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Predicting current and future potential distribution of *Cynaeus angustus* (Coleoptera: Tenebrionidae) in global scale using the MaxEnt model

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ABSTRACT

The larger black flour beetle, *Cynaeus angustus* (LeConte), as a fauna extending storage insect has rapidly spread globally from its native North America to other continents and countries in the last three decades. Based on the occurrence records and environmental variables, the current and future potential distribution on a global scale are predicted using MaxEnt model. The results showed that the current suitable area involved in China, South Korea, North Korea, Japan, Kazakhstan, Afghanistan, Australia, Argentina, the Republic of South Africa, North America, and most of European countries. Under future climate change scenarios, this insect is predicted to remarkably expand its fauna range to the north and Representative Concentration Pathways 8.5 (RCP8.5) provides the largest expansion, and the suitable area expands in the northern hemisphere whereas contraction in the southern hemisphere. The annual mean temperature, temperature annual range were the key factors influencing the potential distribution of *C. angustus*. The results of this study provide basic data for pest monitoring, early warning measures, and quarantine strategies in high-risk countries.

1. Introduction

The larger black flour beetle, *Cynaeus angustus* (Leconte) (Coleoptera: Tenebrionidae), is an emerging species with a high probability of developing into an important storage insect pest in the world (Athanassiou and Rumbos, 2018; Barak et al., 1981; Dunkel et al., 1982; Furui et al., 2020; Soldati and Godinat, 2013). This insect causes damage to a variety of stored grains, flour and related products, especially prefers to maize (Dunkel et al., 1982). The commodity consumed by the pest is more than other for storage beetles, and the larvae consume food at a rate that is comparable to the larvae of *Plodia interpunctella* (Hübner) which is the notorious moth cereal pest (White and Sinha, 1987). In addition, this pest can establish colonies in cotton gin trash piles (stored residue from the cotton ginning process), thus generating serious nuisance effects on public and private structures (Nansen et al., 2008).

Before 1900, *C. angustus* was originally found in the desert of the southwestern USA and Mexico, and its habitat was closely related to the Agavaceae and other semi-succulent plants (Dunkel et al., 1982). However, this insect had been frequently encountered in stored grain and other storage situations in the USA since 1938 (Hatch, 1940). By the 1980s, the species had spread throughout the continental United States and caused damage to maize, beans and other stored products, while the economic importance of this pest was recognized (Dunkel et al., 1982). In the past 40 years, *C. angustus* has been introduced into parts of Europe and Asia by trade, recorded in Sweden and Finland (Ferrer and Andersson, 2002), France (Soldati and Godinat, 2013), Germany (Eichler and Pütz, 2017), Poland (Ruta et al., 2017), the Czech Republic (Mantič and Vavra, 2017), Romania (Pintilioaie and Teodorescu, 2021), Latvia (Telnov et al., 2020), Ukraine and Russia (Kovalenko et al., 2016), China (Zhang et al., 2016), South Korea (Hong and Yun, 2017) and Thailand (Delobel and Tran, 1993). At present, *C. angustus* has a broad international distribution and appears to be spreading rapidly (Fig. 1).

The geographical distribution of pests is mainly determined by climate factors, food, and human activity (Skendžić et al., 2021). The way for *C. angustus* to enter the grain storage from the field may through with the harvest after infecting the grain in the wild, and further spread with the trade. Climate influences the microclimate of the grain storage and determines the species that are available to invade there (Arbogast and Mullen, 1988). Many studies have shown that increased temperature tends to accelerate insect development and movement, which can affect population dynamics by influencing fecundity, survival, generation time, population size, and geographic range (Battisti and Larsson, 2015; Skendžić et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) reported that the earth could experience global warming

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over the next century. Insects are likely to be affected by climate change because they are ectothermic and sensitive to temperature (Battisti and Larsson, 2015). Therefore, with global trade and climate change, whether this species can be introduced more countries and establish there to finally develop into a common and cosmopolitan storage pest remains unknown. Currently, the primary thing is to research potential geographic distribution of *C. angustus*, that is, the area in which it can establish and spread. This information is important since it provides scientific evidence for the grain storage industry and quarantine authorities to formulate prevention and control measures.

Ecological niche models (ENMs) have been widely used to predict biological invasion risk areas by predicting their potential geographic distribution based on inferred environmental fitness of currently known species distribution data (Venette et al., 2010). Prediction models and software for potential geographic distributions mainly include CLIMEX (Sutherst and Maywald, 1985), GARP (Stockwell and Peters, 1999), MaxEnt (Phillips et al., 2006) and mechanistic niche model (Kearney and Porter, 2009). Among the modeling methods, MaxEnt is one of the most widely used models due to its continuous optimization and excellent prediction performance. According to the known distribution area of the species and environmental factors, the Maxent model simulates its niche requirements with the maximum entropy theory and infer potential distribution of the species in the target area (Hernandez et al., 2008; Phillips et al., 2006). Even with limited known distribution data, the prediction performance of the MaxEnt model is still better than other models (Elith et al., 2006; Hernandez et al., 2008; Peterson et al., 2007). The MaxEnt niche model is combined with GIS to species data is combined with environmental data to generate predictions that can visually displayed in the form of thematic maps, which have been widely used in analyzing and evaluating the suitability of invasive species (Baloch et al., 2020; Lee et al., 2021; Wei et al., 2020).

