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Estimation of Potential Habitat of *Caragana acanthophylla* in Xinjiang Based on Maximum Entropy Model

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Abstract [**Objectives**] To determine the potential habitat range of *Caragana acanthophylla* in Xinjiang. [**Methods**] The known distribution points of *C. acanthophylla* were used as samples, and a MaxEnt model was developed based on their climatic variables to identify key environmental factors affecting the potential habitats of *C. acanthophylla* through jackknife method and construction of a response relationship between representative variables and habitat suitability; the suitability of habitats for *C. acanthophylla* in Xinjiang was evaluated based on the output results of the model. [**Results**] (i) The accuracy of the model verified by AUC curve was 0.971, indicating that the potential habitats of *C. acanthophylla* in Xinjiang predicted by MaxEnt model were highly credible. (ii) The optimum climatic characteristics for the distribution of *C. acanthophylla* in Xinjiang were: isothermality 18.8% - 34%, minimum temperature of coldest month -30 ℃ to -13 ℃, mean temperature of coldest quarter -18 ℃ to -4 ℃, annual precipitation 80 - 410 mm, precipitation of driest month 0 - 25 mm, precipitation of driest quarter 0 - 82 mm, and precipitation of coldest quarter 0 - 75 mm. (iii) The total potential distribution area of *C. acanthophylla* in Xinjiang was modeled to be 1.03×10^5 km^2, of which 8.54×10^3 km^2 was high suitability area, mainly in the front mountain belt of the north slope of Tianshan Mountain in Urumqi City, Changji Hui Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, and Yili Kazak Autonomous Prefecture and the front mountain belt of Barluk Mountain in Tacheng Prefecture. [**Conclusions**] This study is of great significance for the future scientific management, regeneration, vegetation restoration and ecological protection of *C. acanthophylla*.

Key words Xinjiang, *Caragana acanthophylla*, MaxEnt model, Potential habitat

1 Introduction

Since Xinjiang is located deep inland with arid climate, the phenomenon of sanding and desertification is more severe. Additionally, due to irrational land use and overgrazing, which aggravates the process of land sanding and desertification[1-2], the ecosystem is seriously threatened and damaged. Shrubs with developed root systems exhibit strong drought resistance, and they can effectively prevent wind erosion and sand fixation[3]. They also help maintain soil and water, and store water, and their abundant litterhas a significant effect on soil improvement. Meanwhile, shrubs play an important role in plant diversity, such as increasing the source of species productivity, improving ecological stability[4], and greatly enriching the diversity of plant communities in nature. Hence, shrubs play an important role in desert ecosystem protection, restoration and reconstruction[5-6].

Caragana acanthophylla is a deciduous shrub of the genus *Caragana* in the family Leguminosae, mostly found in lowlands of premontane alluvial fans, arid gravelly slopes, valleys, riverbanks, premontane plains, sandy areas, barren hills, alluvial fan deserts, and dry-slope meadows, with an altitudinal range of 500 - 2 200 m[7]. *C. acanthophylla* has strong resistance to cold, drought, and barrenness, as well as strong reproduction and regeneration ability, and can play the role of windbreak, sand fixation, and soil and water conservation[8]. Therefore, it is of great significance for future scientific management, regeneration, vegetation restoration and ecological protection of *C. acanthophylla* by carrying out the study on its potential habitat in Xinjiang.

Currently, MaxEnt model is widely used for potential habitat prediction of crops[9-10] and vegetations[11-12], showing high prediction precision and accuracy[13-14]. At present, Chinese scholars mainly use MaxEnt model[15-17] combined with GIS and RS to predict the suitable distribution areas of common shrubs such as *Cornus officinalis*[18], *Lonicera japonica*[19], *Haloxylon ammodendron*[20], *Tamarix chinensis*[21], *Ammopiptanthus mongolicus*[22], and *Ephedra equisetina*[23]. Few studies have been carried out on the potential habitats of *C. acanthophylla* in Xinjiang. In this study, a MaxEnt model was developed based on the climatic variables of the environment in which the known distribution sites of *C. acanthophylla* were sampled. The key environmental factors affecting the potential habitats of *C. acanthophylla* were identified by jackknife method and construction of a response relationship between representative variables and habitat suitability; and the suitability of habitats for *C. acanthophylla* in Xinjiang was evaluated based on the output results of the model.

