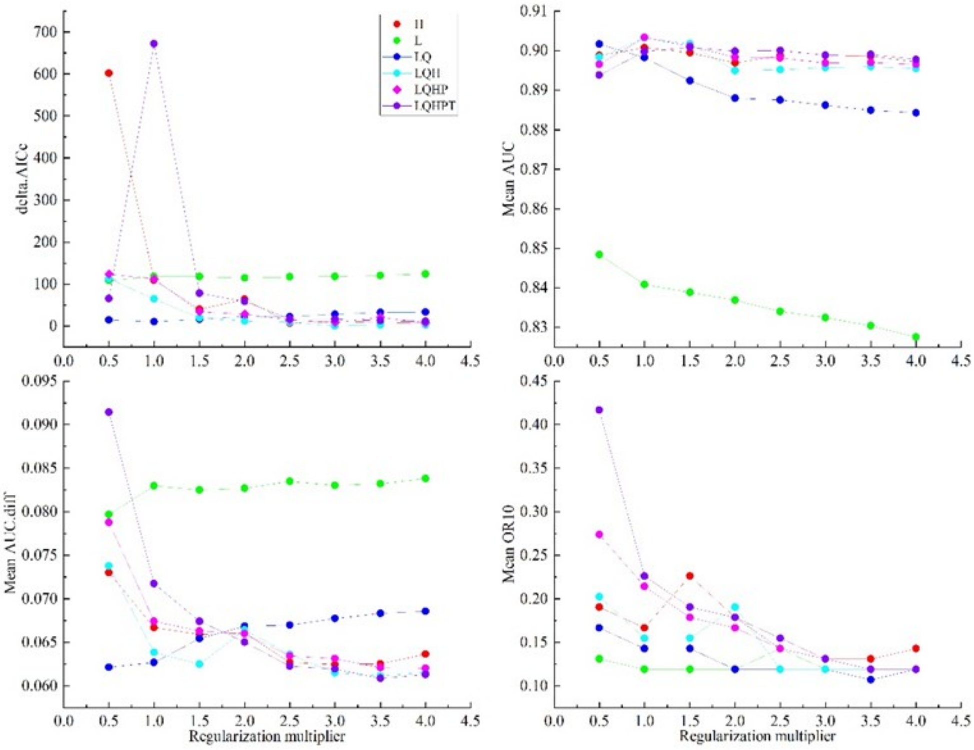


Figure2 Performances of native niche model of *Cossus Linnaeus* under different settings.

Based on the prediction results of MaxEnt model, the ROC curve (Fig3) is obtained, in which the AUC value of training data is 0.913 and the AUC value of test data is 0.914. According to the evaluation standard of AUC value, it shows that the simulation accuracy of MaxEnt model for predicting the potential geographical distribution of *Cossus Linnaeus* in China is very accurate.

Among the 8 environmental variables predicted by MaxEnt model, the top four environmental variables with contribution rate are normalized vegetation index (NDVI,40.3%), annual mean temperature (Bio1,24.1%), coldest month minimum temperature (Bio6,12.4%) and mean temperature diurnal range (Bio2,9.0%) (Fig4). According to the results of knife-cut (Jack knife) test, it is known that when only a single environmental variable is used, the four environmental factors that have significant influence on the normalized training gain are the lowest temperature in the coldest month (Bio6), the mean temperature in the coldest season (Bio11), the normalized vegetation index (NDVI) and the annual mean temperature (Bio1) (Fig5), indicating that these environmental variables have important information that other environmental variables do not have. Generally speaking, the important environmental factor variables that affect the geographical distribution of modern *Cossus Linnaeus* are air temperature factor variables (coldest month minimum temperature, coldest season average temperature and annual mean temperature) and vegetation factor variables (vegetation normalization index).

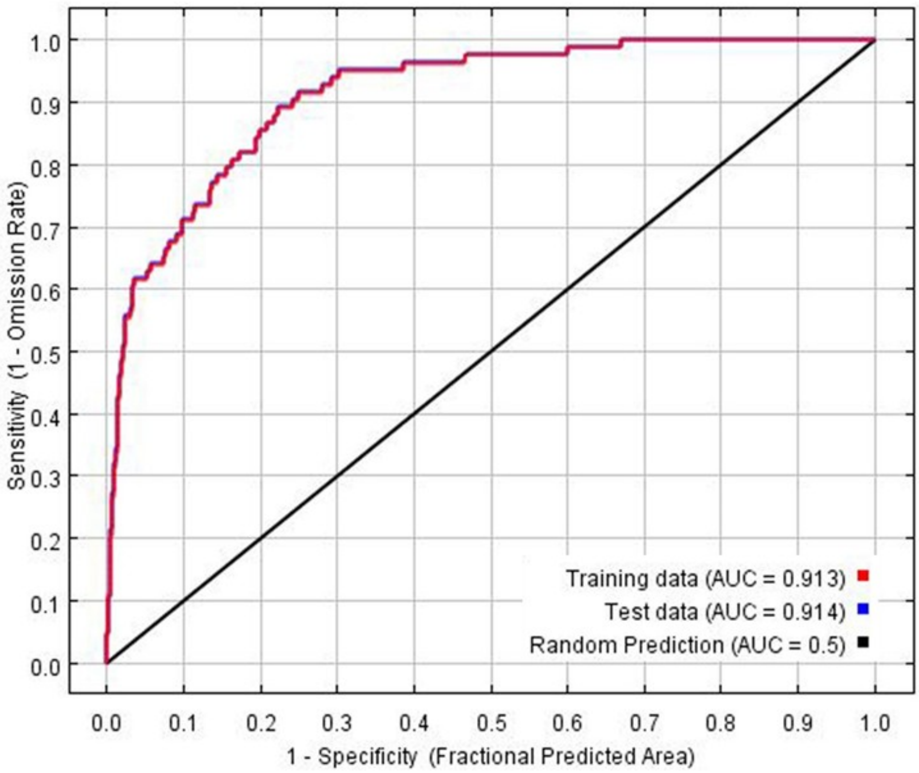


Figure3 Reliability test of the distribution model created for *Cossus Linnaeus*.

