Pak. J. Bot., 55(1): 141-147, 2023. **DOI: http://dx.doi.org/10.30848/PJB2023-1(15)**

PREDICTING IMPACTS OF CLIMATE CHANGE ON DISTRIBUTION OF ALLIGATOR WEED *ALTERNANTHERA PHILOXEROIDES* IN CHINA

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Abstract

To understand the relationship between the alligator weed's potential distribution and environment variables, its potential distribution was analyzed by the Maxent model under the current and future environmental conditions. The results showed that model performances are highly accurate in predicating its potential distribution in model training and testing. The dominate factors were precipitation of the driest month, temperature seasonality, altitude and precipitation of the wettest month, with thresholds of 20-110 mm, 550-925, <200 m and 160-300 mm respectively, indicating that the alligator weed is suitable for the water-land interface of various freshwater ecosystems in tropical to warm temperate regions. Its suitable geographic distributions are mainly distributed on eastern, southern, central, southwestern China, and south of Shaanxi and Hebei provinces. With climate change, its suitable distributions areas will first increase and then decrease from now to the 2070s, however the total suitable area increases relative to that in the current conditions. To 2050s, the increased suitable areas are southwestern Shandong and southern Hebei provinces, southwestern Yunnan province, and Nyingchi in Tibet, while to 2070s only in the southwest of Shandong province. Therefore, the current suitable habitats should be given highly attention to prevent from its spreading to these above three increased suitable and adjacent areas (western Sichuan, southeastern Gansu, southern Shaanxi and Shanxi provinces). Taken together, these informations from this study should be a useful guide for management of the species.

Key words: Alligator weed; Maxent model; Climate change; Potential geographical distribution.

Introduction

In recent years, biological invasion by alien species has been listed as an important factor, affecting the environmental ecology, social economy and public health in its invaded area (Larry *et al.*, 2004; Robinet *et al.*, 2011). Intrusion risk for native species and ecosystems has speeded up with the development of trade and transportation along with other factors of globalization (Hulme, 2009; Kumar *et al.*, 2014). Moreover, climate change in the future will facilitate the invasion of alien species and threaten biological diversity in the world (Bethany *et al.*, 2010; Bertrand *et al.*, 2011). Thus, only when the invasive potential distribution area of invasive species are known well as early as possible, its potential risks can be assessed scientifically in order to take precautions against prevention and control (Li & Gao, 2008). Many studies also have indicated that it is more economical and effective to prevent the invasion of alien species than to take some measures after the outbreak (Chen *et al.*, 2012; Xu *et al.*, 2017). Hence, fully understanding the potential invasion areas of alien species is becoming necessary for management activities and policy development (Gallien *et al.*, 2010). At present, species distribution models (SDMs), are the most important tools available to evaluate species-surrounding relationship and define the potential distributing regions for the species (Guisan & Thuiller, 2005; Qin *et al.*, 2017). However, out of many SDMs, Maxent (Maximum Entropy) model has been verified to perform better compared with other models that use both presence and absence data (Qin *et al.*, 2017). This model is less sensitive to overfitting owing to the interactions between the variables (Hijmans & Graham, 2006; Synes & Osborne, 2011). Besides, the result from this model is more stable, the need for computer configuration is lower, the running time is shorter, and the operation is more easy. Therefore, the Maxent model is commonly utilized to forecast the geographic region of the species with presence-only occurrence points and surrounding variables regarded to affect its distribution (Xu *et al.*, 2017; Qin *et al.*, 2017).

Alligator weed (*Alternanthera philoxeroides*) native to South America, was firstly listed in the invasion list in 2002 by China Environmental Protection Administration (Chen *et al.*, 2008; Chen *et al.*, 2012). And the species was introduced to Shanghai Municipality and Zhejiang province of China by Japanese as horses fodder in 1930 and then into the middle-lower reaches of the Yangtze River as a purified water species (Pan *et al.*, 2007). Later, it spread and reproduced in quantities in Jiangsu, Zhejiang, Jiangxi, Hunan and Fujian etc in China in only a few decades due to artificial introduction and hardly any natural enemy suppression (Chen *et al.*, 2012). At present, it has become one of the main invasive species in tropical, subtropical and southeastern warm temperate regions (Julien *et al*, 1995). Although some measures such as chemical elimination, mechanical control etc., have been adopted in recent years, it is extremely time-consuming, strenuous and expensive. For the alligator weed, it can grow rapidly, adapt to a variety of habitats and be difficult to remove thoroughly so as to form a single dominant community, which may crowd out local plants, harm farmland (paddy field and dry land) and fish ponds, and block river channels (Julien *et al.*, 1995; Chen *et al.*, 2008). As a result, now the species has leaded to many ecological, economic and social questions in our country (Chen *et al.*, 2012; Pan *et al.*, 2009). In the past, a large number of studies mainly focused on the ecological mechanism (Jian *et al.*, 2017), growth and development (Liu *et al.*, 2014) and prevention and control measures (Chen *et al.*, 2012). Even if, at present, several of the potential habitats of *A. philoxeroides* in China have been completed but be lack of future dynamic analysis for the years 2041–2060 and 2061–2080 (Liu *et al.*, 2016; Yan *et al.*, 2020). Consequently, the detailed potential distribution of this species in China remains unclear to create huge challenges for managers of alien invasion.