2 Materials and methods

2.1 Distribution data The distribution data of *C. acantho-*

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phylla were mainly derived from GBIF (the Global Biodiversity Information Facility, https://www.gbif.org), CHV (Chinese Virtual Herbarium, https://www.gbif.org) and related literature[24-29], as well as field survey data in Hutubi County. In order to reduce the sampling bias, only one unique distribution point was taken in each 2.5'×2.5' grid. The data with latitude and longitude records were used directly, and for the distribution points with only location records, their latitude and longitude data were obtained from OvitalMap. A total of 43 distribution points of *C. acanthophylla* were obtained, each of which contained latitude and longitude information (Fig. 1). The distribution points were organized into a CVS format file containing species name, longitude and latitude as a dataset of the distribution of *C. acanthophylla* in Xinjiang. The administrative boundaries of Xinjiang Uygur Autonomous Region were obtained from the Xinjiang Uygur Autonomous Region Geographic Information Public Service Platform (https://xinjiang.tianditu.gov.cn/bzdt_code/bzdt.html#).

2.2 Data source and processin Using secondary survey data of forest resources in the study area, the average age, average height, average DBH and stand density of relatively pure forest sub-compartment of *P. schrenkiana* in the study area was extracted. The forest diameter class was delimited with the step size of 10, and samples with abnormal average tree height and DBH within the range of each forest diameter class were excluded based on plus or minus 2 standard deviation. Finally, 133 *P. schrenkiana* samples were obtained. The average age, average tree height, average DBH and stand density of each forest diameter class are shown in Table 1.

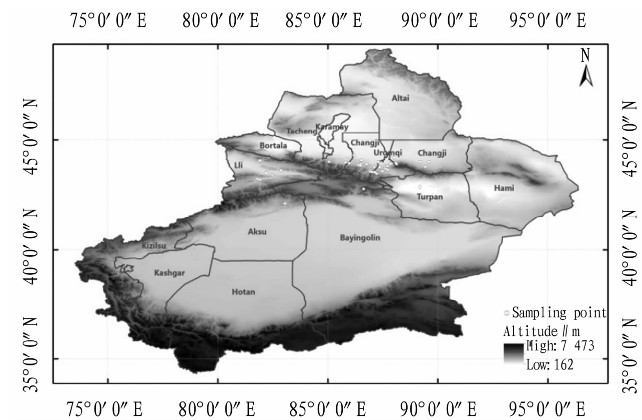


Fig. 1 Location and sampling point distribution map of *Caragana acanthophylla*

Table 1 Environmental factor variables

Variable		Unit	Variable		Unit
bio1	Annual mean temperature	℃	bio11	Mean temperature of coldest quarter	℃
bio2	Monthly mean temperature variation	℃	bio12	Annual precipitation	mm
bio3	Isothermality	%	bio13	Precipitation of wettest month	mm
bio4	Temperature seasonality	-	bio14	Precipitation of driest month	mm
bio5	Maximum temperature of warmest month	℃	bio15	Coefficient of variation of precipitation	%
bio6	Minimum temperature of coldest month	℃	bio16	Precipitation of wettest quarter	mm
bio7	Annual temperature range	℃	bio17	Precipitation of driest quarter	mm
bio8	Mean temperature of wettest quarter	℃	bio18	Precipitation of warmest quarter	mm
bio9	Mean temperature of driest quarter	℃	bio19	Precipitation of coldest quarter	mm
bio10	Mean temperature of warmest quarter	℃			

2.3 Establishment of MaxEnt model MaxEnt is a criterion in probabilistic model learning, and it follows a principle that the model with the highest entropy among all possible models is the best model; if the probabilistic model needs to satisfy some constraints, the principle of maximum entropy is to choose the model with the highest entropy among the set of conditions that satisfy the known constraints. The maximum entropy principle states that when predicting the probability distribution of a random event, the prediction should satisfy all known constraints and make no subjective assumptions about the unknowns. In this case, the probability distribution is the most uniform, the risk of prediction is minimized, and therefore the entropy of the probability distribution obtained is the largest. MaxEnt model[30] uses a computer to simulate the distribution of entropy by taking the image elements of known species distribution points as samples, deriving constraints based on their environmental variables such as climate, soil type, *etc.*, and exploring the possible distribution of maximum entropy under these constraints, accordingly predicting the distribution of species in the study area[31-32].

