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Maxent Model Predictions of Climate Change Impacts on the Suitable Distribution of Crayfish Aquaculture in China

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ABSTRACT

Background: Red swamp crayfish (*Procambarus clarkii*) is one of the most economically important farmed aquatic species in China. However, it is also a famous invasive species in the world.

Methods: The present study simulated near current (1970-2000) and future (2030s, 2050s) suitable distribution areas of *P. clarkii* aquaculture in China under 4 climate scenarios (SSP126, SSP245, SSP370 and SSP585) and screened out the dominant factors affecting the distribution as well, using the MaxEnt model with 60 effective distribution points.

Result: The results showed that mean AUC was 0.986, which indicated a better forecast. The highly suitable aquaculture areas for crayfish were Hubei, Hunan, and Anhui Province. The important environmental factors affecting the distribution of *P. clarkii* were mean temperature of warmest quarter, precipitation of wettest quarter, isothermality and temperature seasonality. Compared to the present-day predictions, the total area of suitable distribution (general-, medium- and high-suitability) gradually increased in the 2030s and 2050s. The ranking of the total area under different climate change scenarios were SSP370 > SSP585 > SSP126 > SSP245 in the 2030s and SSP585 > SSP370 > SSP126 > SSP245 in the 2050s, indicating that as the greenhouse gas emissions increase, the distribution of *P. clarkii* was likely to increase. It was of note that the area of high-suitability distribution for SSP585 greatly increased, but for SSP245 greatly decreased in the 2050s. This suggested that we should attach great importance to the ecological risk of crayfish in China and prevent the blind development of the industry.

Key words: ArcGIS, China, Crayfish, MaxEnt, Suitable distribution area.

INTRODUCTION

It is frequently proposed that species' ranges shift in response to climate change in order to keep the species within their climatic niches (Coristine *et al*., 2015). Although organisms can actively adapt to future climate change, it is still under threat from increasing human activities and global climate change (Xu *et al.,* 2021; Anand *et al*., 2021). Modeling is a powerful method in aquatic animal ecology (Wu *et al.* 2018, 2020, 2021) and for suitable distribution, Maxent model is relatively simple and quick to run, has a small sample demand, provides stable operation results and allows prediction results to be tested (Estes *et al.,* 2013). The red swamp crayfish, *Procambarus clarkii* (Girard 1985), native to north-eastern Mexico and south-central United States, is one of the world's most invasive species (Gherardi, 2006) and its aggressive burrowing leads to the damages of levee, dam and paddy field (Barbaresi *et al*., 2004). In 1920s, *P. clarkii* invaded China from Japan and now widely distributed in almost all types of freshwater habitats. This species has important characteristics that can increase its invasive behaviour-sufficient plasticity to adapt its ecology and life cycle to changing environmental conditions, high somatic growth and reproductive output, short development time, ability to tolerate high temperatures, dry periods and low dissolved oxygen conditions and a flexible feeding strategy (Alcorlo *et al*., 2004; Gherardi, 2006; Jones *et al*., 2009). *P. clarkii* is better adapted to growing in a rice field (Arce *et al*., 2015). Interestingly, it is widely favored and consumed in China and is one of the most economically important farmed aquatic species rather than a devastating invasive species (Yi *et al*., 2018). Distribution of *P. clarkia* aquaculture in China provides us a desirable mode to investigate the climate change impacts on the suitable distribution of an invasive species dispersed mainly by human-mediated factors. The present study simulated suitable distribution aquaculture areas of *P. clarkii* in China and screened out the dominant factors affecting the distribution as well, using the MaxEnt model.

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MATERIALS AND METHODS

Data availability

In this study, the top 30 counties (districts and cities) in terms of aquaculture output in China listed in the China Crayfish

Industry Development Report (2021) were selected as typical distribution areas (China National Fishery Technology Extension Center *et al.*, 2021). Two crayfish aquaculture bases were selected in each county (district and city) to form the distribution data of crayfish aquaculture in China, and a total of 60 distribution points were obtained, as shown in Table 1. In order to avoid excessive fitting, it is necessary to delete the distribution sites (within 1 km) with repeated or too similar longitude and latitude (Phillips *et al.*, 2008). Using chord distance to calculate the above 60 distribution points, it is found that the minimum distance between adjacent points was 1072.01 meters, the average distance was 18742.68 meters and the maximum distance was 46250.78 meters. Therefore, all the above points were used for subsequent analysis.

The climate data used in the prediction of suitable species distributions under climate change scenarios included the baseline climate condition data (time period: present day [average for 1970-2000]) and the climate scenario data (time periods: 2030s [average for 2021-2040] and 2050s [average for 2041-2060]) (http://www.worldclim.org).