Additionally, the global climate change may accelerate the invasion of alien species (Bethany *et al*., 2010; Bertrand *et al*., 2011; Engler *et al*., 2011), so the potential geographic distribution of the alligator weed under future environmental condition need to be also known well as early as possible to adopt some effective measures for prevention and control. In this study, we utilized Maxent model to simulate the geographic distribution of the alligator weed in China in current and future environmental condition. Our aims are: (1) to delineate the potential geographic distribution of this species in current and future environmental conditions, and identify main environmental variables associated with the geographic distributions of this species; (2) to analyze whether the environmental variation will facilitate invasion of this species in China, ultimately offering targeted management measures for stopping this species from afferent and diffusion.

Materials and Methods

Occurrence data: The part occurrence points of the Alligator weed were obtained from published articles (Pan *et al*., 2006; Zhang *et al*., 2010). Most of occurrence records of this species were collected from two free databases, namely, Plant Specimen Database (http://mnh.scu.edu.cn) and Chinese Digital Plant Specimen Data base (http://www.cvh.org.cn), providing names of towns or villages where this species was found. The geographic coordinates of occurrence points were acquired by the the GeoNames geographical data base (http://www.geonames.org/). Based on the above-mentioned data, the coordinates of distributional points for the alligator weeds were kept in csv pattern in accordance with the demand of Maxent model.

The large spatial autocorrelation of localities may affect the accuracy of the model simulation (Yang *et al*., 2013; Record *et al*., 2013). In general, big spatial autocorrelation exists in the observed data of the same distribution area because the neighbouring points tend to be more similar in physical characteristics or ecological niche than are pairs of locations that are far away (Montemayor *et al*., 2015). To overcome the spatial autocorrelation of localities, duplicates points were excluded and only one presence point closest to the centroid of each grid was kept, so the 129 occurrence data were retained from the above sources.

Current environmental parameters: Because climate, terrain, and so on has affected the geographical distribution of the species (Wang *et al*., 2010), so 19 bioclimatic and 3 topographic variables were chosen based on their biological effects on plant species distributions in this study (Li *et al*., 2020). These bioclimatic variables with with approximately 1 km^2 spatial resolution were obtained from the WorldClim data base (http://www.worldclim.org) (Hijmans *et al*., 2005). Elevation also from the WorldClim data base, was used to produce slope degree and slope aspect data in ArcGIS 10.2. Finally, environmental data (GCS-WGS-1984) were acquired from the above-mentioned global raster data overlaid by Chinese administrative boundary maps in shape pattion and then all environment variables data were converted into ASCII format according to the demands of the Maxent model. Additionally, China analysis base map (1:400 million) was obtained from the national fundamental geographic information system (http:‖nfgis.nsdi.gov.cn/).

Future environmental variables: The Representative Concentration Pathways (RCPs), representing the full bandwidth of possible future emission trajectories, were reported by IPCC (Intergovernmental Panel on Climate Change) in The Fifth IPCC Assessment Report (AR5). The RCPs were numbered in according with a possible range of radiative forcing values in the year 2100 compared with the preindustrial values (Hu *et al*., 2015). In this study, we chose two bioclimatic change scenarios including RCP2.6–2050s and RCP4.5–2050s from one global climate model (GTMs: CCSM4), which represent average value for the years of 2041–2060 (2050s), and RCP2.6–2070s and RCP4.5–2070s for the years of 2061–2080 (2070s). These selected future bioclimatic data were obtained from future Worldclimate Data base (http://www.worldclim.org/cmip5_30s). By guess, other 3 environmental parameters such as slope degree, slope aspect and altitude, were remained unchanged under different conditions. Finally, 22 environmental variables were used directly directly by Maxent model in future environmental condition.