In terms of distribution area, *C. angustus* has a wide range of adaptability, but there is no research on its suitable area. Accordingly, this study aims to estimate the current and future potential distribution of this pest worldwide, and explore what are the critical environmental factors that correlate with the distribution of *C. angustus*.

2. Methods

2.1. Occurrence data

The distribution data of *C. angustus* were obtained from the following sources: the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/), previously published literature and the data of recent survey concern on storage pests in China. Locations indicating city, county, town locations are retained, whereas only country are eliminated. The location coordinates are obtained by querying Google Earth. Duplicate locations and errors are removed in distribution data. After that, 261 available occurrences of *C. angustus* were obtained.

To reduce spatial autocorrelation and sampling bias, all occurrences were screened according to the method described by (Brown, 2014). The first step of the work was to define the location cluster range as 7 km, then removed the highly autocorrelated locations and keep only one point within each cluster. After the filtering process, the final occurrence database consists of 115 unique points locations (Table S1).

2.2. Environmental variables and data processing

The 19 climatic datasets were obtained from the WorldClim Global Climate Database (http://www.worldclim.org/) for current and future climate. Current climate conditions were represented by monthly average data from 1950 to 2000. Future climate conditions, estimated for 2050 (average for 2041–2060) and 2070 (average for 2061–2080), were derived from four global climate models (GCMS): NorESM1-M (NO), MIROC-ESM-CHEM (MI), IPSL-CM5A-LR (IP) and HadGEM2-ES (HE), which belong to the GCM climate prediction that are used in the Fifth Assessment Intergovernmental Panel on Climate Change (IPCC) report. These models are selected to give a wide range of climatic factors. The final results are the average of predicted results of the four GCMs. To assess the uncertainty of global climate change, we selected the Representative Concentration Pathway 2.6 (RCP 2.6) as the minimum emission scenario, and the Representative Concentration Pathway 8.5 (RCP 8.5) as the maximum scenario. These scenarios were proposed by IPCC and represents the radiative forcing estimated based on the predicted greenhouse gas emissions. The spatial resolution of each variable is 5 arc-minutes.

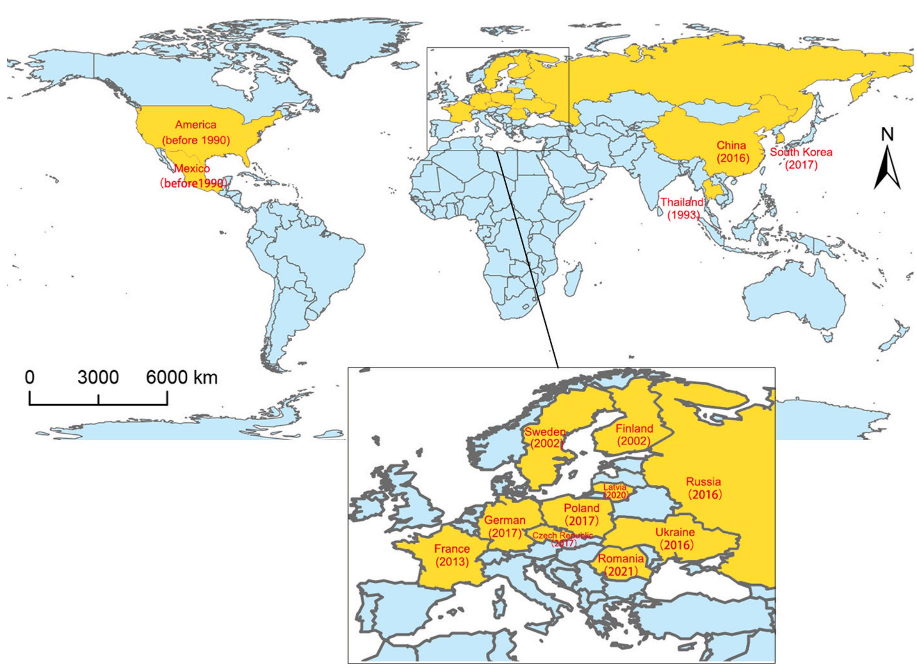

Fig. 1. The country and year of distribution record of *C. angustus*.

Correlations and multicollinearity among climatic factors may negatively affect the accuracy of niche model predictions (Heikkinen et al., 2006). In order to reduce the risk of overfitting and improve the accuracy of the model, the Pearson correlation coefficient is usually used to judge the correlation between each pair of variables ($|r| \geq 0.75$) (Kumar et al., 2014) (Table S2). Multicollinearity was examined using ENMTools (version 1.0.40). Finally, six variables were selected, including annual mean temperature (Bio1), mean diurnal Range (Bio2), temperature annual range (Bio7), annual precipitation (Bio12), precipitation Seasonality (Bio15), precipitation of driest quarter (Bio17).