Model

Maxent model is widely used to predict the impact of niche factors, especially climate, on future long-term changes in habitat suitability (Mukul *et al.*, 2019). Maxent model apparently captures a real, but small, effect of environmental conditions on changes in species' distributions (Venne *et al.*, 2021).

Variable selection

ArcGIS software to 19 environment variables and multi-value 60 distribution points were extracted to point, Spearman correlation analysis using the SPSS (SPSS13.0), when two ecological factors direct correlation coefficient of 0.8 or higher, retain one of the typical environmental factors (Gallagher *et al.*, 2010). Finally, six environmental factors were selected for the modeling of suitability distribution, namely, isothermality (Bio-02/Bio-07) (*100) (Bio-03), temperature seasonality (standard deviation*100) (Bio-04), mean temperature of wettest quarter (Bio-08), mean temperature of warmest quarter (Bio-10), precipitation of wettest month (Bio-13) and precipitation of wettest quarter (Bio-16), as shown in Table 2.

Evaluation criteria

AUC value ranges from 0.5 to 1 and the higher the value, the better the prediction of the model. Five grades of model prediction accuracy can be classified according to the AUC value: 0.5 0.6, fail; 0.6-0.7, poor; 0.7-0.8, fair; 0.8-0.9, good; and 0.9-1, excellent (Fielding, 1997).

Division of suitable distribution area

The suitable distribution area was divided into four grades using the Jenks' natural breaks approach: un-, general-, medium and high-suitability area (Jenks, 1967; Xu *et al.,* 2021).

Table 1: Distribution points of main aquaculture areas of Crayfish in China.

Region	Longitude and latitude		Region	Longitude and latitude	
Jianli county	112.662198,29.969467	113.093876,29.63267	Honghu city	113.314391,29.668777	113.397515,30.033011
Qianjiang city	112.959732,30.212431	112.723939,30.330637	Shayang county	112.608253,30.802859	112.473138,30.640766
Gong 'an county	112.248122,30.248199	112.242285,30.239963	Shishou city	112.411023,29.616819	112.76748,29.727372
huangmei county	115.974402,29.919039	116.056086,30.075315	Hanchuan city	113.48104,30.511034	113.462244,30.518347
Tianmen city	112.819131,30.776186	113.050151,30.64316	Xiantao city	113.593918,30.329285	113.441088,30.293264
Zhongxiang city	112.571792,31.099239	112.400004,31.068912	Nan county	112.569952,29.277409	112.355437,29.141916
Huarong county	112.678457,29.525739	112.713346,29.360186	Yuanjiang city	112.441214,29.007051	112.564624,29.103475
Linxiang city	113.45772,29.755532	113.538307,29.798932	Ningxiang county	112.109016,29.562065	112.140802,29.197984
Hanshou county	111.989765,28.78928	112.036599,28.763054	Junshan district, Yueyang city	112.722545,29.455668	112.752017,29.536444
Huoqiu county	116.058264,32.229306	116.137455,32.232601	Changfeng county	117.053008,32.134081	117.328355,32.171289
Quanjiao county	118.048154,31.871329	118.137337,31.971042	Wuwei city	117.99221,31.384858	117.974687,31.407725
Xuyi county	118.676544,33.037824	118.318614,33.14056	Sihong county	118.784969,33.466215	118.523181,33.419833
Xinghua city	119.719365,33.196014	119.889906,32.804522	Duchang county	116.51995,29.530464	116.554451,29.227137
Pengze county	116.701436,30.023551	116.678683,29.954903	Yutai county	116.74754,34.978926	116.770086,34.943564
Weishan county	116.70728,35.244875	117.162275,34.732972	Huangchuan county	115.307773,32.214992	115.165642,31.927428

RESULTS AND DISCUSSION

Variable selection and accuracy evaluation

The evaluation metric result showed that the test AUC value was 0.986, suggesting that the model worked well and had high prediction accuracy. Additionally, the AUC value of the model with the variable count = 6 (Fig 1a) was just slightly less than the default model (variable count = 19) (Fig 1b). Therefore, to reduce the overfitting and complexity, the model with the variable count = 6 was selected as the optimal model to predict the suitable distribution area for the present day.