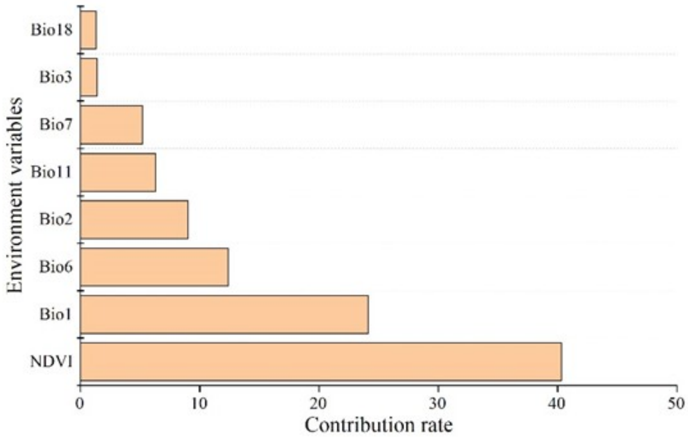


Figure4 Contribution rate of environmental variables on the distribution of *Cossus Linnaeus*.

The variation between the existence probability of *Cossus Linnaeus* and environmental factors can be judged according to the response curve of environmental factor variables. When the probability of existence of *Cossus Linnaeus* is greater than 0.6, the corresponding environmental variables are suitable for the survival of Cossus Linnaeus, thus the suitable growth range of *Cossus Linnaeus* with respect to environmental factor variables can be obtained. The results are as follows: Min temperature of clodest month (Bio6, -13.82~-1.19°C); Mean temperature of coldest quarter (Bio11, -4.73~1.85°C); Normalized Difference Vegetation Index (NDVI, 0.10~0.79) and Annual mean air temperature (Bio1, -0.26~29.81°C) (Fig6).

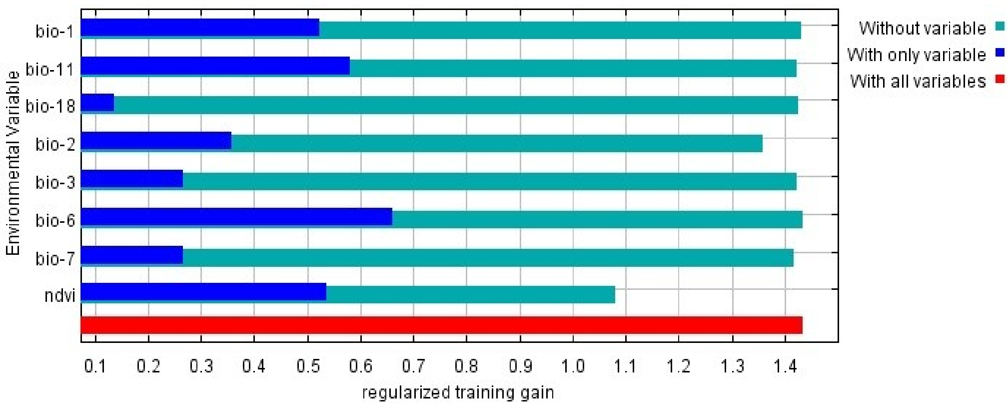


Figure5 Jackknife test of variable importance for *Cossus Linnaeus*.

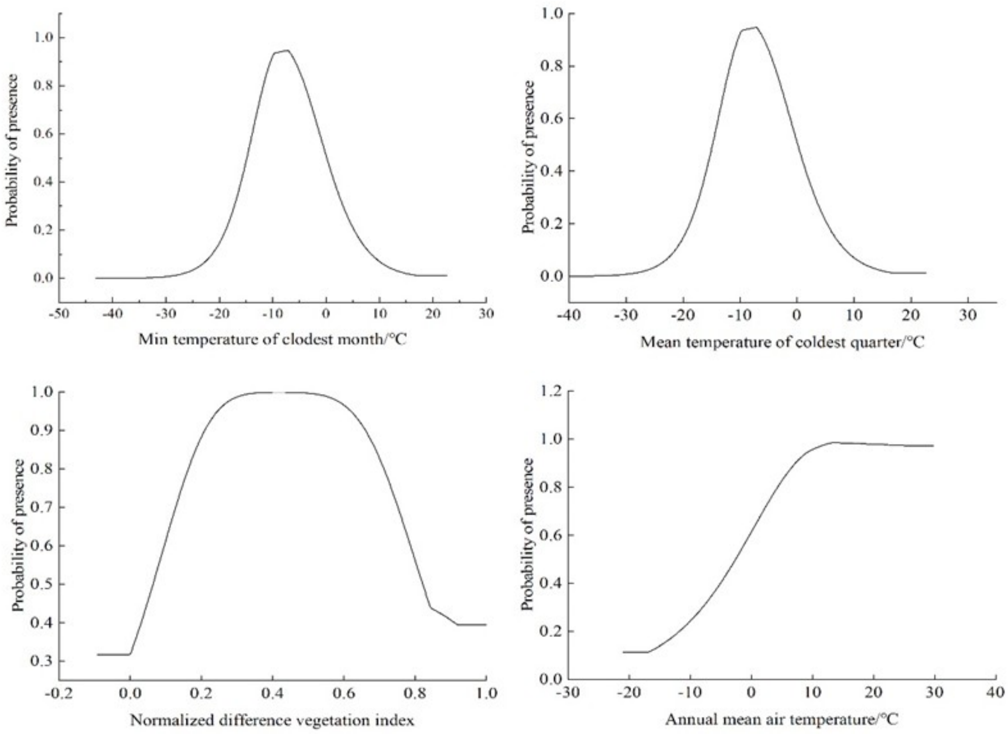


Figure6 Response curves of probability of presence for *Cossus Linnaeus*.

