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Predicting the Distribution of the Invasive Species *Atractosteus spatula*, the Alligator Gar, in China

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Abstract: The Alligator Gar (*Atractosteus spatula*) is a very dangerous species that has an extremely destructive impact on the ecological environment in aquatic areas. As a kind of ornamental fish, it is spreading rapidly all over the world. In order to avoid or delay the spread of Alligator Gar in China, it is urgent to further monitor and clarify its distribution range within the country. In this study, a maximum entropy model (MaxEnt) and geographical information system (ArcGIS) were used to identify suitable regions under climate change scenarios in China, and the significance of environmental factors that shape this species' distribution were evaluated. According to the geographical distribution data of Alligator Gar and selected environmental variables, the potential habitat area of Chinese Alligator Gar under four climate scenarios in the present (2000s) and future (2050s and 2070s) was predicted. (1) The main environmental variables affecting the potential geographical distribution of Alligator Gar are temperature factor variables (the mean temperature of the warmest quarter and the mean temperature of the coldest quarter), precipitation factor variables (precipitation in the driest month and in the driest quarter), and altitude. (2) Under the current climate conditions, the suitable breeding areas of Alligator Gar are mainly concentrated in the Guangxi Zhuang Autonomous Region, Guangdong Province, and Hainan Province. Under the four future climate scenarios, the distribution area of the total suitable area of Alligator Gar will gradually decrease, and the suitable area of Alligator Gar will spread to high latitudes.

Keywords: MaxEnt; Alligator Gar; suitable area; environmental variables; climate change scenario

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1. Introduction

In recent years, global attention to biological invasion has increased [1]. Global climate change and alien biological invasion are two serious ecological problems facing society today. The main characteristic of climate change is global warming. (As a greenhouse gas, carbon dioxide can absorb long-wave radiation radiating from the earth's surface, thus generating a greenhouse effect and warming the global climate.) Under the future scenario of continuous global warming, the average temperature in China will rise by 1.6–5.0 °C [2]. Numerous studies have shown that continuous climate warming may increase the tolerance of invasive species, expand the areas suitable for their survival, and possibly give rise to larger populations [3–8]. Of the more than 660 invasive species found in China, 71 have posed or are expected to pose potential threats to natural ecosystems according to the report on the State of China's Eco-Environment 2020. Therefore, there is both a broad consensus in the field of biological invasion research as well as an internal demand to implement long-term active prevention and control measures to analyze the future changes of invasive species in the context of climate change and explain different change trends and patterns.

The niche model is a mathematical prediction model built on the basis of niche theory, also known as species distribution modelling [9,10]. The niche model is the main method used to study the influence of environmental variables on species distribution range [11].

By collecting data on the known distribution points and related environmental variables of target species, the potential distribution range of target species can be simulated based on relevant concepts and theories regarding ecological niches. The distribution of species under different climatic conditions or backgrounds in the past and future can also be predicted [12]. The maximum entropy (MaxEnt) model is a niche model developed by S.J. Pennps et al. based on the Java platform [13]. This model is an analytical tool for predicting the future geographical distribution of target species. After testing many models, it was found that the MaxEnt model is less affected by the number of species distribution points and the correlation of environmental factors and has fewer constraints. The MaxEnt model can handle continuous variables and categorical variables and has better predictive ability when it is used to simulate species distributions [14–16]. Due to its advantages in terms of its ability to yield stable operation results, its short operation time, and its accurate prediction ability, it has become one of the most widely used mathematical methods in the field of species distribution models [17,18].

The Alligator Gar (scientific name: *Atractosteus spatula*), a type of gar within the gar family and gar genus, is native to North America, inhabiting the Mississippi River basin, chiefly southwestern Ohio and southern Illinois, and the Gulf of Mexico [19–21]. It is listed on the IUCN Red List of threatened species. It has been introduced in many countries around the world via the aquarium trade. It is invasive in China, Singapore, Indonesia, Turkmenistan, and other countries and is listed as an invasive species, with 47,287 recorded occurrences of invasion worldwide. It was first found in Baiyun Lake in Guangzhou, Guangdong Province, in February 2019 and then spread to Hunan, Guangxi, Guangdong, Shandong, Sichuan, Qinghai, Jiangsu, Yunnan, and other provinces [22]. Originally imported to China as pets and ornamental fish, Alligator Gar live mainly in pure fresh water, but due to their large size and aggressive appearance, some are abandoned and released into the wild, where they can have long lifespans (up to 30–50 years), reach large sizes as adults [23,24], be highly fertile, serve as a top carnivore, and thrive because of the near complete absence of natural competitors in China, all of which is due to increased human activities, especially industrialization, resulting in global climate change and water pollution. A potential confounding factor in the increased reproduction rates of larger, older females is that the bioaccumulation of pollutants has an effect on reproduction and larval development [25]. This, coupled with the artificial introduction of invasive species, has led to the rapid spread of Alligator Gar. At the same time, the Alligator Gar has a strong tolerance to new habitats. As an invasive alien species of whole-feeding fish and a top predator, the Alligator Gar feeds on native fish, helping it to survive in non-native habitats, and is extremely harmful [26,27]. At present, there is little research on the suitable range and diffusion trend of Alligator Gar in China. Therefore, in this study, the MaxEnt model was used to predict the distribution of Alligator Gar under global climate change scenarios (SSPs1-2.5, SSPs2-3.5, SSPs3-7.0, and SSPs5-8.5). The aims of this study were to (1) screen out major environmental factors using MaxEnt 3.4.1 and ENMTools 1.0 software and establish an impact model on species distribution patterns and to (2) predict the distribution, change, and shift in the trend of the habitable zone of Alligator Gar under current (1970–2000) and future (2041–2060 and 2061–2080) climate conditions. The research results provide a practical reference for the effective prevention of large-area invasions and have important practical significance for the monitoring and control of invasion areas and the early warning and supervision of uninvaded areas.