The distribution dataset and environmental variables dataset of *C. acanthophylla* were imported into MaxEnt model, with 25% of the samples randomly setting aside for testing and the remaining 75% for training the model, and repeated the run 10 times, with the average of the 10 runs as the final prediction. Jackknife method was chosen to test the importance of the environmental variable factors. The ACSII file generated by the model was imported into ARCGIS for ASCII-TIFF transformation, and the suitability degree took values ranging from 0 to 1, with the value closer to 1 representing a higher degree of suitability. In this study, natural breakpoint method was used to judge the habitat boundary value and count the suitability area using the inflection point of suitable probability distribution frequency curve as the threshold value.

2.4 Model accuracy evaluation The modeling results were examined using the receiver operating characteristic curve, *i.e.*, the ROC curve, where the closer the area under the curve (AUC) value to 1, the better the model prediction. The assessment criteria were: 0.7 – 0.8 more accurate, 0.8 – 0.9 very accurate, and 0.9 or more extremely accurate[33 – 34].

3 Results and analysis

3.1 MaxEnt model evaluation The modeling results were tested by ROC curve (Fig.2), which obtained an AUC value of 0.971 for training set and 0.984 for test set, and the AUC value of the model was more than 0.9, which was excellent. The test results showed that the potential habitats of *C. acanthophylla* in Xinjiang predicted by MaxEnt model were not stochastic, and the prediction results were highly reliable.

3.2 Climatic factors affecting the distribution of *C. acanthophylla* The contribution rate of each climatic factor was outputted by MaxEnt model (Table 2). According to the analysis in Table 2, the top 5 climatic factors contributing to the distribution of *C. acanthophylla* successively were precipitation of driest month (bio14, 42.5%), annual precipitation (bio12, 20.4%), minimum temperature of coldest month (bio6, 10.2%), precipitation of coldest quarter (bio19, 7.5%), and mean temperature of coldest quarter (bio11, 4.3%), and the total contribution rate of the above 5 climate factors was 84.9%, in which the contribution rate of precipitation factors was 70.4% and that of temperature factors was 14.5%.

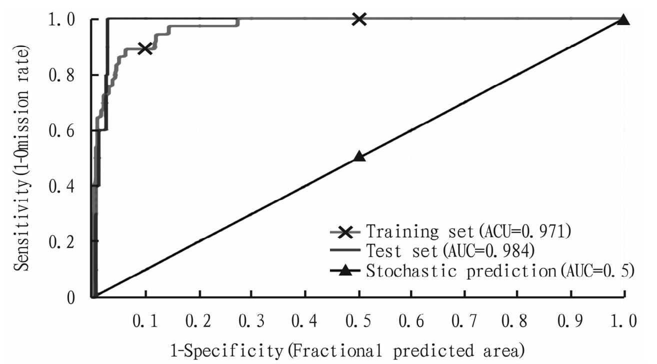


Fig.2 AUC curve of MaxEnt model

Table 2 Contribution and importance of climate variables

Variable		Contribution rate//%	Variable		Contribution rate//%
bio14	Precipitation of driest month	42.5	bio5	Maximum temperature of warmest month	0.8
bio12	Annual precipitation	20.4	bio8	Mean temperature of wettest quarter	0.7
bio6	Minimum temperature of coldest month	10.2	bio2	Monthly mean temperature variation	0.6
bio19	Precipitation of coldest quarter	7.5	bio16	Precipitation of wettest quarter	0.4
bio11	Mean temperature of coldest quarter	4.3	bio17	Precipitation of driest quarter	0.2
bio4	Temperature seasonality	4.1	bio9	Mean temperature of driest quarter	0.1
bio3	Isothermality	2.8	bio18	Precipitation of warmest quarter	0
bio1	Annual mean temperature	2.0	bio7	Annual temperature range	0
bio13	Precipitation of wettest month	2.0	bio10	Mean temperature of warmest quarter	0
bio15	Coefficient of variation of precipitation	1.4			