2.3. Modeling approach

The Maxent software (version 3.3.3 k) was used to predict the potential geographic distribution of this pest. The 75% of the occurrence were set as training points, and the rest were set as test points. The result is the average of 10 replicates.

Feature types and regularization multipliers are adjustable parameters in MaxEnt, which have a great impact on model optimization (Phillips et al., 2017). An appropriate combination of parameters can prevent the model from being too simple or too complicated (Morales et al., 2017). To select the optimal combination parameters of regularization multiplier (RM) value and feature combinations (FCs), the R package "ENMeval" and a method for automatically performing model were used tcalculations based on user-specified ranges (Muscarella et al., 2014). The RM range from 0.5 to 4, with the increments of 0.5 and all combinations of six features, were examined for this species. The ENMeval package was executed in R (v 3.6.3) (R-Core-Team, 2022). After the computation, the parameter combination with the lowest delta of the standardized Akaike information criterion coefficient AICc score was chosen (Tables S3 and S4). Finally, RM = 2, and FC = LQPTH (Linear, Quadratic, Product, Threshold, Hinge) were selected for this species to run final MaxEnt models.

2.4. Model evaluation and interpretation

The accuracy of the model was evaluated by the AUC value of the ROC curve. The range of the AUC value was between [0, 1]. When AUC<0.7, the accuracy of the prediction result is considered to be poor, and when $0.7 \leq$ AUC< 0.9 means that the accuracy of the prediction results is average, and when AUC ≥ 0.9, it is considered that the prediction results are accurate. The accuracy of the test results is high (Jiménez-Valverde, 2012).

The jackknife method was used to test various environmental variables for the importance and influence of the spatial distribution of this species (Phillips et al., 2004). A higher percentage contribution (PC) or permutation importance (PI) can indicate the importance of the environmental variables to the model predictions. Response curves of each variable were used to analyze the relationship between habitat suitability and each environmental variable.

2.5. Estimating habitat changes between current and future

The "maximum sensitivity plus specificity" probability threshold was adopted as the boundary threshold between suitable and non-suitable areas for this species. This threshold is considered to be one of the best thresholds that provides the most accurate predictions and has been widely used in modeling studies (Jiménez-Valverde and Lobo, 2007; Liu et al., 2005). Based on this threshold, we transformed the continuous suitability map into a binary model of presence/absence maps. The grids above this threshold in the prediction results are suitable areas, and those below this value are non-suitable areas. This study compares habitats in future scenarios with the current and calculates the extent of habitat expansion or contraction based on binary models.

To explore the orientation of the centroid distribution area of the distribution area under current and future climatic conditions, the distribution was summarized as a point, the centroid of the niche (Brown, 2014; VanDerWal et al., 2013). The centroid is the result by calculating the mean coordinates of all 'suitable' grids in binary models.

3. Results

3.1. Current distribution

The ROC curve of the predicted results of this study is shown in Fig. 2. The curve analysis results show that the average AUC value of the model is 0.921 ± 0.04, which indicated a high level of accuracy in the model prediction.

There is suitability in all the continents for *C. angustus* except Antarctica, mainly in zones from 20° to 60° in the Northern Hemisphere, and from 20° to 50° in the Southern Hemisphere (Fig. 3). **Most areas in Europe** are suitable for this pest, and the northern reaches of the southernmost part of Finland. **In Asia,** the high suitability areas are in Central and Eastern China, South Korea, North Korea, Japan, Southeast of Kazakhstan, the border between Tajikistan and Kyrgyzstan, Southwest of Afghanistan, Median and Northern of Pakistan, Western of Iran and the border with Turkmenistan, Turkey, Georgia, Armenia, Azerbaijan. **In Africa,** the high suitability is located mainly in the Republic of South Africa, Morocco, Northern coast of Algeria and Tunisia near the Mediterranean. **In Oceania**, large suitability areas are in the Australia especially in southern part. **In North America**, *C. angustus* has high suitability in almost all of United States, Mexico, and the southernmost areas of Canada. **In South America,** the main suitability areas are located mostly in Central Argentina and some areas of Peru, Bolivia, and Chile.

3.2. Future distribution prediction and change

Under the two future climatic models, the global total suitability areas of this pest will increase to varying degrees (Fig. 4). Some of the current suitable areas of *C. angustus* will not be (e.g. contraction), whereas some current unsuitable areas will become suitable areas in the future (e.g. expansion). The expansion and contraction of ranges are visualized in binary models (Fig. 5). The range of suitable areas will have a larger area of expansion and a smaller contraction under all future scenarios. Under RCP 2.6 scenarios, the expansion of this pest is mainly in the Northern Hemisphere, including north Americas, Europe, Asia. Large areas of new habitat will be established in Canada, Kazakhstan, Southwestern Russia, Northern Europe, Northern China. However, some