2. Materials and Methods

2.1. Distribution Data

By searching the relevant species distribution database (GBIF, http://www.gbif.org/, accessed on 1 August 2022) and the China national quarantine pest information platform (http://www.pestchina.com/, accessed on 1 August 2022), consulting the relevant monitoring department for the census results, reading the relevant literature, etc., we collected data on the Alligator Gar. Moreover, distribution data on Alligator Gar were proofread and screened using ENMtools 1.0 software, and insufficient and repetitive distribution data were eliminated. The specific latitude and longitude information of each distribution point was collected using Google Earth [28], and 669 effective distribution point data were finally obtained. According to the basic data format prepared using the MaxEnt model, the longitude and latitude coordinates were input into Excel and saved in CSV format.

2.2. Environmental Variables and Processing

The climate variable data selected in this study include modern climate data (1970–2000) and future climate data (the data for the bioclimate of 2050 represent mean values from 2041 to 2060, and the data for 2070 represent mean values from 2061 to 2080). The climate variable dataset includes 19 bioclimatic variables, and altitude data were also incorporated in this study (Table 1). Data on global climate from the WorldClim 2.0 database (http://www.worldclim.org/, accessed on 1 August 2022), with a resolution of the arc of −2.5 min, were used. The BCC-CSM2-MR climate model was used to predict the suitable area of Alligator Gar. Because IPCC AR6, released in 2021, uses a new climate scenario model in CMIP6, namely, Shared Economy Path (SSPs), four emission scenarios, SSPs1-2.5, SSPs2-3.5, SSPs3-7.0, and SSPs5-8.5, were selected for this study.

Table 1. The 20 environmental variables selected for this study.

Code	Description
Bio1	Annual Mean Temperature (°C)
Bio2	Mean Diurnal Air Temperature Range (°C)
Bio3	Isothermality (BIO2/BIO7) (×100)
Bio4	Temperature Seasonality (standard deviation ×100)
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)
Altitude	Altitude (m)

Twenty influence factors were selected to simulate the habitable zone of Alligator Gar in China. SPSS 24 correlation analysis, ENMTtools 1.0 software, and the iterative algorithm in the MaxEnt model were used to select the influence factors required for the establishment of the ecological niche model. The influence factors employed for modeling were tested using the jackknife method, and the main environmental variables affecting the distribution of Alligator Gar were determined.

2.3. MaxEnt Model Construction

Firstly, based on the sites of Alligator Gar and their corresponding environmental factors, the MaxEnt model was used to predict the range of the habitable zone of Alligator Gar. Before modeling using the MaxEnt 3.4.1 software product, 25% of the verification set of the distribution points of Alligator Gar should be set. Furthermore, 75% of the known distribution points of Alligator Gar should be randomly selected as the training set, and the cross-verification method should be adopted. The background points and the number of iterations were set to no more than 10,000 and 1000, respectively. Visualization analysis was conducted on the prediction results yielded by the MaxEnt model in ArcGIS10.7, and the grading scheme of the suitable area was as follows: unsuitable area, <0.1; 0.1≤ and <0.3, undesirable suitable area; 0.3≤ and <0.5, moderately suitable area; ≥0.5, highly suitable area.

2.4. Model Accuracy Evaluation

The receiver operating characteristic curve (ROC) was used to test the simulation prediction effect, and the area under the curve (AUC), as a measure of model prediction, can be used to compare different models because the value of AUC is not affected by the judgment threshold, making it the best measure of model prediction accuracy at present. The value of AUC ranges from 0 to 1. The larger the value, the farther the AUC from the random distribution and the better the prediction effect. The evaluation criteria are as follows: 0.7–0.8, relatively accurate; 0.8–0.9, very accurate; and 0.9–1.0, extremely accurate.

2.5. Importance of Environmental Variables

Twenty environmental variables were selected to simulate the suitability of Alligator Gar in China. The r value was analyzed using SPSS, and environmental variables greater than or equal to 2% were screened using the iterative algorithm in the MaxEnt model to obtain the environmental variables required for the establishment of the ecological niche model. The environmental variables used for modeling were tested using the jackknife method in the MaxEnt model. The higher the contribution value, the greater the influence on the distribution of Alligator Gar. The main influence factors affecting the distribution of Alligator Gar were obtained, and the response curve between the main environmental variables and the probability of the existence of Alligator Gar was plotted.

3. Results

3.1. Model Test Evaluation and Importance of Environmental Factors

The maximum entropy principle (MaxEnt) was used to predict the potential distribution of Alligator Gar, with a training AUC value of 0.971 and a test AUC value of 0.957; our results regarding the AUC levels show that we predicted the potential geographical distribution of Alligator Gar in China with very high simulation accuracy, and the ROC curve obtained is shown below (Figure 1).