The gain test of each climatic factor involved in the modeling was performed by jackknife method (Fig.3). According to the analysis in Fig.3, the top 5 climatic factors affecting the distribution of *C. acanthophylla* in Xinjiang were, in order, annual precipitation (bio12), precipitation of driest month (bio14), precipitation of coldest quarter (bio19), precipitation of driest quarter (bio17), and isothermality (bio3).

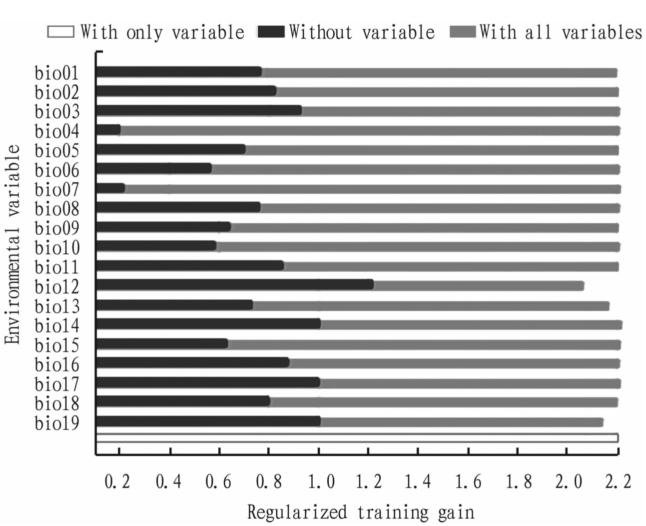
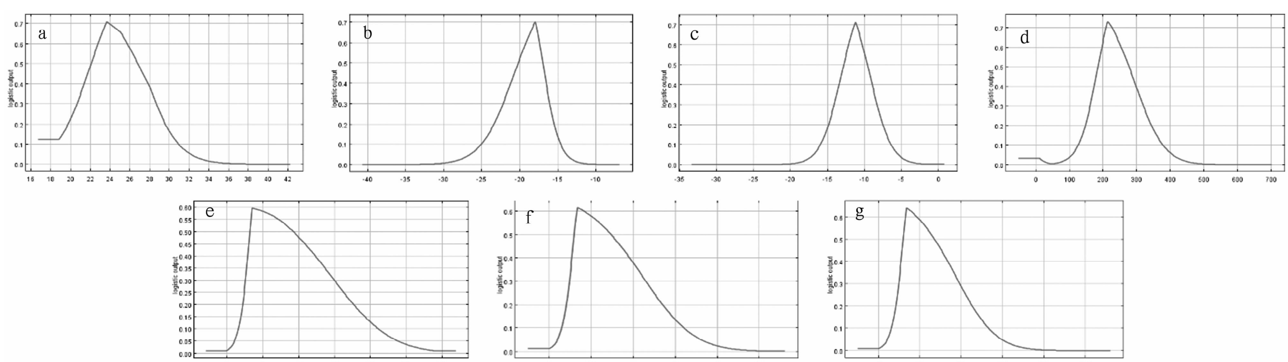


Fig.3 Jackknife diagram of MaxEnt model

3.3 Climate characteristics of the habitat area of *C. acanthophylla* MaxEnt model was used to plot the response curves of the main climatic factors and the suitability of *C. acanthophylla*. According to Fig.4, the response curves of climatic factors all showed the pattern of slowly increasing – rapidly increasing – rapidly decreasing – slowly decreasing in the existence probability. However, the maximum survival probability varied among the climatic factors, as shown by annual precipitation (bio12) > mean temperature of coldest quarter (bio11) > isothermality (bio3) > minimum temperature of coldest month (bio6) > precipitation of coldest quarter (bio19) > precipitation of driest quarter (bio17) > precipitation of driest month (bio14).