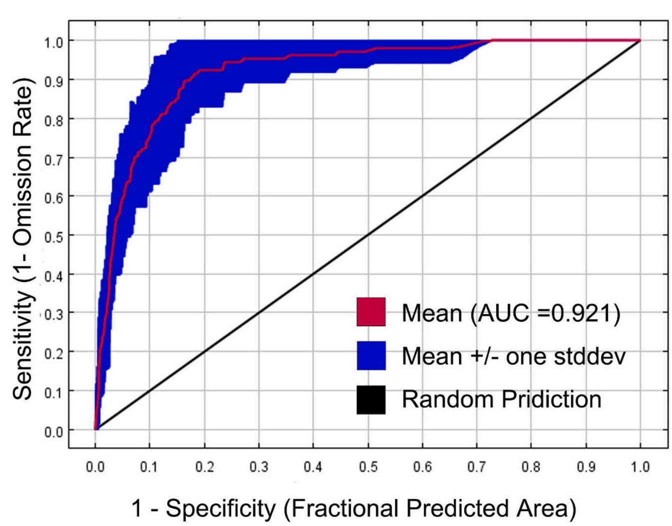

Fig. 2. ROC curve verification of the predicted potential distribution for *C. angustus* by MaxEnt.

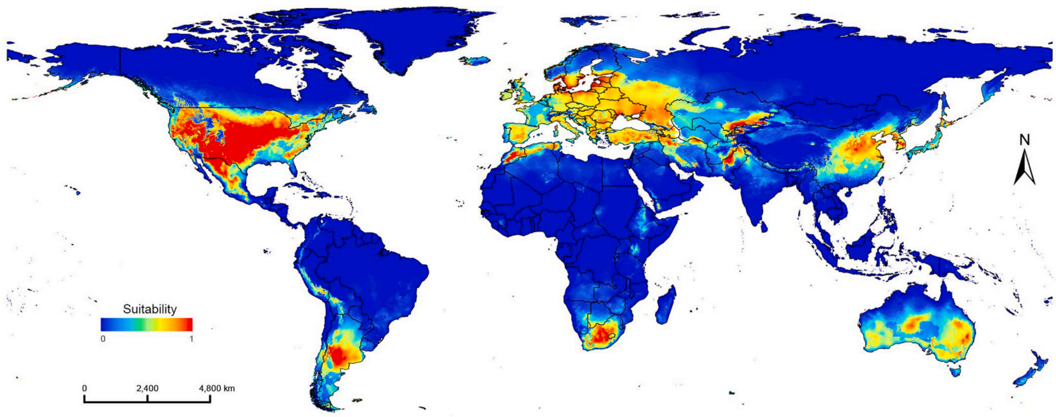

Fig. 3. Predicted potential distribution of *C. angustus* in world under current climate.

contractions are in Australia, the Republic of South Africa, and Southern China. RCP 8.5 causes the larger expansion and contraction than RCP 2.6.

With the increase of hypothetical emissions of GHGs, habitat suitability of *C. angustus* was also predicted to increase in the world (Table 1). Under emission scenario RCP 2.6, the total suitability areas of *C. angustus* in 2050 would increase to approximately 0.41×10^7 km^2, accounting for 20.6% of current predicted areas. Under the same climate scenario in 2070, there is little change in the areas of contraction and expansion. Under emission scenario RCP 8.5, the total potential distribution of *C. angustus* in 2050 would increase to approximately 0.62×10^7 km^2, accounting for approximately 31.0% of current predicted area. More seriously, the total potential distribution of *C. angustus* in 2070 would increase to approximately 1.12×10^7 km^2, accounting for approximately 61.9% of current predicted area.

3.3. Range shifts between current and future models

The direction and extent of the centroid change under future conditions is shown in Fig. 6. The current centroid is in Algeria. Under two climate change scenarios, the centroids are shifted northward to varying degrees. The centroids are predicted to shift in Spain under RCP 2.6, and in France under RCP 8.5. As emissions increase, the centroid of suitability areas is shifted further north.

3.4. Variable contribution and environmental responses

Table 2 shows that the PC and PI of each variable used in the final models. Annual mean temperature (Bio1) and temperature annual range (Bio7) were major factors influencing the model performance for *C. angustus*. Other contributing factors were annual precipitation (Bio12), precipitation of driest quarter (Bio17), mean diurnal range (Bio2). Results show that thermal factors are more important than precipitation factors for model predictions.

The prediction results also provide a relationship between survival probability and environmental factors (Fig. 7). Annual mean temperature (bio1) shows high response values at approximately 4–21 °C, indicating a positive response with the suitability of *C. angustus* for temperature below 14 °C but a negative relationship for temperature above 14 °C. When the temperature annual range (bio7) is lower than 37 °C, the suitability of *C. angustus* increases with temperature, once it exceeds 37 °C, the value will decrease rapidly. Annual precipitation (bio12) shows high response values at approximately 200–1300 mm. As for precipitation of driest quarter (Bio17), it shows high response values at approximately 20–200 mm. Mean diurnal range (Bio2) ranged from 9 to 22 °C, indicating a positive response with the occurrence of *C. angustus* for temperature. Precipitation seasonality (Bio15) has the highest probability of presence at approximately 20, and then the value decrease when precipitation seasonality exceeds 20.