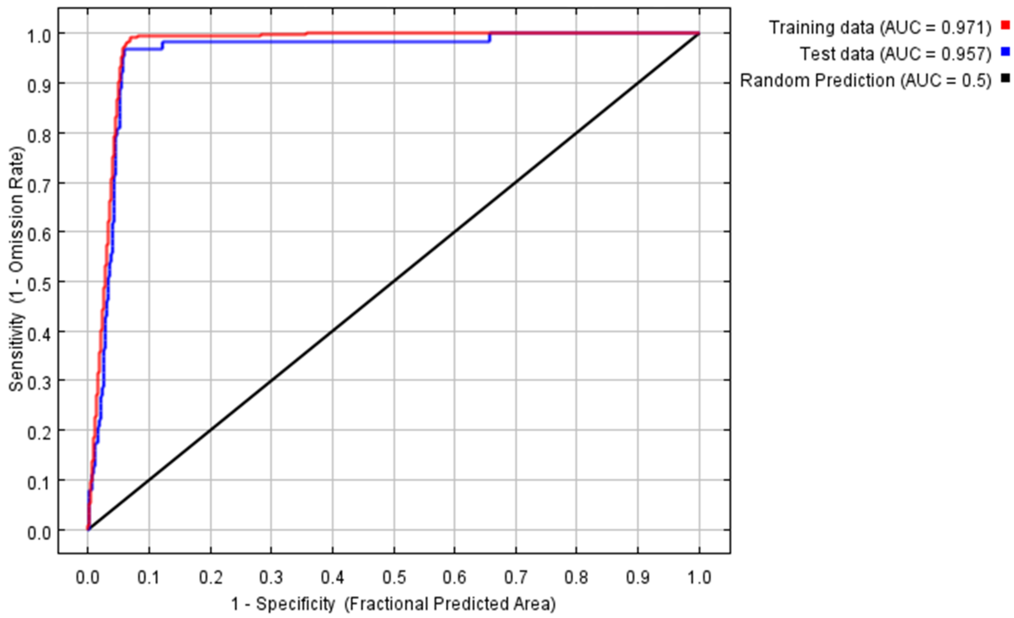

Figure 1. Reliability test of the distribution model created for Alligator Gar (*Atractosteus spatula*).

Among the 11 influence factors predicted by the MaxEnt model (Table 2), the top three contributing factors were bio, altitude, and bio4. Regarding the displacement important value (displacement important value refers to the random displacement of the value of each influence factor variable on the training presence and background data, where the larger the value, the greater the model's dependence on the variable), the top three environmental factor variables in terms of importance were bio10, Bio16, bio14.

Table 2. Contribution rate and permutation importance of variables for modeling.

Variable	Percent Contribution	Permutation Importance
bio17	32.2	1
Altitude	31.1	2
bio4	9.3	1.4
bio10	8.4	65.8
bio3	7.2	1.2
bio13	5.4	0
bio11	4.1	0.9
bio14	1.3	19.7
bio16	0.4	7.3
bio2	0.3	0.3
bio7	0.3	0.3

According to the jackknife test results (Figure 2), when only a single environmental factor variable was used, the three environmental factors that had the greatest influence on the normalized training gain were bio10, bio11, and altitude, indicating that these environmental factor variables contain information that other environmental factor variables do not. In summary, the main factors affecting the potential geographical distribution of modern Alligator Gar were found to be temperature variables (bio10 and bio11) and precipitation variables (bio14, bio17, and altitude).

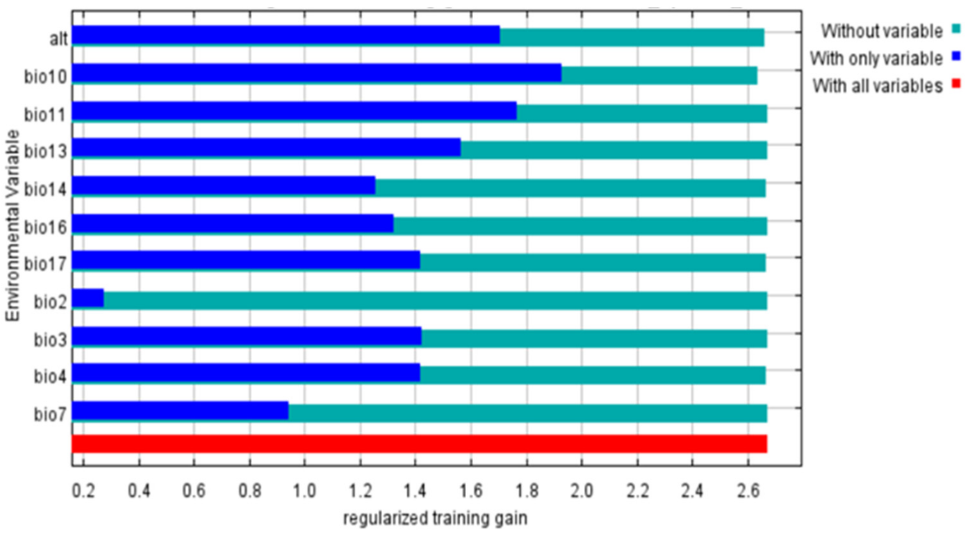

Figure 2. Test results concerning the environmental variables obtained using the jackknife test.

By referring to the response curve of the environmental factors, the relationship between the existence probability of Alligator Gar and environmental factors can be judged (Figure 3). The influence factor of Alligator Gar is only favorable for the survival of Alligator Gar when the range of its existence probability is greater than 0.5. The response curves show the following:

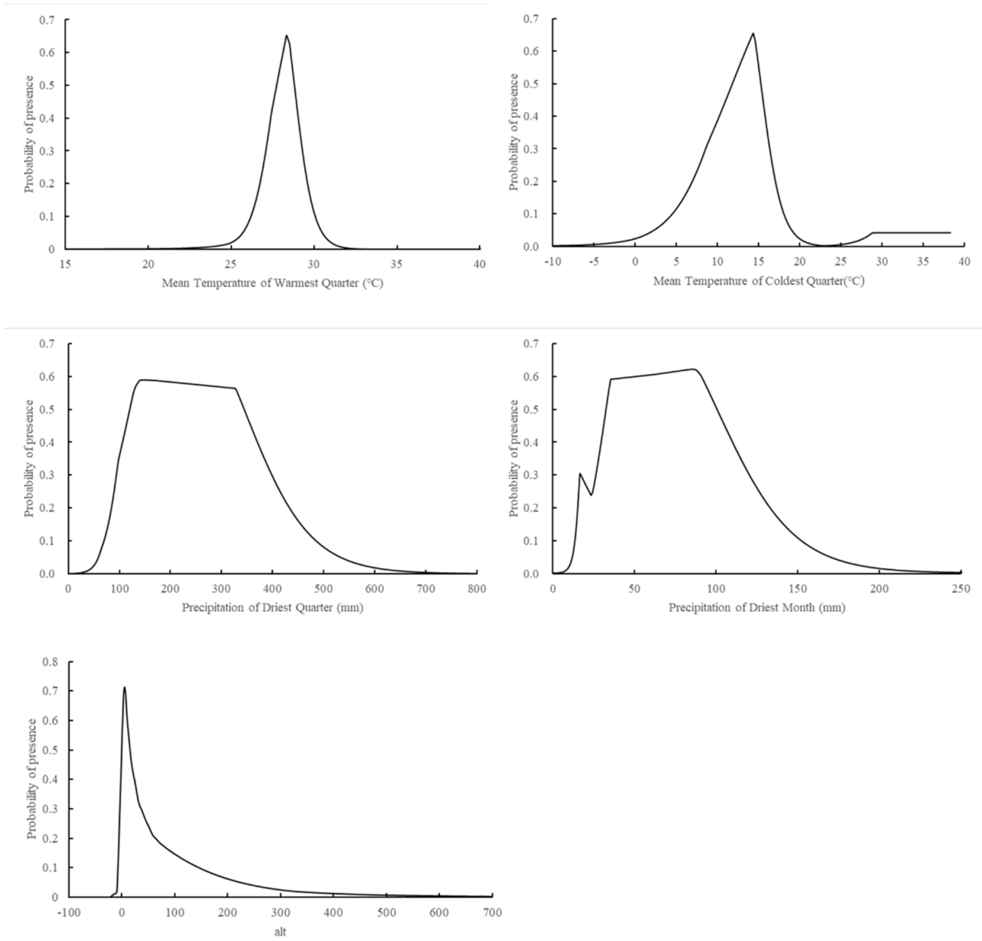

Figure 3. Response curves of the existence probability of Alligator Gar (*Atractosteus spatula*) considering dominant environmental factors.

As the mean temperature of the warmest quarter rises, the Alligator Gar existence probability increases. In addition, the highest probability of existence is at 28.3 °C(0.65), and this is reached after gradually declining as temperatures rises, indicating that the bio10 range appropriate for the Alligator Gar's survival is 27.7 to 28.8 °C. The mean temperature of the coldest quarter has the highest probability (0.66) at 14.3 °C, and its survival probability also begins to decrease with the rise and fall in temperature. Therefore, the mean temperature of the coldest quarter suitable for the survival of Alligator Gar is 11.8–15.3 °C. With the increase in precipitation in the driest quarter, the distribution probability of Alligator Gar increases first, decreases slowly, and finally drops sharply. Among the precipitation levels, the highest probability (0.59) exists at 140.3 mm, so the habitable zone range with respect to the precipitation in the driest quarter for the survival of Alligator Gar is 120–341 mm. With the increase in precipitation in the driest month, the distribution probability of Alligator Gar rises first, gradually flattens, and finally declines. Among the precipitation levels, the probability of 88.4 mm is highest (0.66), so the suitable range of precipitation in the driest month for Alligator Gar survival is 32.6–100.3 mm. Altitude has the highest probability (0.72) at 5 m, and its survival probability also begins to decrease with the increase and decrease in altitude. Therefore, the suitable altitude range for Alligator Gar survival is 0–15.5 m.

3.2. Potential Habitat Area of Alligator Gar under Current Climate Conditions

According to the distribution of suitable areas of Alligator Gar in China under the current climate conditions (Table 3), the results show that the total suitable area of Alligator Gar is 97.95×10^4 km^2, accounting for 10.20% of the total land area. High suitability area, medium suitability area, and low suitability area accounted for 11.72%, 39.09%, and 49.19% of the total suitability area, respectively. Under the current climate conditions, Alligator Gar is mainly found in Guangxi, the coastal provinces of Guangdong, Hainan, Fujian, Hunan, Jiangxi, Anhui, Jiangsu, eastern Hubei, and northern Zhejiang. Among these, the area of high suitability was found to be 11.48 × 10^4 km^2, which is mainly distributed in Guangxi, southern Guangdong, the coastal areas of Fujian, northern Hainan, and other sporadically dispersed areas. The suitable area is 39.09 × 10^4 km^2, which is mainly distributed in Hunan, Hubei, Anhui, Zhejiang, Jiangsu, Shanghai, Guangxi Zhuang Autonomous Region, Guangdong, Hainan, Taiwan, and other fragmented parts (Figure 4).

Table 3. Suitable areas for Alligator Gar (*Atractosteus spatula*) under climate change scenarios (×10^4 km^2).