The climatic characteristics of the habitat area of *C. acanthophylla* in Xinjiang were: isothermality 18.8% – 34%, minimum temperature of coldest month –30 ℃ to –13 ℃, mean temperature of coldest quarter –18 ℃ to –4 ℃, annual precipitation 80 – 410 mm, precipitation of driest month 0 – 25 mm, precipitation of driest quarter 0 – 82 mm, and precipitation of coldest quarter 0 – 75 mm.

3.4 Potential distribution area and suitability evaluation of *C. acanthophylla* in Xinjiang The results simulated by Maxent model were transformed and visualized to obtain the geospatial distribution map of the predicted habitat suitability of *C. acanthophylla* in Xinjiang, and natural breakpoint method was used to judge the habitat boundary value and count the suitability area, with the predicted value of >0.743 as the high suitability area of *C. acanthophylla*, *the predicted value of* 0.496 – 0.743 as the medium suitability area, the predicted value of 0.248 – 0.496 as the low suitability area, and the predicted value of less than 0.248 as the unsuitable area (Fig. 5). Statistically, the high suitability area is 8.54×10^3 km^2, mainly distributed in the front mountain belt of the north slope of Tianshan Mountain in Urumqi City, Changji Hui Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, and Yili Kazak Autonomous Prefecture and the front mountain belt of Barluk Mountain in Tacheng Prefecture, in which Urumqi City has the largest distribution area, followed by Changji Hui Autonomous Prefecture, and Bortala Mongolian Autonomous Prefecture has the smallest distribution area; the medium suitability area is 3.36×10^4 km^2, mainly distributed in the front mountain belt of the north slope of Tianshan Mountain in Urumqi City, Changji Hui Autonomous Prefecture, Kelamayi City, Bortala Mongol Autonomous Prefecture, and Yili Kazak Autonomous Prefecture, the front mountain belt of Barluk and Tarbagatai Mountains in Tacheng Prefecture, the front mountain belt of the north slope of Tianshan Mountain in Aksu Prefecture, and the desert zone of the Turpan Basin in Turpan City, in which Tacheng Prefecture has the largest distribution area, followed by Ili Kazak Autonomous Prefecture, while Aksu Prefecture and Turpan City have smaller distribution area; the low suitability area is 6.05×10^4 km^2, mainly distributed in Urumqi City, Changji Hui Autonomous Prefecture, Tacheng Prefecture, Bortala Mongol Autonomous Prefecture, Yili Kazak Autonomous Prefecture, Altai Prefecture, Aksu Prefecture, Kizilsu Kirgiz Autonomous Prefecture, Kashgar Prefecture, Bayingolin Mongol Autonomous Prefecture, Turpan City and Hami City. The unsuitable area is the area other than the high, medium and low suitability areas, covering an area of 1.56×10^6 km^2.



NOTE a. Isothermality (bio3); b. Minimum temperature of coldest month (bio6); c. mean temperature of coldest quarter (bio11); d. Annual precipitation (bio12); e. Precipitation of driest month (bio14); f. Precipitation of driest quarter (bio17); g. Precipitation of coldest quarter(bio19).

Fig. 4 Probabilistic response curves for the presence of major climate factors

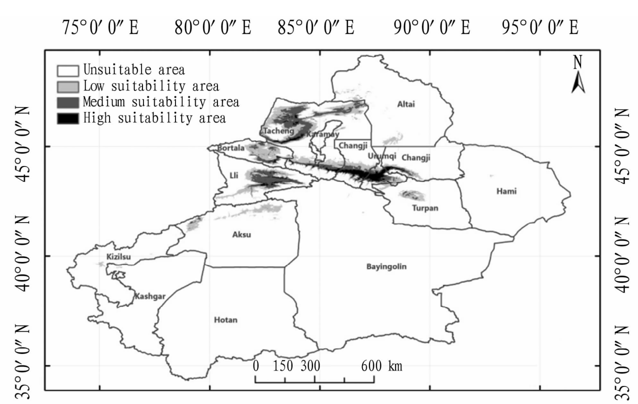


Fig. 5 Potential distribution of *Caragana acanthophylla* in Xinjiang Uygur Autonomous Region predicted by MaxEnt model

4 Discussion

(i) The factors affecting the growth of *C. acanthophylla* were all climatic variables centered on temperature and precipitation, which was based on our finding that the habitat of *C. acanthophylla* was not typical and representative of all types of landscapes and terrains during the field survey. Coupled with the fact that the shrubs have a wide range of ecological adaptations to natural conditions such as soil[35], we believe that topography and soil conditions are difficult to be a determinant of the expansion or decline of *C. acanthophylla* community.