Modeling procedure: Geographic distribution of the alligator weed was simulated by the Maxent model (Version 3.4.1), which is a freely available software (http://www.cs.princeton.edu/~schapire/maxent/).

Concretely, during modeling, 75% of these occurrence points were randomly selected for model training, and the remaining 25% for model testing (Qin *et al*., 2017). Linear, quadratic, and hinge features were selected in the modeling process. Meanwhile, the "jackknife" and "response curves" command were also selected in this model and then this model run with other default parameter settings. The output of the model reflects the suitability of habitat in logistic format and asc types. For display and analysis in depth, this result was translated into raster format (GEOTIFF) that varies from 0 (lowest) to 1 (highest). To generate binary map (*i.e*., suitable and unsuitable habitats), the maximum Youden index (Maximum training sensitivity plus specificity Logistic threshold) was selected as the threshold value (Liu *et al*, 2013; Li *et al*., 2020). And based on the past literature (York *et al*., 2011), the suitable habitat with an occurrence probability above the threshold is authorized as 1 and on the contrary the unsuitable one is 2 under current environmental condition, while in future environmental conditions the suitable one is assigned as 3 and the unsuitable one is 4. Then, the two raster data are multiplied in raster calculator of ArcGIS 10.2, so that the pixel value of 3 is not suitable for the target species, 8 indicates the common suitable habitat over the two periods, while 4 indicates the increased suitable habitat for the target species, 6 indicates the decreased suitable habitat in future environmental conditions. Finally, habitat areas by category are calculated after projection conversion (Asia_North_Albers_Equal_Area_Conic).

Model evaluation and important variables: The area under the ROC (receiver operating characteristic) curve or AUC value was used to assess the model performance, and this method was widely utilized in ecological researches (Yang *et al*., 2013; Wang *et al*., 2017). The AUC value ranged from 0.5, implying that the model performance is close to random, to 1.0, indicating that the model offered an excellent prediction. According to the standard adjusted slightly (Zhang *et al*., 2016; Wang *et al*., 2017), model performance was classified as poor (<0.5), moderate (0.5~0.7), good (0.7~0.9), or excellent (>0.9).

Based on percent contribution, we could evaluate the importance of each environmental variable to the species's habitat suitability (Wang *et al*., 2010). In addition, response curves generated from this model also were adopted to analyse species-environment relationships.

Result

Current geographic distribution and evaluation: Current suitable habitats of the alligator weed were simulated by Maxent model. In the forecast results, the AUC value in case of training (0.915) and testing (0.908) is close to 1, showing that the model performance is excellent. Hence, the model for the alligator weed can provide satisfactory results. According to the classification standard above, the final potential distribution was reclassified into 2 category, namely 'unsuitable habitat' and 'suitable one'. The suitable distribution of alligator weed in China is largely distributed on parts of east, south, central and southwest China (Fig. 1). Therein, specifically, its suitable distribution areas are mainly distributed in Shanghai, Jiangsu, Anhui, Zhejiang, Fujian, Jiangxi, Guangdong, Guangxi, Guizhou, Chongqing, Hubei, Hunan, northern Hainan, southwestern Shandong, southeastern Taiwan, eastern Sichuan, most parts of Henan and Yunnan, and Nyingchi in Tibet. Moreover, there are also a few in southern Shaanxi and Hebei provinces. The statistical analysis after projection showed that the suitable habitat area accounted for 22.76% of the total area of China.