Different Climate Scenarios (×10^4 km^2) and Periods	Poorly Suitable	Moderately Suitable
current	48.18	38.29
2050s, SSPs1-2.6	48.94	38.24
2070s, SSPs1-2.6	49.86	43.77
2050s, SSPs2-4.5	49.07	39.21
2070s, SSPs2-4.5	50.65	37.73
2050s, SSPs3-7.0	49.78	38.35
2070s, SSPs3-7.0	51.22	35.51
2050s, SSPs5-8.5	50.64	40.29
2070s, SSPs5-8.5	53.80	35.28

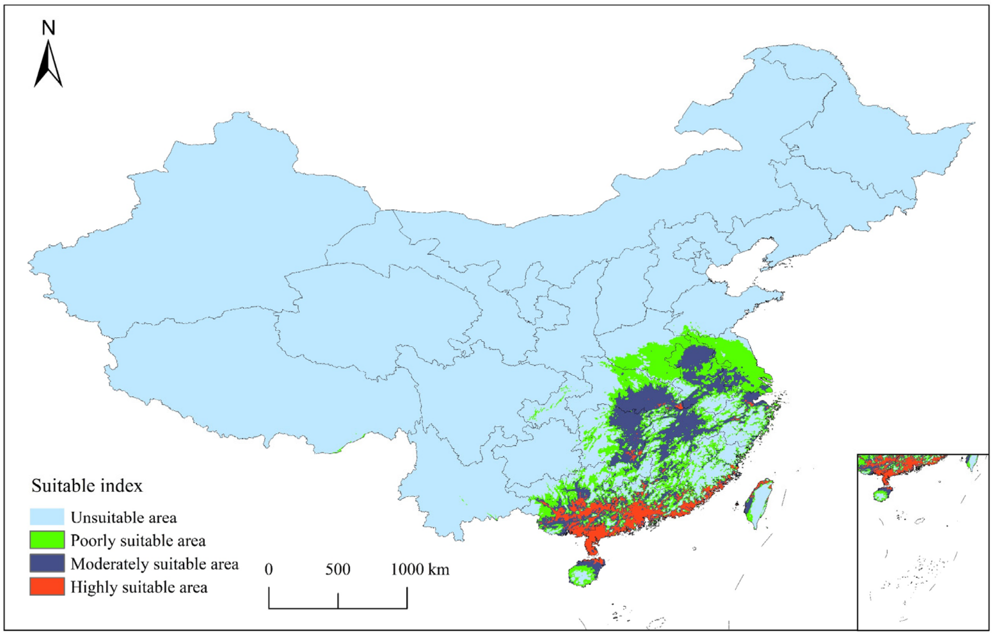

Figure 4. Potential geographical distribution of Alligator Gar (*Atractosteus spatula*) under modern climate conditions.

3.3. Potential Habitat Area of Alligator Gar under Future Climate Conditions

The potential suitable habitats of Chinese Alligator Gar under different emission scenarios (SSPs1-2.6, SSPs2-4.5, SSPs3-7.0, and SSPs5-8.5) in 2050 and 2070 were predicted, and the results compared with the current suitable habitat prediction results. It is found that the high suitability area will decrease in 2070 under the SSPs1-2.6 climate scenario, while the total suitability area and high suitability area will increase in the future under other emission scenarios (Table 3, Figure 5).

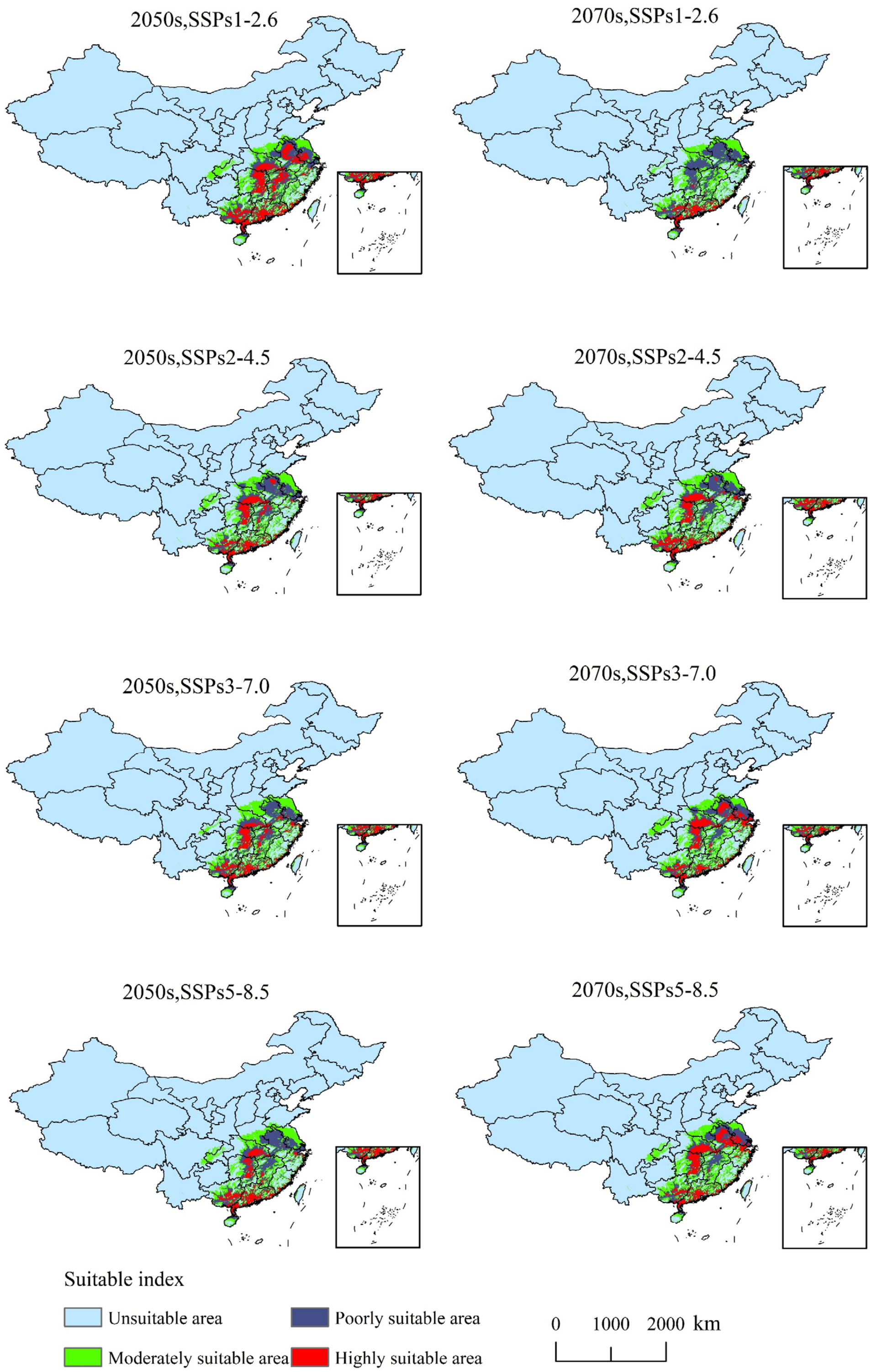

Figure 5. Potential geographical distribution of Alligator Gar (*Atractosteus spatula*) under future climate change scenarios.