2.2 Potential distribution of *Cossus Linnaeus* under modern climatic conditions

The potential geographical distribution (Fig7) of *Cossus Linnaeus* under modern climatic conditions is simulated by MaxEnt model, and the potential suitable area is $311.38\times10^4km^2$, accounting for about 32.44% of the total area (Table4). The area area of high, moderate and low suitable areas was $25.80\times10^4km^2$, $87.72\times10^4km^2$ and $197.86\times10^4km^2$, respectively, and the proportion of the total suitable area was 8.29%, 28.17% and 63.54%, respectively.

The main distribution areas of *Cossus Linnaeus* in China are Hebei, Beijing, Tianjin, Shandong Province, the north of Henan Province, the south of Shaanxi Province, the south of Shanxi Province, the southeast of Gansu Province and Ningxia. The main distribution of medium-suitable areas and high-suitable areas are very similar, in addition, there are a small amount of distribution in central Inner Mongolia, Yunnan Province, Guizhou Province, Hunan Province, Jiangxi Province and Jilin Province. Low fitness areas are widely distributed, mainly in the northeast, southeast coastal areas, eastern and southern Xinjiang, northwest and Tibet.

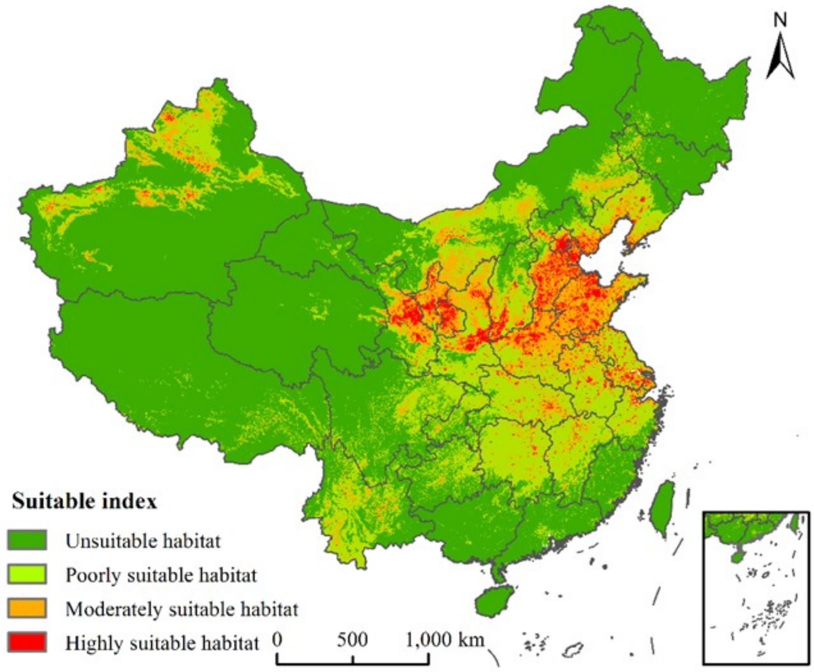


Figure7 Potential current and suitable habitat for *Cossus Linnaeus* in China.

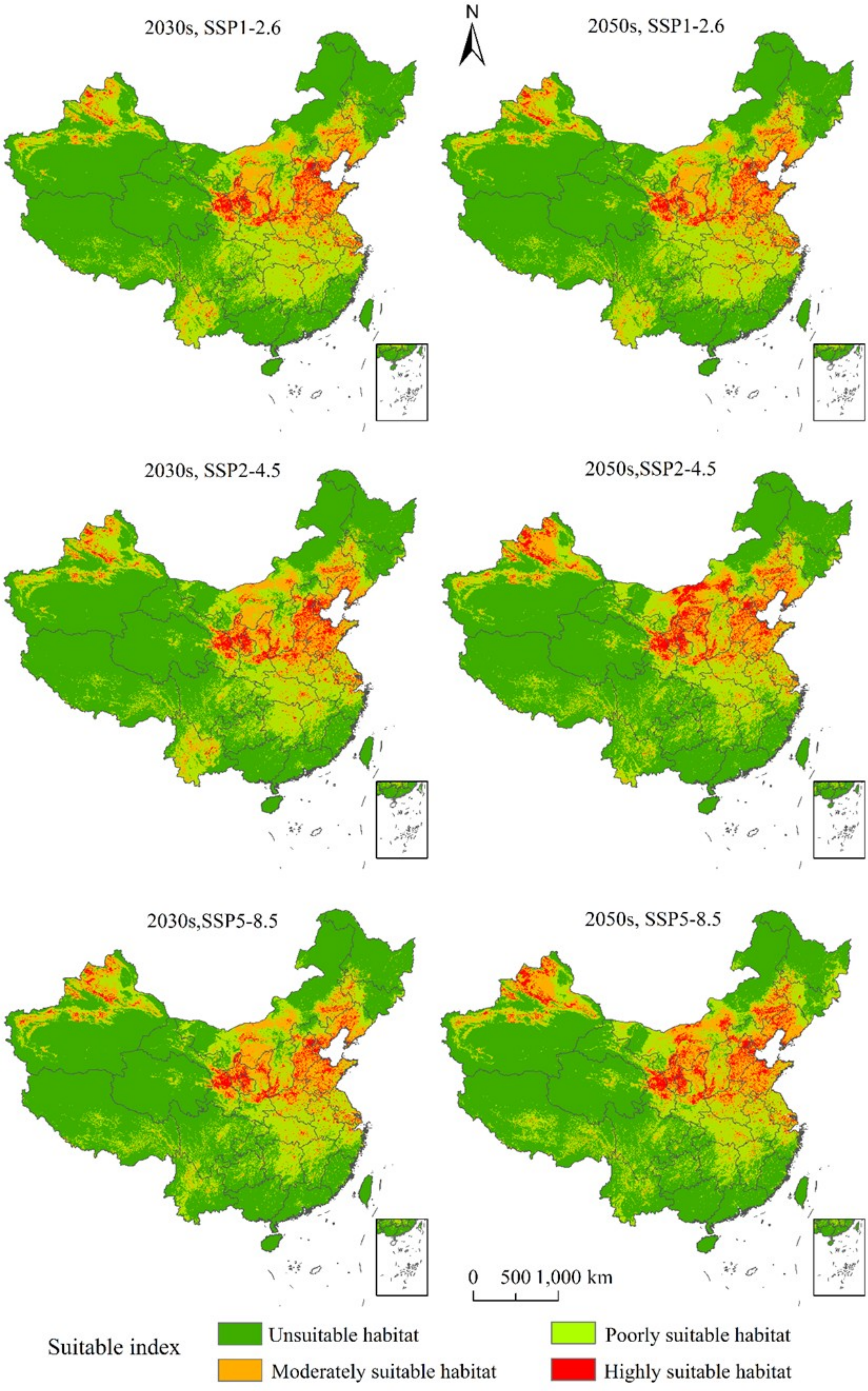
Table4 Suitable areas for Cossus Linnaeus under different climate change scenarios($10^4 km^2$)