Overall, the results showed that the maximum suitability of *C. angustus* occurred when the annual mean temperature was 14 °C, temperature annual range was 37 °C, mean diurnal range was 22 °C, the range of annual precipitation was 200–1300 mm and the precipitation of driest quarter was 40 mm.

4. Discussion

The current potential global distribution of *C. angustus* predicted by the MaxEnt mode indicated high performance of the model, as it included the current actual distribution areas for this species. For example, potential areas were found in most of Europe, which is consistent with the known distribution of *C. angustus*. Furthermore, the current potential distribution predicted by the model involved some parts of south Africa, south America, Australia, Western and Central Asia, where *C. angustus* has not yet been recorded. This indicates that the current potential distribution area might be broader than the actual observed area.

Different species probably have different responses to climate warming. Some species may increase their global habitat in the future (Carvajal et al., 2019), while others may decrease (Lee et al., 2021; Santana et al., 2019). In this study, under various climate scenarios in the future, the suitable area of *C. angustus* will expand to varying degrees in world. The centroids shift for *C. angustus* under RCP 2.6 and RCP 8.5 are north, and the degree of centroids shift is positively correlated with the climate warming. Although the area of suitable habitats is increasing globally, there are different trends in the northern and southern hemispheres. With global warming, extensive areas in Northern Hemisphere will probably to turn out be new habitats for *C. angustus* in the future, with suitable areas in Canada, Sweden, Finland, Norway, Russia, China, Kazakhstan, and other countries will see a further increase in populations to the north. On the contrary, in the Southern Hemisphere, the habitable areas of South Africa, Argentina, Australia will continue to decrease in the future. This seems to indicate that it is necessary to strengthen the monitoring of this pest in countries in the northern hemisphere.

The distribution and dispersal of species are influenced by environmental and biological factors (Chuine, 2010). In this study, the annual mean temperature and temperature annual range were most influential on the global distribution of *C. angustus*. These factors naturally affect the movement of pests, resulting in short-distance and slower dispersal. The rate of dispersal is positively related to the population density of the species (Takahashi and Park, 2020). However, *C. angustus* displays a high dispersal speed and long-distance dispersal, which are highly related to human activities (Choi et al., 2019). In particular, an increase in international trade and travel accelerates the dispersal of various invasive species on a global scale (Hulme, 2010). Among the countries at