Under the SSPs1-2.6 climate scenario, the total habitat area in 2050 will be 115.64 $\times$ 10^4 km^2, in which the highly suitable habitat area is 28.46 $\times$ 10^4 km^2. These values are 18.06% and 147.91% higher than those in the current period, respectively. In 2070, the total suitable area is projected to be 103.39 $\times$ 10^4 km^2, in which the highly suitable area is 9.76 $\times$ 10^4 km^2, which is 5.55% greater than the total habitat area under the current climate conditions, though the highly suitable habitat area will be reduced by $-$14.98%.

Under the SSPs2-4.5 climate scenario, the total habitat area in 2050 is projected to be 107.28×10^4 km^2, in which the highly suitable habitat area is 19.00×10^4 km^2. These values are 9.53% and 65.51% higher than those in the current period, respectively. In 2070, the total suitable area is 109.19×10^4 km^2, in which the highly suitable area is 20.81×10^4 km^2. These values are 11.48% and 81.27% higher than those in the current period, respectively.

Under the SSPs3-7.0 climate scenario, the total suitable area in 2050 is 108.02×10^4 km^2, in which the highly suitable area is 19.89×10^4 km^2. These values are 10.28% and 73.26% higher than those in the current period, respectively. In 2070, the total suitable area is 109.43×10^4 km^2, in which the highly suitable area is 22.70×10^4 km^2. These values are 11.72% and 97.74% higher than those in the current period, respectively.

Under the SSPs5-8.5 climate scenario, the total suitable area in 2050 is 108.36×10^4 km^2, in which the highly suitable area is 17.43×10^4 km^2. These values are 10.63% and 51.83% higher than those in the current period, respectively. In 2070, the total suitable area is 113.60×10^4 km^2, in which the highly suitable area is 24.52×10^4 km^2, corresponding to increases of 15.98% and 113.59% when compared with the decreased total suitable area and highly suitable area, respectively, under the current climate conditions.

3.4. Distributional Shift of Centroid in Highly Suitable Area

The distribution center of the suitable area of Alligator Gar is located in Gaomao District, Foshan City, Guangdong Province, with geographical coordinates of 22°43′53″ N, 112°36′33″ E. The future changes in suitable habitat area (Table 4, Figure 6) show that the total suitable habitat area of Alligator Gar is decreasing, and its center of gravity is shifting to higher latitudes and to northeast China.

Table 4. Results regarding the prediction of future changes in the suitable habitat area of Alligator Gar (*Atractosteus spatula*) (10^4 km^2) obtained using the MaxEnt model.

Period	Loss	Gain
2050s, SSPs1-2.6	3.35	0.12
2070s, SSPs1-2.6	4.86	2.13
2050s, SSPs2-4.5	5.64	0.01
2070s, SSPs2-4.5	5.40	0.01
2050s, SSPs3-7.0	5.76	0.02
2070s, SSPs3-7.0	6.67	0.05
2050s, SSPs5-8.5	5.25	0.01
2070s, SSPs5-8.5	6.75	0

(1) Under SSPs1-2.6, the optimal growth area of Alligator Gar in 2050 is 0.12×10^4 km^2, the disappearing area is 3.35×10^4 km^2, and the stabilizing area is 3.64×10^4 km^2. The center of gravity was located in Panyu District, Guangzhou City, Guangdong Province, which is about 0.18° higher than the current center of gravity. In 2070, the growth area of Alligator Gar is projected to be 2.13×10^4 km^2, the disappearance area will be 4.86×10^4 km^2, and the stabilization area will be 0.01×10^4 km^2. The center of gravity is located in Boluo County, Huizhou City, Guangdong Province, and the latitude of the center of gravity is about 0.68° higher than the current latitude.

(2) Under SSPs2-4.5, the optimum growth area of Alligator Gar in 2050 is 0.01×10^4 km^2, the disappearance area is 5.64×10^4 km^2, and the stabilizing area is 1.35×10^4 km^2. The center of gravity is located in Boluo County, Huizhou City, Guangdong Province, and the latitude of the center of gravity is about 0.66° higher than that of the current center of gravity. In 2070, the growth area of Alligator Gar will be 0.01×10^4 km^2, the disappearance area will be 5.40×10^4 km^2, and the stabilizing area will be 1.60×10^4 km^2. The center of gravity is located in Conghua District, Guangzhou City, Guangdong Province, and it is about 0.70° higher than the current center of gravity.

(3) Under SSPs3-7.0, the optimum growth area of Alligator Gar in 2050 is 0.02×10^4 km^2, the disappearance area is 5.76×10^4 km^2, and the stabilizing area is 1.24×10^4 km^2. The

center of gravity is located in Yucheng District, Heyuan City, Guangdong Province, and the latitude of the center of gravity is about 0.95° higher than that of the current center of gravity. In 2070, the growth area of Alligator Gar will be 0.05×10^4 km^2, the disappearance area will be 6.67×10^4 km^2, and the stabilization area will be 0.32×10^4 km^2. The center of gravity is located in Nanjing County, Zhangzhou City, Fujian Province, and the latitude of the center of gravity is about 2.04° higher than that of the current center of gravity.