(ii) The high suitability areas of *C. acanthophylla* are distributed in Urumqi, Changji Hui Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, Yili Kazak Autonomous Prefecture, and Tacheng Prefecture, *etc*. The simulation results basically match with the relevant literature[7], indicating that the simulation of the potential distribution areas of *C. acanthophylla* in Xinjiang based on climatic factors and the results of its suitability evaluation are reliable.

(iii) In the study, precipitation of driest month, annual precipitation, minimum temperature of coldest month, precipitation of coldest quarter and mean temperature of coldest quarter were identified as the main climatic factors affecting the distribution of *C. acanthophylla* in Xinjiang, among which the contribution rate of precipitation of driest month, annual precipitation, and precipitation of coldest quarter to the potential distribution of *C. acanthophylla* amounted to 70.4%, suggesting that precipitation is the dominant climatic factor affecting the distribution of *C. acanthophylla* in Xinjiang. Xinjiang has cold and long winters, and the extreme cold conditions will affect and control the potential distribution of vegetation by limiting the growth and development process of individual plants[36], thus minimum temperature of coldest month and mean temperature of coldest quarter become the main climatic factors affecting the potential distribution of *C. acanthophylla*.

(iv) The climate data used in the study are current climate data, but the climate is not static, and in the future climate change scenarios, the habitat area of *C. acanthophylla* in Xinjiang will inevitably produce corresponding changes. It is the focus of the next step by introducing the simulation prediction of climate changes into the prediction simulation of *C. acanthophylla* habitat area. Furthermore, the growth and expansion of *C. acanthophylla* is limited not only by temperature and precipitation, but also by solar radiation, nutrient availability, CO_2 concentration, disturbance, snow cover and melting, length of the growing season, *etc.* In addition to climatic factors, a number of non-climatic factors also affect the growth and dynamics of *C. acanthophylla*, such as interspecific relationships, human activities, and herbivore nibbling[37]. Since the driving mechanism is complicated by the confluence of a number of factors, it becomes a difficulty and direction of the research in the habitat area by quantifying the above factors and exploring their correlation with the growth dynamics of *C. acanthophylla*.

5 Conclusions

(i) In this study, MaxEnt maximum entropy modeling method was used to introduce 19 climatic variables such as mean annual temperature, annual precipitation, isothermality, *etc.* to predict the potential distribution area of *C. acanthophylla* in Xinjiang. AUC curve method was used to validate the model accuracy, and an accuracy of 0.971 was obtained, indicating that this method has a high credibility for the simulation of the potential distribution area of *C. acanthophylla* in Xinjiang.

(ii) An analysis of the response relationship between habitat suitability and environmental variables for representative variables of suitability factors of *C. acanthophylla* in Xinjiang showed that the most suitable climatic characteristics for the distribution of *C. acanthophylla* in Xinjiang were: isothermality 18.8% – 34%, minimum temperature of coldest month –30 ℃ to –13 ℃, mean temperature of coldest quarter –18 ℃ to –4 ℃, annual precipitation 80 – 410 mm, precipitation of driest month 0 – 25 mm, precipitation of driest quarter 0 – 82 mm, and precipitation of coldest quarter 0 – 75 mm.

(iii) Natural breakpoint method was used to determine the habitat boundary value and count the suitability area, and the predicted value > 0.743 was the high suitability area of *C. acanthophylla*, with an area of 8.54×10^3 km^2; the predicted value of 0.496 – 0.743 was the medium suitability area, with an area of 3.36×10^4 km^2; the predicted value of 0.248 – 0.496 was the low suitability area, with an area of 6.05×10^4 km^2; and the predicted value of less than 0.248 was the unsuitable area, with an area of 1.56×10^6 km^2.

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