Variable importance

The cumulative contribution of Bio-10 and Bio-03 was about 80%, rising to over 92% with the inclusion of Bio-16, indicating that these variables best explain the data, as shown in Table 3. Therefore, temperature variables appear more important to the Maxent predictions for *P.clarkii* than precipitation variables. The following figure shows the results of the jackknife test of variable importance (Fig 2). The environmental variable with highest gain when used in isolation was Bio-10, which therefore appears to have the most useful information by itself. The environmental variable that decreased the gain the most when it was omitted was Bio-10, which therefore appears to have the most information indicates the importance of these variables for predicting distribution patterns of *P. clarkii*. By contrast, the probability value was high for most Bio 13 and Bio 8 values; however, the roles these variables were not obvious and the significance of other variables to the optimal model suggests that they were not of high importance in predicting distribution patterns. The red lines in Fig 3 show how each of the six optimal-model variables independently affect the predicted probability of suitable conditions, namely, a Maxent model created using only the corresponding variable. The probability of presence of *P. clarkii* was close to 0 when mean temperature of warmest quarter (Bio-10, the most significant variable), was less than 23.34°C, then increased rapidly and reached the maximum when Bio-10 was 27.65°C. Similarly, the probability of presence was close to 0 when wettest seasonal rainfall (Bio-16) was less than 311.45 mm, then increased rapidly and reached the maximum when Bio-16 was 447.10 mm. the probability of presence was close to 0 when isothermality (Bio-03) was less than 19.78%, then increases rapidly and reached the maximum when Bio-03

Table 2: Pearson correlation coefficients among key environmental variables of geographical distribution of main aquaculture areas of crayfish in China.

Environment variables	bio16	bio13	bio10	bio08	bio04	bio03
bio16	1.000	0.744	0.739	-0.700	-0.461	-0.533
bio13	0.744	1.000	0.178	-0.298	0.116	-0.122
bio10	0.739	0.178	1.000	-0.794	-0.745	-0.683
bio08	-0.700	-0.298	-0.794	1.000	0.653	0.762
bio04	-0.461	0.116	-0.745	0.653	1.000	0.754
bio03	-0.533	-0.122	-0.683	0.762	0.754	1.000

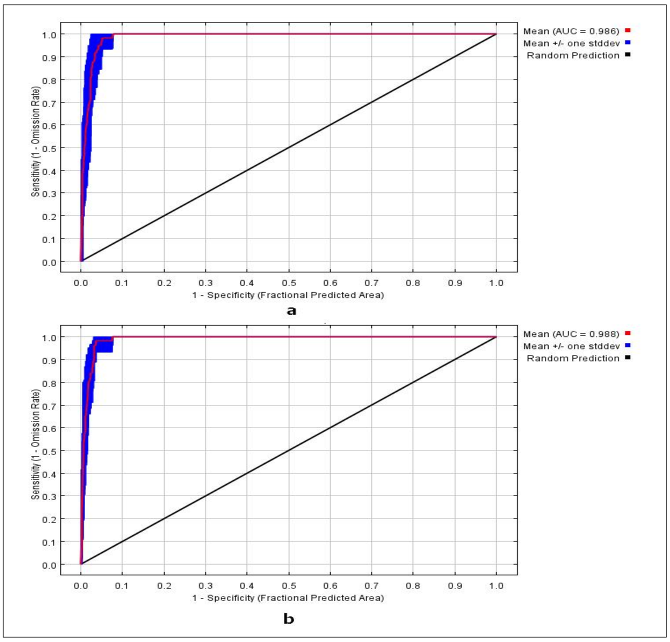

Fig 1: The receiver operating characteristic (ROC) curve (a, variable count = 5; b, variable count = 19).

was 23.82%. the probability of presence was close to 0 when temperature seasonality (Bio-04) was less than 719.67°C, then increases rapidly and reached the maximum when Bio-04 is 873.79°C. Probability ≥0.6 is generally regarded as the critical value of suitability (Lu *et al.*, 2012). According to the suitability standard, the suitable distribution area (probability ≥0.6) for *P. clarkii* required the lower limit and upper limit of mean temperature of warmest quarter were 27.22 and 28.03°C, the lower limit and upper limit of wettest seasonal rainfall were 438.05 mm and 508.14 mm, the lower limit and upper limit of isothermality were 23.40 and 24.77% and the lower limit and upper limit of temperature seasonality were 863.28 and 898.31°C. By contrast, the suitable distribution area of *P. clarkii* had strict upper and lower limits for mean temperature of wettest quarter (Bio-08, 25.78°C and 26.93°C), and precipitation of wettest month (Bio-13, 184.00 mm and 207.88 mm).

Table 3: Contribution (*i.e.*, important) parameters of the five climate variables included in the optimal model.