Period	Highly suitable	Moderately suitable	Poorly suitable	Total suitable
Current	25.80	87.72	197.86	311.38
2030s, SSP1-2.6	33.42	116.76	222.36	372.54
2030s, SSP2-4.5	34.64	119.10	209.44	363.18
2030s, SSP5-8.5	32.69	116.48	202.63	351.80
2050s, SSP1-2.6	33.37	121.95	228.67	383.99
2050s, SSP2-4.5	47.65	122.90	198.43	368.98
2050s, SSP5-8.5	45.37	130.87	212.20	388.54

2.3 Potential distribution of Cossus Linnaeus under future climatic conditions

Based on the MaxEnt model, this paper predicts the potential geographical distribution (Fig8) of *Cossus Linnaeus* under three emission scenarios: SSP1-2.6, SSP2-4.5and SSP5-8.5 under modern climatic conditions, 2030s and 2050s, so as to analyze the different grades of *Cossus Linnaeus* potential geographical distribution in China.

Figure8 Potentially suitable climatic distribution of *Cossus Linnaeus* under different climate change scenarios in China.



The results show that the distributions of SSP1-2.6, SSP2-4.5and SSP5-8.5 under, *Cossus Linnaeus* emission scenarios are very similar, mainly in eastern and central Inner Mongolia, Hebei, Beijing, Tianjin, northern Henan, southern Shanxi, central and northern Shaanxi, Ningxia, southeastern Gansu and northwestern Xinjiang. Under the SSP1-2.6 emission scenario, the area of high suitable zone is $33.42\times10^4km^2$, the area of middle suitable zone is $116.76\times10^4km^2$, and the total area of suitable zone is $372.54\times10^4km^2$. Under the scenario of SSP2-4.5. The area of high suitable zone is $34.64\times10^4km^2$, the area of medium suitable zone is $119.10\times10^4km^2$, and the total area of suitable zone is $363.18\times10^4km^2$. Under the SSP5-8.5emission scenario, the area of the high, medium and total suitable zones is $32.69\times10^4km^2$, $116.48\times10^4km^2$ and $351.80\times10^4km^2$ respectively.

Under the emission scenarios of SSP1-2.6, SSP2-4.5 and SSP5-8.5 in 2050, the geographical distribution of the high and medium suitable areas of the *Cossus Linnaeus* was very similar to that of the three emission patterns in 2030, and the size of the appropriate zone changed. Under SSP1-2.6emission scenario, the size of the high growth zone is $33.37\times10^4km^2$, the size of the medium zone is $121.95\times10^4km^2$, and the total size of the growth zone is $383.99\times10^4km^2$; under the SSP2-4.5emission scenario, the size of the high growth zone is $47.65\times10^4km^2$, the size of the medium growth zone is $122.90\times10^4km^2$, and the total size of the suitable site is $368.98\times10^4km^2$, under the SSP5-8.5emission scenario, the size of high growth zone was $45.37\times10^4km^2$, the size of the medium zone was $130.87\times10^4km^2$, and the total size was $388.54\times10^4km^2$.

The total suitable regions in *Cossus Linnaeus* were the largest under SSP5-8.5 emission scenarios in 2050; the geographical distribution of modern climate and 2030 and 2050 climatic emission scenarios was similar; the areas of high and medium suitable regions in *Cossus Linnaeus* increased under the three emission scenarios in 2030 and 2050; the distribution of high and medium appropriate areas of *Cossus Linnaeus* was very close.

2.4 Changes in the area and centre of gravity of suitable regions under future climate change

Our results show that the predictive reduced area of the *Cossus Linnaeus* is $9.40\times10^4km^2$, the predictive increased size is $45.49\times10^4km^2$, and the predictive entire area is $103.47\times10^4km^2$ (Table5), under the SSP1-2.6 emission model in 2030. The reduced size is mainly located in southwestern Shandong Province, southeastern Henan Province and Anhui Province. In contrast the increased size is mainly primarily located in northern Xinjiang, central Inner Mongolia, Liaoning Province and northern Shaanxi Province (Fig.9).

Under the SSP2-4.5 emission model in 2030, it is predicted that the reduced area of the *Cossus Linnaeus* is $10.47\times10^4km^2$, the increased size is $50.47\times10^4km^2$, and the entire area is $102.13\times10^4km^2$. The reduced size is mainly located in southern Shandong Province, south Henan Province, Anhui Province, eastern Hubei Province and Jiangsu Province. In contrast the increased size is mainly located primarily in central Inner Mongolia, Liaoning Province and northern Shaanxi Province.