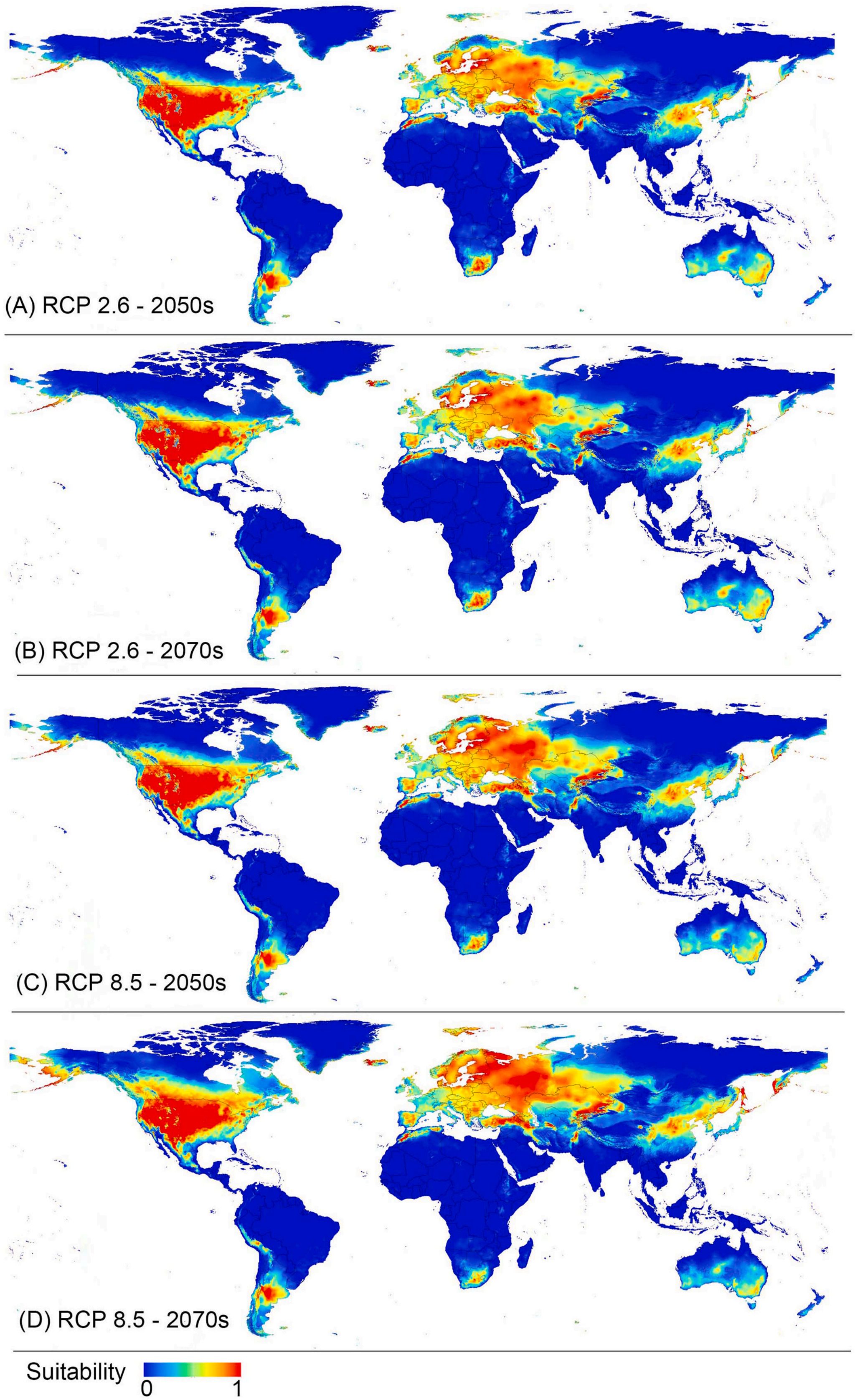

Fig. 4. Predicted potential distribution of *C. angustus* in world under future climate: (A) in 2050s under scenario RCP 2.6, (B) in 2070s under scenario RCP 2.6, (C) in 2050s under scenario RCP 8.5, (C) in 2070s under scenario RCP 8.5. These scenarios were proposed by IPCC and represents the radiative forcing estimated based on the predicted greenhouse gas emissions.

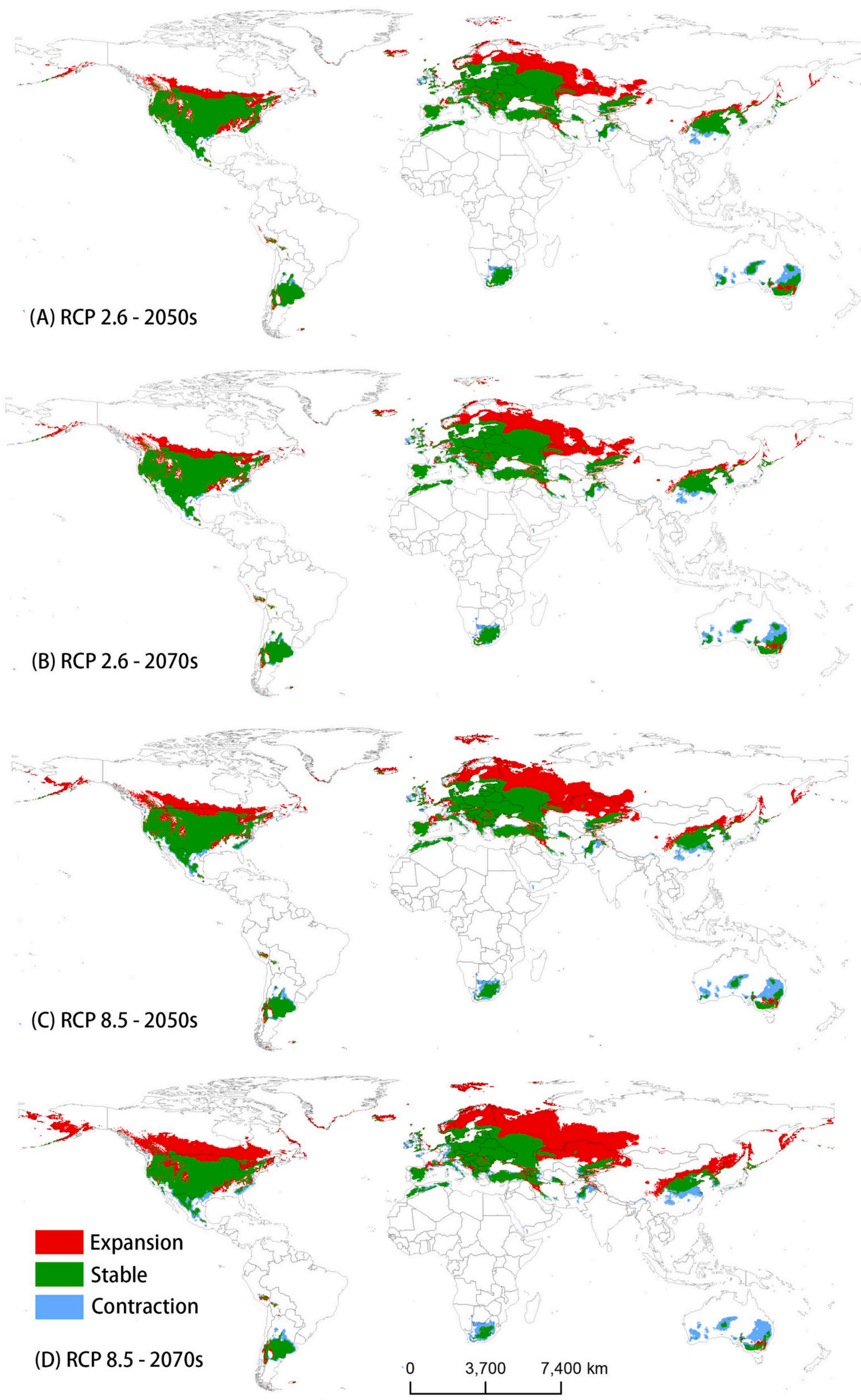

Fig. 5. Predicted changes in modelled range of *C. angustus* under current and future climate. Binary models were generated based on 'Maximum sensitivity plus specificity' threshold (0.3555). Red color represents the current suitable areas of *C. angustus* will not be (e.g. contraction), green color represents the suitable areas will not change in the future, and blue color represents current unsuitable areas will become suitable areas in the future (e.g. expansion).