Variable name	PC (%)	PI (%)
Mean temperature of warmest quarter (Bio-10)	32.8	67.2
Precipitation of wettest quarter (Bio-16)	32	12
Temperature seasonality (standard deviation*100) (Bio-04)	27.3	3.3
Isothermality (Bio-02/Bio-07) (*100) (Bio-03)	7.2	13.5
Mean temperature of wettest quarter (Bio-08)	0.6	1.1
Wettest monthly rainfall (Bio-13)	0.2	3

Analysis of potential suitable distribution

The present-day predicted suitable distribution area of *P. clarkii* was situated in Hubei, Hunan, Anhui Province coincident with the actual distribution (Fig 4).

The per cent of area of general-, medium-, and high-suitability distribution was 3.58%, 1.37% and 1.93%, respectively (Table 4). The suitable distribution areas markedly changed for different time periods under different

Table 4: Suitable area of aquaculture crayfish in China in different periods (ten thousand km^2).

	1970-2000	2030s				2050s			
		SSP126	SSP245	SSP370	SSP585	SSP126	SSP245	SSP370	SSP585
Unsuitability	893.94	881.82	883.27	871.48	871.98	872.13	872.61	866.95	863.12
General	34.38	32.61	32.77	40.60	40.80	42.74	41.24	42.39	43.40
Medium	18.53	19.64	17.80	18.69	18.71	19.11	21.01	20.20	22.02
High	13.15	10.30	10.52	13.59	12.87	10.38	9.51	14.83	15.84

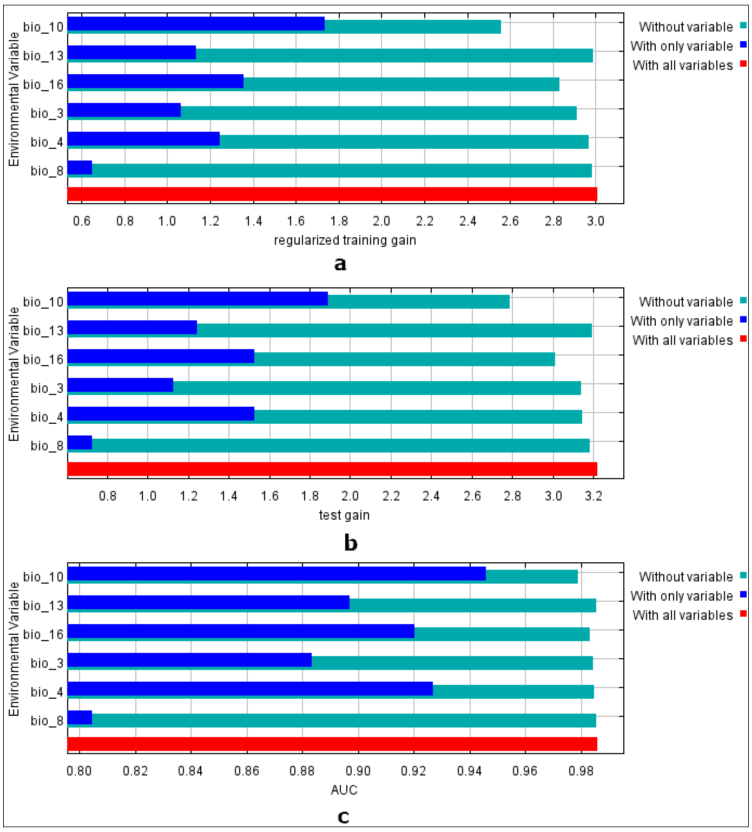

Fig 2: The jackknife test of variable importance (a, regularized training gain; b, test gain; c, AUC on test data).