Under the SSP5-8.5 emission model in 2030, it is predicted that the reduced area of the *Cossus Linnaeus* is $15.29\times10^4km^2$, the increased size is $51.62\times10^4km^2$, and the entire area is $102.76\times10^4km^2$. The reduced size is mainly located in the southwest of Shandong Province, the eastern and southern of Henan Province, Anhui Province, the eastern of Hubei Province, the western of Yunnan Province and Jiangsu Province, etc.; the increased area is mainly located in central and eastern Inner Mongolia, northern Xinjiang, Liaoning Province and northern Shaanxi Province.

Table5 Future changes in suitable habitat area (10^4km^2)

Period	Loss	Gain	Unchanged
2030s, SSP1-2.6	9.40	45.49	103.47
2030s, SSP2-4.5	10.47	50.47	102.13
2030s, SSP5-8.5	15.29	51.62	96.87
2050s, SSP1-2.6	9.98	51.27	102.76
2050s, SSP2-4.5	18.00	76.33	93.68
2050s, SSP5-8.5	15.70	79.40	96.11

Under the SSP1-2.6 emission model in 2050, it is predicted that the reduced area of the *Cossus Linnaeus* is $9.98\times10^4km^2$, the increased area is $51.27\times10^4km^2$, and the entire area is $102.76\times10^4km^2$. The reduced size is mainly located in southwestern Shandong Province, southeastern Henan Province and Anhui Province. In contrast, the increased size primarily located in central and northern Inner Mongolia, Liaoning Province and northern Xinjiang.

Under the SSP2-4.5 emission model in 2050, it is predicted that the reduced area of the *Cossus Linnaeus* is $18.00\times10^4km^2$, the increased area is $76.33\times10^4km^2$, and the entire area is $93.68\times10^4km^2$. The reduced size is mainly located in southwestern Shandong Province, Henan Province, Anhui Province, Hubei Province and Jiangsu Province. In contrast, the increased size primarily located in central and northern Inner Mongolia, Liaoning Province and northern Xinjiang.

Under the SSP5-8.5 emission model in 2050, it is predicted that the reduced area of the *Cossus Linnaeus* is $15.70\times10^4km^2$, the increased area is $79.40\times10^4km^2$, and the entire area is $96.11\times10^4km^2$. The reduced area is mainly located in southwestern Shandong Province, Henan Province, Anhui Province, Hubei Province, western Yunnan Province and Jiangsu Province. In contrast, the increased area primarily located in central and eastern Inner Mongolia, northern Xinjiang, Liaoning Province and so on.

Cossus Linnaeus high center of gravity is located in suitable areas 112°43'E, 36°31'N (Fig10) under modern climate conditions. In the case of SSP1-2.6 emissions, the center of gravity of the suitable zone will be 110°47'E, 37°20'N in 2030; it will shift to 110°12'E, 37°46'N in 2050. In the case of SSP2-4.5 emissions, the center of gravity of the suitable zone in 2030 will be located at 110°20′E, 37°44′N; in 2050, it will shift to 107°29′E, 39°44′N. In the case of SSP5-8.5 emissions, the center of gravity of the suitable zone in 2030 will be 108°43'E, 38°25'N; in 2050, it will shift to 108°4'E, 39°34'N. In summary, under the conditions of SSP5-8.5 emissions in 2030 and 2050, the center of gravity of the highly suitable areas is more northwest; under modern climatic conditions, the center of gravity has a lower latitude.