(4) Under SSPs5-8.5, the optimal growth area of Alligator Gar in 2050 is 0.01×10^4 km^2, the disappearing area is 5.25×10^4 km^2, and the stabilization area is 1.74×10^4 km^2. The center of gravity is located in Longmen County, Huizhou City, Guangdong Province, and the latitude of the center of gravity is about 0.77° higher than that of the current center of gravity. In 2070, the optimum growth area of Alligator Gar will be 0, the disappearance area will be 6.75×10^4 km^2, and the stabilization area will be 0.24×10^4 km^2. The center of gravity is located in Dapu County, Meizhou City, Guangdong Province, and the latitude of the center of gravity is about 1.55° higher than that of the current center of gravity.

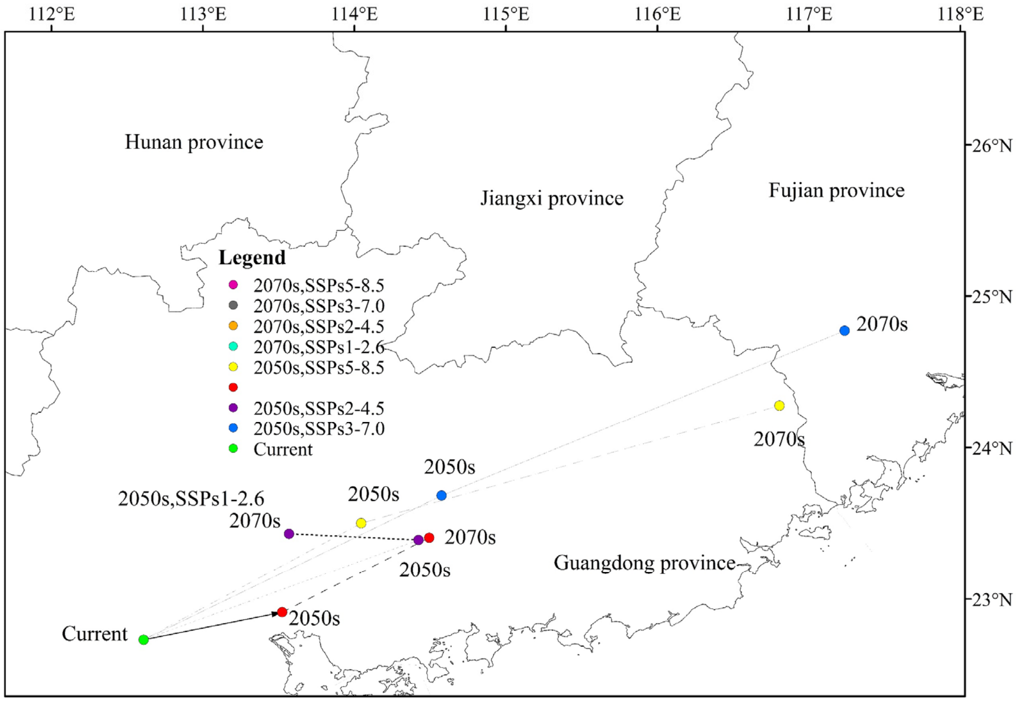

Figure 6. Distributional shifts of centroid in the most suitable area under climate change scenarios.

4. Discussion

In this paper, the MaxEnt model was applied. From the evaluation index values, it was gleaned that the simulation accuracy of the MaxEnt model in predicting the potential geographical distribution of Alligator Gars in China is very accurate. As revealed by the prediction results, the important influencing factors that influence the distribution of Alligator Gars are temperature factor variables (the mean temperature of the warmest quarter and the mean temperature of the coldest quarter), precipitation factor variables (precipitation in the driest month and in the driest quarter), and altitude. As shown in this paper, when the mean temperature of the warmest quarter is 27.7–28.8 °C and the mean temperature of the coldest quarter is 11.8–15.3 °C, the probability of the existence of Alligator Gars is higher, and the probability of the existence of Alligator Gars decreases with the increase and decrease in temperature. The probability of their existence is highest when the amount of precipitation in the driest quarter is 120–341 mm, and the probability of their existence decreases with the increase and decrease in precipitation. Altitude corresponds with a high probability of existence between 0 and 15.5 m, and, here, survival probability also begins to decrease with the increase and decrease in altitude.

When Wu Bin et al. used the MaxEnt model to predict the distribution of Yangtze finless porpoises in suitable areas of Jiangxi, they found that temperature and precipitation had great impacts on the potential geographical distribution of these porpoises, among which the precipitation of the driest quarter was the most severe [29]. In a study on the potential distribution area of the three zones beak culex forecast, Liu qing et al. showed that the three zones beak culex probability distribution, with an increase in warmest-season precipitation, presents an initial gentle rise after a slight downward trend that occurs gradually with the increase in the mean temperature of the coldest quarter, also exhibiting a trend of rising after initially falling [30]. Zhang used the MaxEnt model to predict the global fitness of invasive fish (cotillion and crucian carp). Their results show that temperature and altitude are the most important environmental factors affecting the distribution of cotillion and crucian carp, indicating that temperature is an important factor limiting the distribution of fish. The growth and reproduction of fish are closely related to temperature, and altitude also affects temperature, thus indirectly affecting the distribution of fish [31]. Li sheng predicted the potential suitable distribution area of Emeia pseudosauteri in Zhejiang Province and found that elevation and seasonal temperature affected the distribution of Emeia pseudosauteri [32].