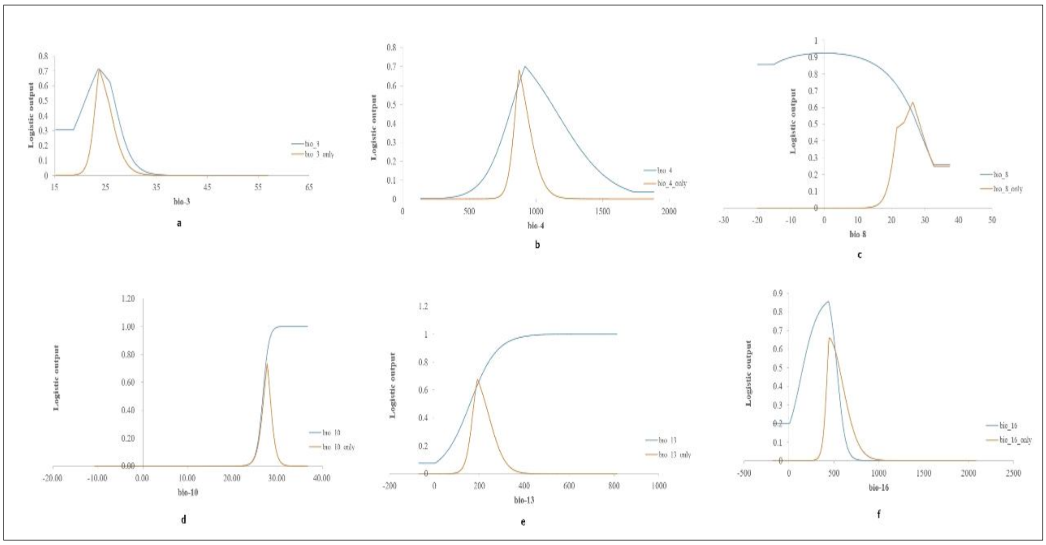

Fig 3: Response curves (a, Bio-03; b, Bio-04; c, Bio-08; d, Bio-10; e, Bio-13; f, Bio-16).

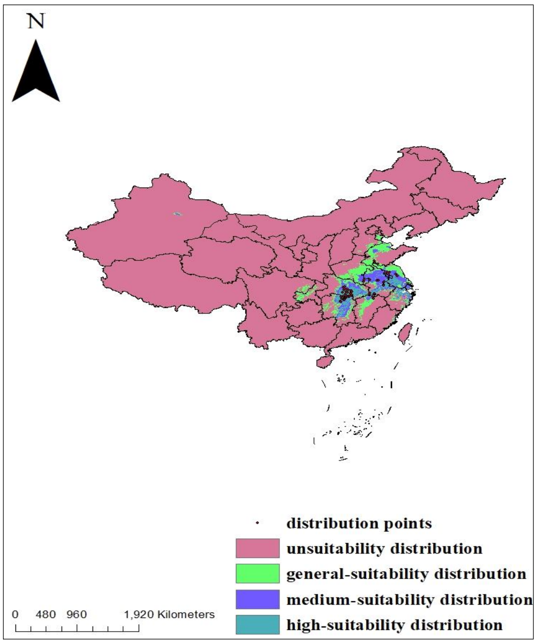

Fig 4: Distribution map of the suitability aquaculture areas of Crayfish in China under current climatic conditions.

climate change scenarios. The spread of invasive alien species is closely associated with global climatic changes, and they interact with each other in a complex manner (Frank *et al*., 2008). Compared to the present-day predictions, the total area of suitable distribution (general-, medium-, and high-suitability) gradually increased in the 2030s and 2050s (Table 4). The ranking of the total area under different climate change scenarios were SSP370> SSP585> SSP126> SSP245 in the 2030s, SSP585> SSP370> SSP126> SSP245 in the 2050s, indicating that as the greenhouse gas emissions increase, the distribution of *P. clarkii* was likely to increase. It was of note that the area of high-suitability distribution for SSP585 greatly increased, but for SSP245 greatly decreased in the 2050s. In 2020, the total aquaculture area of crayfish in China reached 1.46 ten thousand km^2 and the total aquaculture output reached 2,393,700 tons, ranking the sixth in China's freshwater aquaculture species (the top five are all major freshwater fish species), with a year-on-year increase of 13.25% and 14.55% respectively in 2019 (China National Fishery Technology Extension Center *et al*., 2021). This suggested that the overall crayfish industry in China had been affected by the COVID-19 epidemic, but with the effective control of the epidemic and the recovery of crayfish consumption, there was still a large space for the growth of the crayfish aquaculture areas, especially the rice- crayfish integrated farming system would get greater development in China. However, we should also attach great importance to the ecological risk of crayfish in China and prevent the blind development of the industry.

CONCLUSION

P. clarkii has been transformed from an invasive species into an important aquaculture species in China. To monitor, control crayfish, and achieve ecological protection and dissolve the risk of industrial blind expansion, it is necessary to investigate the potential distribution area of this species. In this approach, ecological Niche Modeling software MaxEnt (the maximum Entropy Model), combined with ArcGIS (Geographic Information System) was applied to predict the potential geographic distribution of Crayfish aquaculture in China. Bioclimatic dominant factors and the appropriate ranges of their values were also investigational. The results showed that training data AUC were 0.986, which indicated a better forecast. The highly suitable aquaculture areas for crayfish were Hubei, Hunan, and Anhui Province. The important environmental factors affecting the distribution of crayfish were mean temperature of warmest quarter, precipitation of wettest quarter, isothermality and temperature seasonality.

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Conflict of interest: None.

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