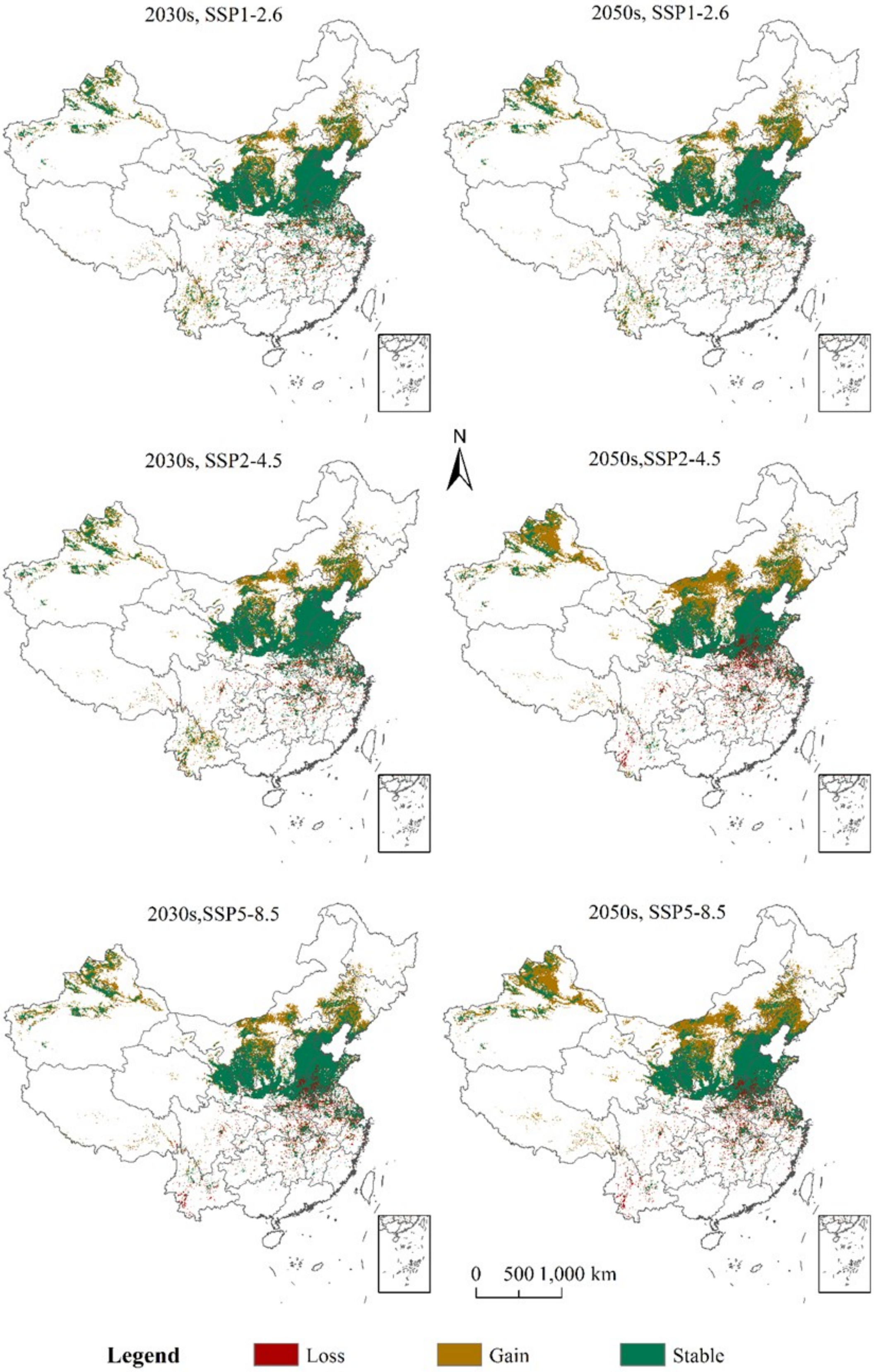


Figure9 Changes in the potential geographical distribution of *Cossus Linnaeus* under climate change scenarios.

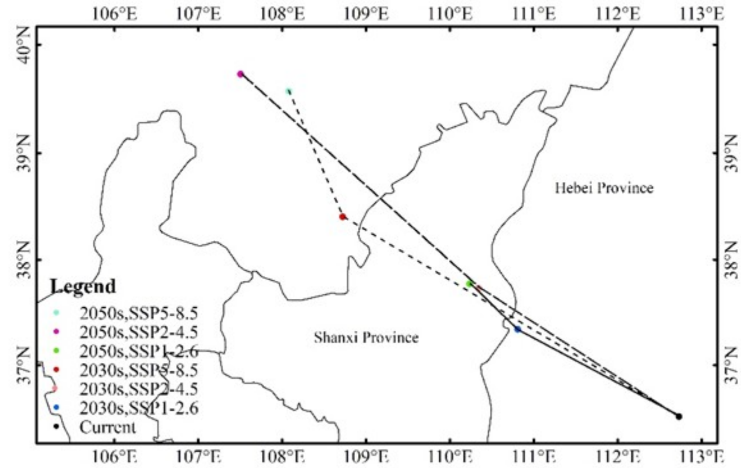


Figure10 Highly suitable area centroid distributional shifts under climate change for *Cossus Linnaeus*.

3 Discussion

The results show that the environmental variables affecting the potential geographical distribution of the Cossus Linnaeus are temperature, precipitation and NDVI, under the future climatic conditions, the area of the suitable size of the Cossus Linnaeus will increase, and the position of the relevant place will move to high altitudes.

When Xu[35] studied the limiting factors affecting the potential geographical distribution of *Heortia vitessoides Moore*, it was found that precipitation had the greatest influence on the potential geographical distribution of the pest, followed by the lowest temperature in the coldest month and the average temperature in the warmest season. Anouschka et al[36] studied 30 pest species in Sweden and found that the hottest season average temperature and annual average temperature are important factors affecting the current distribution of most harmful species. When studying the potential geographical distribution of *Euplatypus parallelus* in China, Tang et al[33] found that seasonal variation of temperature, annual range of average temperature, annual precipitation and average temperature in the coldest season are important variables to predict the potential geographical distribution of *Euplatypus parallelus* in China. These variables indicate that tropical and subtropical are ideal living areas for the pest. These studies show that precipitation and air temperature have important effects on the geographical distribution of pests, which is basically consistent with the conclusions of this paper, except that NDVI is an important variable that affects the distribution of *Cossus Linnaeus*. This study believes that this has a lot to do with the living habits of the species. *Cossus Linnaeus* hosts are *Populus L*, *Salix* and *Malus pumila Mill*. Larvae enter the branches and roots of trees, destroying the physiological function of trees and causing trees to wither or even die. Therefore, vegetation is closely related to the living habits of the species among the environmental variables that affect the potential geographical distribution of *Cossus Linnaeus*.

In this paper, the suitable growth areas of *Cossus Linnaeus* in modern and future climatic conditions of China are predicted by using MaxEnt model. It is found that the main suitable areas of *Cossus Linnaeus* in China are in Liaoning Province, Hebei Province, Shandong Province, Henan Province, Shaanxi Province, Shanxi Province, Ningxia Province and Gansu Province, etc., which is consistent with the actual distribution results[34]. And in the future climatic conditions, the suitable area of aromatic bark moth will increase. Wei Ji[17] used MaxEnt model to predict the potential geographical distribution of *Planococcus ficus* under three different climatic backgrounds, and found that the area of suitable growth area of *Planococcus ficus* increased in China and Australia. Wang Tao[37] studied the prediction of suitable growth area of D *Dendroctonus valens* in China, and found that under the condition of climate warming in the future, the suitable growth area of *Dendroctonus valens* japonicus will expand to the northwest and northeast. Negret et al[38] studied the prediction of potential suitable growth areas of *Obama nungara* in the world, and found that under the condition of future climate warming, there will be a large increase in suitable growth areas of *Obama nungara* worldwide. Xu et al[35] studied the prediction of suitable growth areas of *Heortia vitessoides Moore* in China in the case of future climate change, and found that the area of suitable growth areas of *Heortia vitessoides Moore* in the future climate conditions is 21.62% 40.65% more than that of now. In the study of harmful insects, many scholars have found that the suitable area of species with pests will increase under the condition of climate change in the future. The research results of this paper also confirm this conclusion, in the future three climate emission models, the area ratio of *Cossus Linnaeus* high suitable areas will increase by 26.7% to 87.4%, which will cause significant damage to forestry planting and ecosystem stability. At the same time, the study of this paper shows that the position of the suitable growth zone of the aromatic bark moth in China moves to high latitudes under the future climatic conditions. Zhang[38] and others found that under the climatic conditions of 2050 and 2070, the location of the suitable growth area of Phymata will move to the northwest; when studying the potential geographical distribution of *Aethina tumida*, Zakia[39] found that *Aethina tumida* will expand to northern Africa and some parts of Europe. Therefore, it is suggested that plant quarantine and other relevant departments should be highly vigilant and take necessary measures to control the expansion of the *Cossus Linnaeus*.