In this study, we predicted the potential geographical distribution of Alligator Gars in China and identified the environmental factors affecting their distribution. In this regard, in addition to environmental factors, the distribution of this species may also be affected by interspecific competition, species reproductive pressure, and human disturbance [33,34]. The Alligator Gar is an apex carnivore; this means that it plays a role in controlling the dynamics of fish populations within the trophic pyramid beneath it. The smallest Alligator Gar eat almost exclusively zooplankton, but as their size increases, their consumption of zooplankton decreases and their consumption of fish prey increases. However, unlike some top carnivores, they feed mostly on large-bodied nongame fish (e.g., freshwater drum (*Aplodinotus grunniens*), gizzard shad (*Dorosoma cepedianum*), *buffalo Ictiobus* spp.), and channel catfish (*Ictalurus punctatus*)). Therefore, competition for Alligator Gars' prey can affect their reproduction.

In this study, the MaxEnt model was used to predict the suitable growth area of Alligator Gar in China combined with the environmental factors of modern climate conditions and four different emission scenarios under future climate change scenarios. The results show that the suitable areas of Alligator Gars range from 18.21° N to 32.98° N and 91.69° E to 121.93° E under the current climate conditions, and that the suitable areas are mainly concentrated in the Guangxi Zhuang Autonomous Region, Guangdong Province, Hainan Province, Fujian Province, Hunan Province, Jiangxi Province, Anhui Province, Jiangsu Province, eastern Hubei Province, and northern Zhejiang Province. The suitable area accounts for 13.36% of the total land area. The center of gravity of the suitable area is located in Gaoming District, Foshan City, Guangdong Province, with geographical coordinates of 22°43′53″ N and 112°36′33″ E. In terms of the overall trend, the Alligator Gar, an invasive species, is most widely distributed in the southeast, where temperature, humidity, and precipitation are high. This species can survive in at least 10 provinces in mainland China. The above areas face the highest threat of invasion by this species and may become the main areas harmed by the Alligator Gars' invasion in the future. Therefore, these areas should be the key monitoring areas for the prevention and control of Alligator Gar invasions.

In this study, the geometric distribution center of gravity of Alligator Gar was predicted to migrate to higher latitudes, and the range of the suitable distribution area was projected to gradually spread to the northeast, which is consistent with the trend of species' migration to higher latitudes under the conditions of global warming. Under the scenario of future climate change, as the years pass and emission concentrations increase, the disappearance area of Alligator Gar will be much larger than the increase, indicating that the Alligator Gar may face extinction in the future and that its numbers will continue to decrease. Tang Zhonghai et al. analyzed the potentially suitable habitat of Cervus albirostris in China using the MaxEnt model, and the results show that the potential geographical distribution of

Cervus albirostris under the future climate change scenario will clearly move toward high-latitude areas [35]. Bohata Lucie et al. found that, in the case of mild global warming, the suitable conditions for lionfish could be extended to higher latitudes [36]. Liu Xiaoxian et al. used the MaxEnt and CLIMEX models to predict the geographical components of tomato Mycelia and found that the suitable potential geographical distribution is also spreading to higher latitudes [37]. According to Gong Yanyan et al.'s prediction of potentially suitable areas of *P. pentacarpus* in China under the background of climate change, the suitable areas of *P. pentacarpus* in China are presenting a decreasing trend, which suggests that climate change may lead to a decrease in the suitable areas for *P. pentacarpus* in China, and that its invasion and diffusion process may be inhibited [38]. This finding is consistent with the results of this study.

The shared socio-economic path scenario proposed in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) shows that the warming range and temperature increase are more obvious because temperature has an important impact on the growth of Alligator Gar, and that, in the future climate change scenario, with the increase in temperature caused by the increase in emission concentrations, the range of habitable zone loss for Alligator Gar might extend. With the intensification of global warming, the geographical distribution of species has also experienced an important change and this is mainly manifested in the transfer of the potential geographical distribution area to high latitude or high altitude areas and the increase and decrease in potential geographical distribution area.

In view of the invasion and loss of Alligator Gar, the following guidelines can be put forward: (1) Monitoring should be strengthened, and early warnings should be given in a timely manner. Monitoring points should be set up in suitable and highly suitable areas and areas with suitable climatic conditions according to the occurrence rules and biological characteristics of Alligator Gar. (2) Active and effective measures should be taken to prevent and control harm inflicted on Alligator Gar and minimize the economic loss caused by disasters. (3) These actions should not be merely a one-sided sweep up but also aim to be protective.

5. Conclusions

In this study, based on 669 effective distribution points and 10 environmental factors, the MaxEnt model was used to predict the distribution of Alligator Gar in current and future suitable areas. According to the AUC value, the MaxEnt model was found to have high prediction accuracy, and the results show that Alligator Gar can survive in several provinces. The Alligator Gar has strong adaptability and can tolerate low temperatures. The lowest temperature suitable for their survival in the coldest area is 11.8 °C, but even if the temperature is lower than 10 °C, Alligator Gar will not freeze to death within a short amount of time but will enter into a state much like hibernation. The distribution center of gravity of the suitable area under current climatic conditions is located in Gaomao District, Foshan City, Guangdong Province, with geographical coordinates of 22°43′53″ N and 112°36′33″ E. In addition, the average temperature in the hottest season, the average temperature in the coldest season, precipitation in the driest month, precipitation in the driest season, and altitude all play important roles in affecting the suitability of Alligator Gar. Under the four future climate change scenarios, the disappearing distribution area of Alligator Gar is much larger than the increasing distribution area, and the Alligator Gar may face extinction in the future. At the same time, species are moving to higher latitudes in this warming world. Therefore, in order to prevent the spread of the Alligator Gar, an invasive species, we should not only prevent its harm, but also keep an eye on the trend of its decline in numbers.

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