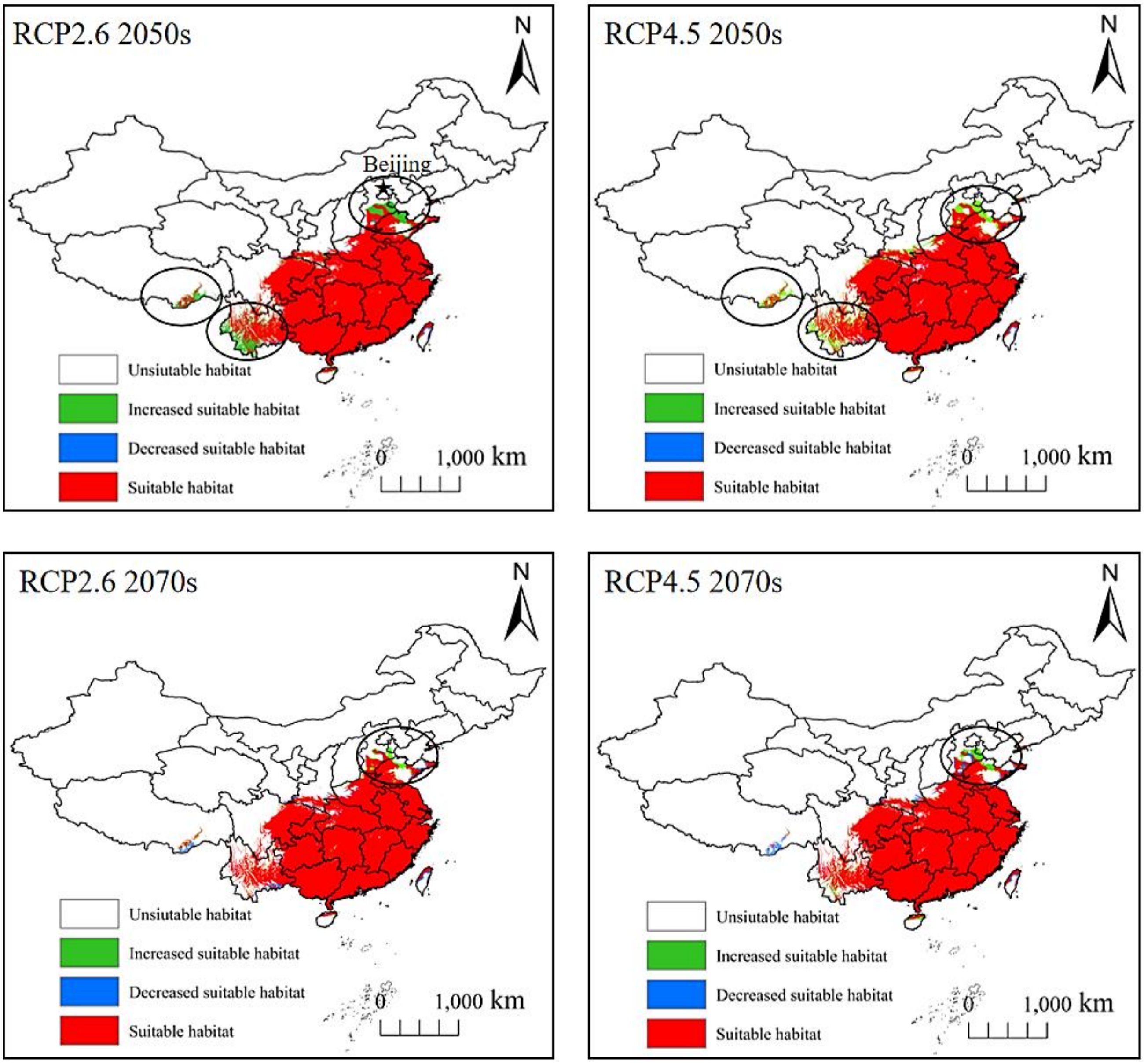

Fig. 1. Distribution of habitat suitability for the alligator weed under different environmental conditions in China.

Importance of environmental parameters: Among the 22 environmental parameters, the top four variables (the precipitation of the driest month, the temperature seasonality, the altitude, the precipitation of the wettest month) significantly affects the model performance for the alligator weed relative to other variables. Therein, the precipitation of driest month made the greatest contribution (70.8%); and then, followed by the temperature seasonality with 5.1%. The percent contributions of altitude and precipitation of the wettest month were 4.4% and 3.6%. The cumulative contributions rate of these variables accounts for 83.9%. Hence, the top four variables were considered as the main environmental variables. Using response curve for the above top four variables alone (Figures are not shown), we acquired the thresholds for the above top four variables (probability >0.5): the precipitation of driest month（Bio-14） (>20, <110 mm), temperature seasonality (Bio-04) (>550, <925), namely, standard deviation (>5.5, <9.25), altitude under 200 m and precipitation of the wettest month (Bio-13) (>160, <300 mm).