According to the research results, the suitable area of the Cossus Linnaeus will expand under the future climatic conditions, which is bound to cause significant harm to the growth of poplar, willow and apple trees. Therefore, it is necessary to pay attention to the spread of the Cossus Linnaeus and do the following control work: (1) carry out regular scavenging activities, including physical and chemical scavenging activities in pest suitable areas. (2) carry out strict quarantine during the transportation of parasitic trees to prevent human-made spread, and (3) regular inspection around the suitable growth area to prevent natural spread.

This study explores the geographical distribution of Cossus Linnaeus under present and future climatic conditions, and the results were consistent with expectations. Still, the survey of the environmental variables affecting the geographical distribution of Cossus Linnaeus was not thorough enough. Whether these ecological variables affect the geographical distribution of Cossus Linnaeus alone or interactively, and whether there are significant differences between these ecological variables need to be further studied.

4 Conclusion

Under current climatic conditions, the main distribution ranges of *Cossus Linnaeus* are Hebei Province, Beijing, Tianjin, Shandong Province, northern Henan Province, southern Shaanxi Province, southern Shanxi Province, southeastern Gansu Province and Ningxia. Under the 2030s and 2050s emissions, the suitable area of the *Cossus Linnaeus* will increase, and the position will move to high altitudes. The main environmental variables limiting the potential geographical distribution of the *Cossus Linnaeus* in China are normalized difference vegetation index (NDVI,40.3%), annual mean temperature (Bio1,24.1%), the min temperature of coldest month (Bio6,12.4%), the mean diurnal range (Bio2,90%). The content of environmental variables suitable for the growth of the *Cossus Linnaeus* is as follows: the average annual temperature (Bio1) is-0.26~29.81℃, the vegetation difference normalized index (NDVI) is 0.10~0.79, Min temperature of clodest month (Bio6) is -13.82~-1.1°C, and the mean temperature of coldest quarter (Bio11) is -5.48~4.78°C. Our research provides a scientific basis for the control of *Cossus Linnaeus* and the management and protection of trees in the future.

Funding: This work was supported by the National natural science foundation of China [grant numbers 40461011]; Lanzhou Talent Innovation and Entrepreneurship Project [grant number 2019-RC-105].

Conflicts of Interest: The authors declare no conflicts of interest.

Data Accessibility Statement: The data of this study is willing to upload to Dryad after the article is accepted.

REFERENCES

1. Lampert, A.; Hastings, A.; Sanchirico, J.N. Slow treatment promotes control of harmful species by multiple agents. *Conservation Letters* **2018**, *11*.
2. Sturrock, R.N.; Frankel, S.J.; Brown, A.V.; Hennon, P.E.; Kliejunas, J.T.; Lewis, K.J.; Worrall, J.J.; Woods, A.J. Climate change and forest diseases. *Plant Pathology* **2011**, *60*.
3. Bebber, D.P.; Holmes, T.; Gurr, S.J. The global spread of crop pests and pathogens. *Global Ecology and Biogeography* **2014**, *23*.
4. Crowl, T.A.; Crist, T.O.; Parmenter, R.R.; Belovsky, G.; Lugo, A.E. The spread of invasive species and infectious disease as drivers of ecosystem change. *Frontiers in Ecology and the Environment* **2008**, *6*.
5. Kozak, K.H.; Graham, C.H.; Wiens, J.J. Integrating GIS-based environmental data into evolutionary biology. *Trends in Ecology & Evolution* **2008**, *23*.
6. Willis, K.J.; Bhagwat, S.A. Biodiversity and Climate Change. *Science* **2009**, *326*, 806-807, doi:10.1126/science.1178838.
7. Brito, J.C.; Acosta, A.L.; Álvares, F.; Cuzin, F. Biogeography and conservation of taxa from remote regions: An application of ecological-niche based models and GIS to North-African canids. *Biological Conservation* **2009**, *142*.
8. John, H.; Annette, O.; L, G.J.; Ann, K. Biodiversity conservation: climate change and extinction risk. *Nature* **2004**, *430*.
9. Lenoir, J.; Gégout, J.C.; Marquet, P.A.; Ruffray, P.d.; Brisse, H. A Significant Upward Shift in Plant Species Optimum Elevation During the 20th Century. *Science* **2008**, *320*.
10. Dai, J.; Roberts, D.A.; Stow, D.A.; An, L.; Hall, S.J.; Yabiku, S.T.; Kyriakidis, P.C. Mapping understory invasive plant species with field and remotely sensed data in Chitwan, Nepal. *Remote Sensing of Environment* **2020**, *250*.
11. Deb, J.C.; Forbes, G.; MacLean, D.A. Modelling the spatial distribution of selected North American woodland mammals under future climate scenarios. *Mammal Review* **2020**, *50*.
12. Jiménez-Valverde, A.; Peterson, A.T.; Soberón, J.; Overton, J.M.; Aragón, P.; Lobo, J.M. Use of niche models in invasive species risk assessments. *Biological Invasions* **2011**, *13*.