Table 1
Area of suitability change of different climate scenarios (km^2).

Area change	RCP 2.6–2050	RCP 8.5–2050	RCP 2.6–2070	RCP 8.5–2070
Stable	1.77×10^7	1.67×10^7	1.76×10^7	1.37×10^7
Expansion	0.63×10^7	0.95×10^7	0.66×10^7	1.56×10^7
Contraction	0.22×10^7	0.33×10^7	0.24×10^7	0.44×10^7

risk of *C. angustus* predicted in this study, some countries have frequently intercepted this pest in import trade and have taken corresponding measures. For example, Japan had reported *C. angustus* detection during plant quarantine (Furui et al., 2020). In the importing of maize from United States, *C. angustus* had been listed as a regulated pest after risk analysis by the Australian Quarantine & Inspection Service (Ikin et al., 1999). However, most of the predicted at-risk countries are apparently unaware of the high risk of this pest and its serious impact on stored maize together with its related products in the future. Once this pest is introduced into countries with high suitable through human trade, its dispersal is rapid and control is difficult. Eventually this pest will develop into an important stored grain pest in the world. Therefore, to prevent further introductions and expansions of *C. angustus*, the results of the MaxEnt model show that high-risk countries should establish an intensive plant quarantine program and control strategy.

5. Conclusions

This study predicted the current and future potential distribution of *C. angustus* on a global scale using the MaxEnt model, and the prediction results have high reliability. Areas of potential distribution identified by the modeling approaches included China, South Korea, North Korea, Japan, Kazakhstan, Afghanistan, Australia, Argentina, the Republic of South Africa, North America, and most countries located in Europe. The annual mean temperature, temperature annual range were the key factors influencing the potential distribution of *C. angustus*. The future potential distribution areas of *C. angustus* were predicted to a significant increase with global warming, and the suitability habitats for *C. angustus* was predicted to expand in the northern hemisphere and contract in the southern hemisphere. The results of this study provide basic data for pest monitoring, early warning measures, and quarantine strategies in high-risk countries.

Table 2
Percent contribution (%) and Permutation importance (%) of environmental variables in predicting the occurrence of *C. angustus* in the MaxEnt model.

Variable	Percent contribution	Permutation importance
Annual mean temperature (bio1)	60.7	70.9
Temperature annual range (bio7)	13.2	14
Annual precipitation (bio12)	9.3	4.4
Precipitation of driest quarter (bio17)	9	4.6
Mean Diurnal Range (bio2)	5.9	5.2
Precipitation Seasonality (bio15)	1.9	0.8