Future changes in potential habitat distribution: This model is also applied to simulate its geographic distribution change from the period of 2050s to 2070s. Therein, these model performances in the future environmental conditions were excellent, with an AUC greater than 0.9 for model training and testing. According to the maximum Youden index from our models' output separately, habitat suitability for the alligator weed is separated into two categories, and their area are calculated after projection in the light of same projection coordinate systems. As shows in (Fig. 1), under future environmental conditions, the alligator weed could be potentially distributed in eastern, southern, central and southwestern China and there are also a few in southern Shaanxi and Hebei provinces, which are generally consistent with the current distribution. However, because the increased area is greater than the reduced area in the study area (Table 1), for example, in the period of 2050s, percentages of the suitable areas for RCP2.6 and RCP4.5, increased by 7.52% (223,541.2 km^2) and 6.98% (207,497.2 km^2) in CCSM4. In the period of 2070s (Table 1), the percentage increased by 0.38% (11, 440.5 km^2) and 1.22 % (36,252 km^2) in CCSM4 for RCP2.6 and RCP4.5. The results indicate that the suitable areas for the alligator weed in China will increase until the 2050s and 2070s of this century, however, the increase in the 2050s was greater than that in the 2070s, indicating that the suitable areas for this weed decrease from the 2050s to the 2070s. Besides, the results also show that compared with the suitable area in the current condition, in the 2050s period, the increased suitable areas are mainly concentrated on three regions, namely, southwestern Shandong and southern Hebei provinces, southwestern Yunnan, and Nyingchi in Tibet, while in the 2070s period the increased suitable area only exists in the southwest of Shandong province (Fig. 1).

Table 1. Changes of the suitable habitat for the alligator weed under different environmental conditions.

Climate scenarios	Comparative periods	Decreased habitat		Increased habitat		Total habitat change	
		Area (km^2)	Percent (%)	Area (km^2)	Percent (%)	Area (km^2)	Percent (%)
RCP2.6	Current-2050s	15 561.8	0.52	239 103	8.04	223 541.2	7.52
	Current-2070s	51 201.2	1.72	62 641.7	2.11	11 440.5	0.38
RCP4.5	Current-2050s	16 385.8	0.55	223 883	7.53	207 497.2	6.98
	Current-2070s	54 303.9	1.83	90 555.9	3.05	36 252	1.22

Note: the suitable areas in current environmental variables is 2,972,950 km^2

Discussion

The alligator weed, now spreading to all parts of the world, has resulted in a serious threat to the ecological environment and social economy of the invaded area (Julien *et al*., 1995; Pan *et al*., 2007). Chen *et al*., (2008) estimated potential distribution of the alligator weed in China by using the Garp model associating with 64 district-level occurrences and 14 bioclimatic variables at a resolution of 0.1° arc degree (Chen *et al*., 2012). The result indicated that this species lies in similar geographic distribution but distribution region obviously greater than the results of our prediction. This difference could be from the models selected, environment variable resolution, and the sampling error (Xu *et al*., 2014). Previous research indicated that coordinates of species occurrences at district-levels can only generate a preliminary map of potential risk (Kumar *et al*., 2014). Other studies also found that beyond upper resolution limit, the model performance decreases with respect to prediction accuracy (Seo *et al*., 2009; Franklin *et al*., 2013). Additionally, potential invasion areas of many species, such as the alligator weed and the chestnut phylloxerid (*Moritziella castaneivora*) are greater than the actual distribution area using Garp (genetic algorithm for rule-set production) model (Chen *et al*., 2012; Wang *et al*., 2010). At a result, these bias may produce incomplete predictions in the study area. In this study, we selected Maxent model with 22 environmental variables at 30 seconds spatial resolution and accurately 387 known coordinates, and this model is a commonly popular tool for accurately predicting species distribution in the regional and global scales (Phillips *et al*., 2006; Qin *et al*., 2017). The result indicates that the Maxent model performed excellent with all of the AUCs greater than 0.9 for model training and testing, respectively. As shown in Fig. 1 and (Table 1), to 2050s and 2070s, the suitable distribution will be roughly consistent with that under present environmental conditions, but continue to spread in the future. However, as report goes, the tropics, subtropical and southeastern warm temperate regions are suitable for the growth of the alligator weed (Yan *et al.*, 2020), so this weed has only continued to be spreading in eastern, southern, central and southwestern China, and southern Shaanxi and Hebei provinces. For example, to 2050s, the increased suitable areas are mainly concentrated on southwestern Shandong and southern Hebei provinces, southwest Yunnan, and Nyingchi in Tibet, while to 2070s the increased suitable area only exists in the southwest of Shandong province. Nowadays, these places including western Sichuan, central and northern Shaanxi and Hebei, and most of Gansu, Shanxi, Liaoning and Tibet, etc have not been invaded by alligator weed (Fig. 1). By guess, adjacen areas very near to these suitable areas may be invaded by alligator weed. However, this species are suitable for living in tropical, subtropical and southeastern warm temperate regions (Pan *et al.*, 2007; Yan *et al.*, 2020), so except for adjacent areas of suitable areas (western Sichuan, southeastern Gansu, and southern Shaanxi and Shanxi), other areas away from suitable areas should be relatively safe even if there are sporadic distributions of the alligator weed there. This could be reason that these areas have not been invaded by this species since the invasion of China in 1930. Therefore, the current suitable habitats should be given highly attention to prevent from its spreading to these above-mentioned three increased suitable regions and adjacent areas including western Sichuan, southeastern Gansu, southern Shaanxi and Shanxi. Furthermore, the increase in the 2050s was greater than that in the 2070s. Previous studies have shown that since 1960, the degree, scope, frequency and duration of drought in various regions of China have increased under the background of climate warming (Ma *et al.*, 2019). By guess, the possible reason is that the original suitable areas for the alligator weed with higher altitude become unsuitable with the increase of temperature, so it shifts to grow in low altitude areas below 200 m.