13. Sobek-Swant, S.; Kluza, D.A.; Cuddington, K.; Lyons, D.B. Potential distribution of emerald ash borer: What can we learn from ecological niche models using Maxent and GARP? *Forest Ecology and Management* **2012**, *281*.
14. Phillips, S.J.; Anderson, R.P.; Schapire, R.E. Maximum entropy modeling of species geographic distributions. *Ecological Modelling* **2006**, *190*.
15. Phillips, S.J.; Dudík, M. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* **2008**, *31*.
16. Zhao, H.; Zhang, H.; XU, C. Study on Taiwania cryptomerioides Under Climate Change: MaxEnt Modeling for Predicting the Potential Geographical Distribution. *Global Ecology and Conservation* **2020**.
17. Ji, W.; Han, K.; Lu, Y.; Wei, J. Predicting the potential distribution of the vine mealybug, Planococcus ficus under climate change by MaxEnt. *Crop Protection* **2020**, *137*.
18. Li, Y.; Li, M.; Li, C.; Liu, Z. Optimized Maxent Model Predictions of Climate Change Impacts on the Suitable Distribution of Cunninghamia lanceolata in China. *Forests* **2020**, *11*.
19. Muscarella, R.; Galante, P.J.; Soley-Guardia, M.; Boria, R.A.; Kass, J.M.; Uriarte, M.; Anderson, R.P.; Mcpherson, J. ENMeval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods in Ecology & Evolution* **2015**, *5*, 1198-1205.
20. Wang, J.-F.; Hu, Y. Environmental health risk detection with GeogDetector. *Environmental Modelling and Software* **2012**, *33*.
21. Yang, Y.; Yang, J.; Xu, C.; Xu, C.; Song, C. Local-scale landslide susceptibility mapping using the B-GeoSVC model. *Landslides* **2019**, *16*.
22. Xie, Z.; Qin, Y.; Li, Y.; Shen, W.; Zheng, Z.; Liu, S. Spatial and temporal differentiation of COVID-19 epidemic spread in mainland China and its influencing factors. *Science of the Total Environment* **2020**, *744*.
23. Ma, R.; Liang, L.; Kong, Y.; Zhai, S.; Gu, J.; Zhang, G.; Wang, T. Hotspot detection and socio-ecological factor analysis of asthma hospitalization rate in Guangxi, China. *Environmental Research* **2020**, *183*.
24. Wang, T.; Song, H.; Wang, F.; Zhai, S.; Han, Z.; Wang, D.; Li, X.; Zhao, H.; Ma, R.; Zhang, G. Hysteretic effects of meteorological conditions and their interactions on particulate matter in Chinese cities. *Journal of Cleaner Production* **2020**, *274*.
25. Xiaomeng, L.; Hongquan, S.; Tianjie, L.; Pengfei, L.; Chengdong, X.; Dong, W.; Zhongling, Y.; Haoming, X.; Tuanhui, W.; Haipeng, Z. Effects of natural and anthropogenic factors and their interactions on dust events in Northern China. *Catena* **2021**, *196*.
26. Yu, G.; Xinyu, Z.; Qiubing, W.; Hongkun, C.; Xianyuan, D.; Yuping, M. Temporal changes in vegetation around a shale gas development area in a subtropical karst region in southwestern China. *The Science of the total environment* **2020**, *701*.
27. Parmesan, C. Ecological and Evolutionary Responses to Recent Climate Change. *Annual Review of Ecology, Evolution, and Systematics* **2006**, *37*.
28. Zeng, Y.; Low, B.W.; Yeo, D.C.J. Novel methods to select environmental variables in MaxEnt: A case study using invasive crayfish. *Ecological Modelling* **2016**, *341*.
29. Zhang, J.; Cao, G.-L.; Li, X.-C.; Zhan, M.-J.; Jiang, T. The latest progress in the study of new socio-economic scenarios (SSPs) in IPCC AR5. *Climate Change Research* **2013**, *9*, 225-228.
30. Wang, J.-F.; Xu, C.-F. Geodetector: Principle and prospective. *Acta Geographica Sinica* **2017**,

72, 116-134.

31. Wang, J.-F.; Li, X.-H.; Christakos, G.; Liao, Y.-L.; Zhang, T.; Gu, X.; Zheng, X.-Y. Geographical Detectors-Based Health Risk Assessment and its Application in the Neural Tube Defects Study of the Heshun Region, China. *International Journal of Geographical Information Science* **2010**, *24*.
32. A., S.J. Measuring the accuracy of diagnostic systems. *Science* **1988**, *240*.
33. Jihong, T.; Jinhua, L.; Hui, L.; Fuping, L.; Baoqian, L. Potential distribution of an invasive pest, Euplatypus parallelus, in China as predicted by Maxent. *Pest Management Science* **2019**, *75*.
34. Zhang, D.-J. Control methods of Cossus Linnaeus. C*hina Flowers & Horticulture* **2016**, 47.
35. Xu, D.; Li, X.; Jin, Y.; Zhuo, Z.; Yang, H.; Hu, J.; Wang, R. Influence of climatic factors on the potential distribution of pest Heortia vitessoides Moore in China. *Global Ecology and Conservation* **2020**, *23*.
36. Hof, A.R.; Svahlin, A. The potential effect of climate change on the geographical distribution of insect pest species in the Swedish boreal forest. *Scandinavian Journal of Forest Research* **2016**, *31*.
37. Wang, T.; Ge, X.-Z.; Zong, S.-X. Predicting the potential distribution in China of Dendroctonus valens Leconte. *Journal of Environmental Entomology* **2018**, *40*, 758-768.
38. Mengyuan, Z.V.; David, P.; Locke, R. Climate change has different predicted effects on the range shifts of two hybridizing ambush bug (Phymata, Family Reduviidae, Order Hemiptera) species. *Ecology and Evolution* **2020**, *10*.
39. A., J.Z.; F., A.-S.H.; Samina, Q.; Mashael, A.A.; Khalid, A.K.; Muhammad, F.K.; Muhammad, A.B.; Abdul, H.; N., A.-K.S.; A., T.E.-K., et al. Future expansion of small hive beetles, Aethina tumida, towards North Africa and South Europe based on temperature factors using maximum entropy algorithm. *Journal of King Saud University - Science* **2021**, *33*.