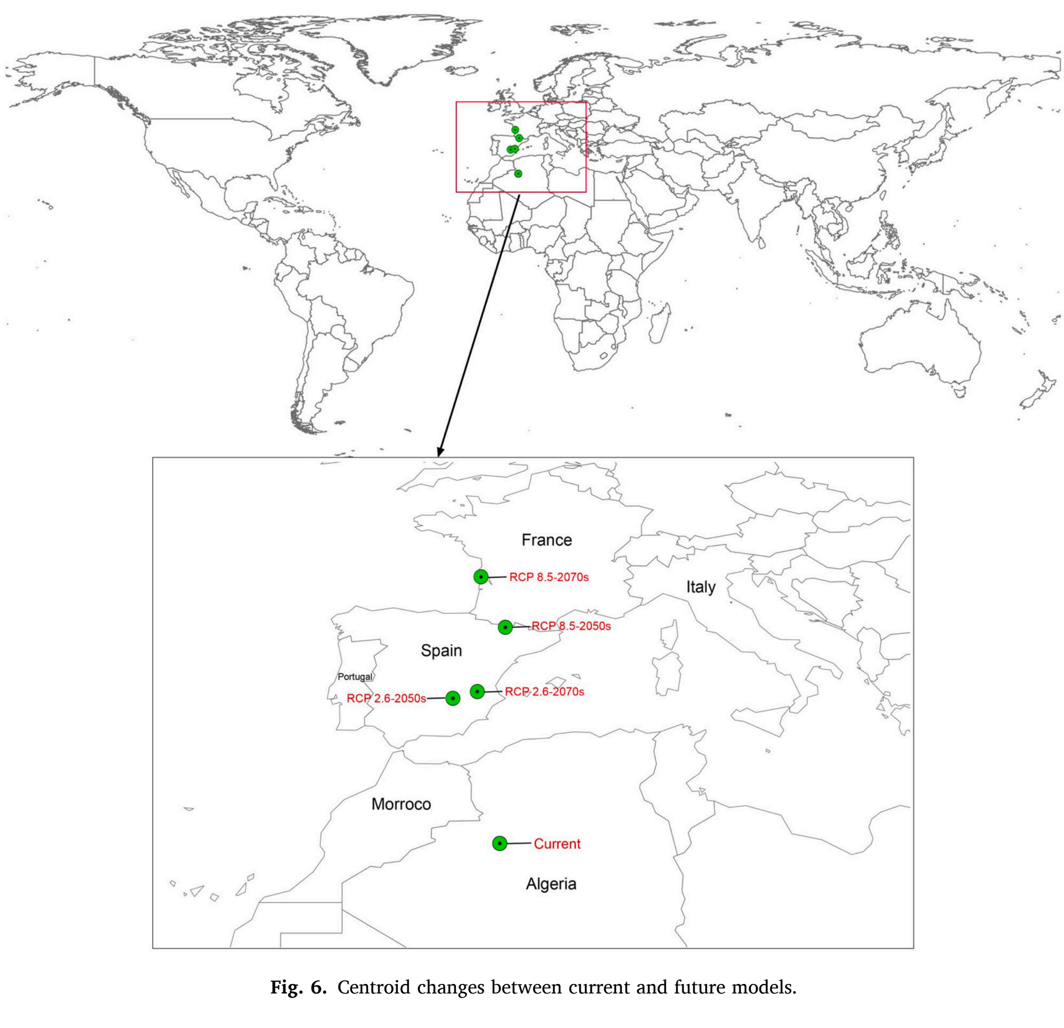

Fig. 6. Centroid changes between current and future models.

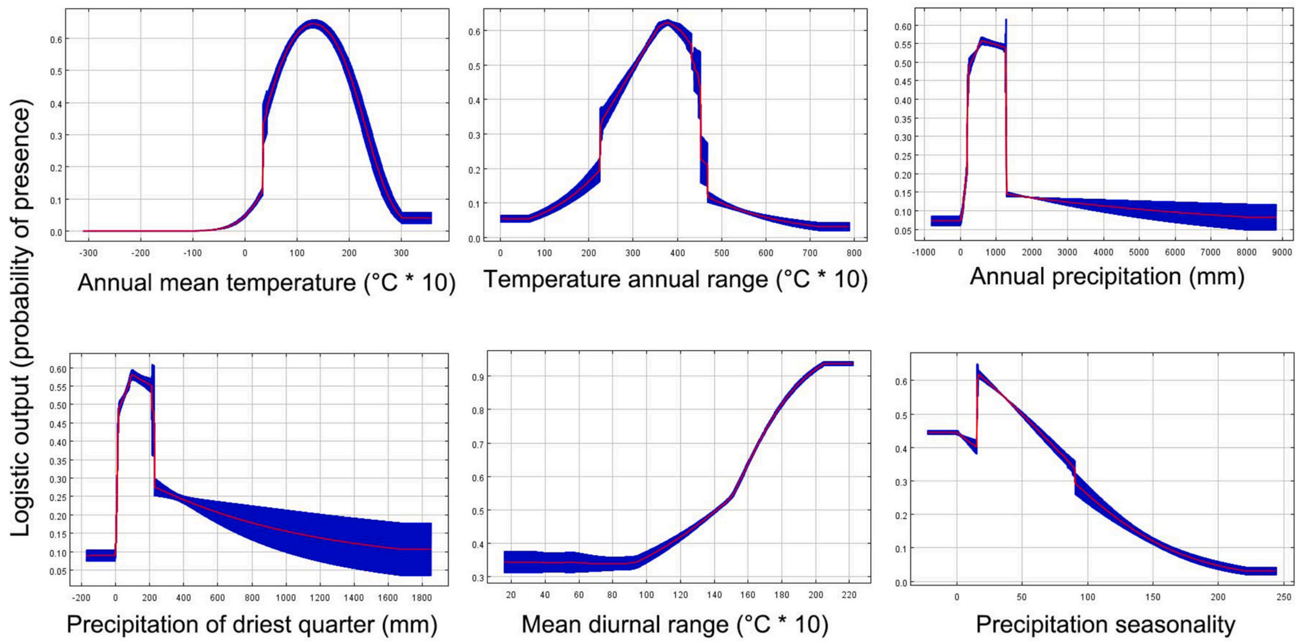

Fig. 7. Response curves showing the relationships between the probability of presence of *C. angustus* and six bioclimatic variables. Values shown are average over 10 replicate runs: blue margins show ± SD calculated over 10 replicates.

Author statement

Chao Zhao: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing - original draft, Writing - review & editing.

Chunqi Bai: Resources, Validation, Resources, Writing - review & editing. Dianxuan Wang: Resources, Writing - review & editing.

Declaration of competing 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.

Data availability

I have shared the link to my data/code at the Attach File step

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jspr.2023.102089.

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