Pan *et al.*, (2007) found that water plays an important role in the population regeneration and growth of the alligator weed, which is especially suitable for growing in the water-land interface of various freshwater ecosystems, such as ponds, lakes, reservoirs, ditches, freshwater swamps, estuarine wetlands, floodplains and riparian zones etc. (Pan *et al.*, 2007). In this study, precipitation of driest month (bio-14) made the greatest contribution (70.8%), indicating that the precipitation of the driest month (bio-14) with thresholds value of 20-200 mm was the dominant factor affecting the distribution of the alligator weed. It is reported that the precipitation in the driest month has an effect on germination of the alligator weed (Burke *et al.*, 2003). For example, when the soil moisture is 10%, the germination percentage is about 20%, and when it reaches to 30%, the germination rate is the highest (Shen *et al.*, 2005; Shen & Zhi, 2006). The contribution rate of altitude and precipitation of the wettest month (bio-13) were 4.4% and 3.6%, although the contribution rate was not significant, it also showed that water was an important factor restricting the distribution of this weed, for example, the elevation below 200 m and the precipitation of the wettest month with thresholds value of 160-300 mm etc guaranteed a full river network system. Furthermore, the river network system is an important carrier for the spread of alligator weed (Pan *et al.*, 2007). In other words, the contribution rate of the above 3 environmental factors relating to water sums up to 78.8%, implying that water is the key factor to determine the distribution of this weed's suitable habitat. The results are in agreement with the existing research conclusions (Pan *et al.*, 2007; Koncki *et al.*, 2008). This study also indicates that the contribution rate of temperature seasonality (bio-04) is 5.1%, with threshold of 550-925, namely, standard deviation of 5.5-9.25, indicating that the seasonal temperature change range was small. This proves the fact that the alligator weeds can germinate and grow normally in the temperature range of 10-40°C (Pan *et al.*, 2007). For northwestern and northeastern China, there are distinct changes in the four seasons of one year, indicating that the seasonal temperature change range was big relative to southeastern China. Especially in winter, the temperature there drops below 0°C in most of the time. When the temperature drops below 0°C in winter, its surface or upper part (stems and leaves) of the ground may freeze or to death, but the roots below water or ground remain alive (Lou *et al.*, 2002). When the temperature rises to 10°C in spring, the roots underground can germinate. This may be the reason why this plant can sporadically spread to north China (*i.e.*, recorded point in Gansu, Hebei provinces and Beijing municipality). Pan *et al.*, (2007) also found that *A. philoxeroides* could not germinate below 5°C (Pan *et al.*, 2007). This may be the reason why it is difficult for the alligator weeds to aggressively colonize in northwestern and northeastern China. To sum up, this study in Maxent model predicts the geographical distribution of the species, which is consistent with the current actual situation, and highlight the specific areas, which will be invaded by the alligator weed yet, so the results have an important scientific significance for its control and prevention.

Conclusions

[1]The suitable distributions of the alligator weed are mainly distributed on eastern, southern, central, southwestern China, and south of Shaanxi and Hebei provinces under current environmental condition; [2]The future environmental condition will facilitate the invasion of the species in mainland of China. To 2050s, the increased suitable areas are mainly distributed on southwestern Shandong and Hebei provinces, southwestern Yunnan, and Nyingchi in Tibet, while to 2070s only in the southwestern of Shandong province; [3]The precipitation of driest month, temperature seasonality, altitude and the precipitation of the wettest month significantly affects the model performance relative to other factors.

Acknowledgments

The work was financially supported by National Natural Science Foundation of China (31870515).

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(Received for publication 23 June 2021)