Ecological Engineering 113 (2018) 27–34

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Simulating the potential distribution of *Elaeagnus angustifolia* L. based on climatic constraints in China

Xiaoqin Zhang[a,b,c], Guoqing Li[a,c,*], Sheng Du[a,c]

[a] *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China*
[b] *College of Agricultural and Biological Engineering, Heze University, Heze 274015, China*
[c] *University of Chinese Academy of Sciences, China*

ARTICLE INFO

Keywords:
Russian olive
Limiting climatic factors
Annual range of temperature
Climatically suitable habitats
Climatic threshold
MaxEnt

ABSTRACT

Elaeagnus angustifolia L. has considerable ecological value and plays an important role in windbreak and sand fixation, soil and water conservation, vegetation restoration and afforestation in Asia. Understanding the potential distribution and the limiting climatic factors is the first step for sustainable use of this species at regional scale. Here, we simulated the potential distribution of *E. angustifolia* and evaluated its limiting climatic factors using a maximum entropy model (MaxEnt) and geographical information system (GIS) in China, based on 190 occurrence grid cells and 13 climatic variables in China. The results show that: (1) annual range of temperature (ART), annual mean temperature (AMT), humidity index (HI), and coldness index (CI) are the dominant climatic factors limiting its potential distribution range; (2) low temperature is an important climatic factor that limits both southern and northern distribution boundaries, and high rainfall is another climatically limiting factor for the southern boundary, and (3) the potential distribution areas are mainly located in the warm temperate and middle temperate zone with cold and dry winters, and in the arid and semi-arid regions of China between 30°N and 50°N. The simulating results can improve our understanding of the geographical and ecological characteristics of *E. angustifolia*, and provide references for the introduction of this species for control and restoration of degraded land in China.

1. Introduction

Elaeagnus angustifolia L, also known as Russian olive or oleaster, is a deciduous small arbor or large multi-stemmed shrub, which is a member of the family Elaeagnaceae (Heywood, 1993), and is native to southern Europe, central and eastern Asia (Katz and Shafroth, 2003). It is a species with multiple traits of economic, ornamental, and high ecological value. Its branches, leaves, flowers, fruits, and juice extracts are widely used in food, medicine, papermaking, forage, wood, and furniture (Huang et al., 2005). Its oval crowns, silver leaves, fragrant flowers, and delicate fruits, as well as its distinct ability of resisting cold and drought stress, make it an excellent landscape tree species, especially in cold and arid areas (Asgarzadeh et al., 2014). Moreover, given its nitrogen-fixing ability (Khamzina et al., 2009; Shah et al., 2010) and saline-alkali tolerance (Liu et al., 2014), it is used as an excellent tree species for windbreak and sand fixation, soil and water conservation, vegetation restoration and afforestation not only in many native countries, but has also been introduced to non-native countries in poor soil for drought-resistant ornamental plant, such as United States and Canada (Collette and Pither, 2015a,b). Now, it has been the frequently occurring and the most dominant riparian tree species in all western United States and southern Canadian provinces (Friedman et al., 2005), where it has already been regarded it as an invasive plant because of concerns about its potential negative impacts, such as replacing native vegetation and altering stream nutrient dynamics (Katz and Shafroth, 2003; Collette and Pither, 2015b). This, however, does not prevent it from being widely used as an excellent plant for afforestation and land rehabilitation in native countries, such as China (Fu, 2016), Turkey (Yildiz et al., 2017) and Uzbekistan (Dubovyk et al., 2016).

In China, one of its native regions, *E. angustifolia* has been widely cultivated in the arid and semi-arid land since the 1980s, as an important pioneer tree species for afforestation. Currently, there are a large number of shelterbelts and windbreaks made by *E. angustifolia* in the arid and semi-arid regions in the Northwest of China. Furthermore, some economic forests are established by farmers in Ningxia, Qinghai, and Gansu provinces. Besides, it has also been cultivated massively in

---

* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China.
E-mail address: liguoqing@nwsuaf.edu.cn (G. Li).

https://doi.org/10.1016/j.ecoleng.2018.01.009
Received 15 July 2017; Received in revised form 25 December 2017; Accepted 17 January 2018

sandy wastelands and saline-alkali lands in the Northeast of China (Yu and Yan, 2009). Currently, there have been many explorations from the perspective of its germplasm resources and economic value (Guo and Wang, 2008), morphological and ecological characteristics (Sun and Lin, 2010), resistance physiology (Liu et al., 2014), and so forth. Recently, the environmental constraints of this species have been well studied in United States and Canada (Nagler et al., 2011; Friedman et al., 2005; Guilbault et al., 2012; Collette and Pither, 2015a), but these predictions were not informed by occurrence records from native countries. Whether their results is necessarily in line with China is still unknown. Therefore, the efforts to estimate the potentially distribution areas based on a wide range of occurrences data is still needed for widespread planting and afforestation management of this species at the national and provincial scale in China.

At present, the common method to study potentially species distribution and environmental suitable habitats is to use species distribution models (SDMs) (Hirzel and Le Lay, 2008; Elith and Leathwick, 2009; Booth et al., 2014; Booth, 2016). SDMs explore the niche requirements and potential distribution range of a species using specimen records from museums and a series of environmental variables (Khamzina et al., 2009; Li et al., 2014; Booth, 2016). The popular species distribution models include ecological niche factor analysis (ENFA), genetic algorithm for rule-set production (GARP) and maximum entropy (MaxEnt), among others. Each model has its own advantages and disadvantages. Nevertheless, several comparative studies show that MaxEnt has better prediction ability than most other models and it is considered as a robust modelling approach that incorporates statistical models and machine learning for characterizing probability distributions from incomplete information and determining the current and/or projected potential distribution of different species (Elith et al., 2006; Phillips et al., 2006; Pearson et al., 2007; Wisz et al., 2008). For example, Phillips et al. (2004, 2006) found that MaxEnt outperformed GARP on observational data for North American breeding birds and two Neotropical mammals (*Bradypus variegatus* and *Microryzomys minutus*). Furthermore, the ability of mapping the limiting factor and similar surface for range-shifting species, which expanded in the MaxEnt model by Elith et al. (2010), make it especially suitable for predicting potential species distributions and interrogate the causes behind predictions.

Many environmental variables are used to simulate the species niches with MaxEnt. Among them, climatic factors are widely used as the predictive variables, because they are thought to play a much more important role in determining the potential distribution of a species than soil and topographical factors with coarse resolution, and at a large scale (global or national) (Toledo et al., 2011; Guisan et al., 2013; Li et al., 2016a,b). Previous studies have also shown that climatic factors have a significant effect on the distribution of on *E. angustifolia* (Nagler et al., 2011) and its occurrence frequency is closely related to low temperature (Friedman et al., 2005; Guilbault et al., 2012) in western USA and Canada. Therefore, our goal was to identify the potential distribution of *E. angustifolia*, and climatic constraints in China using MaxEnt and geographic information system (GIS). This study mainly focused on the following two questions: (1) Whether the climatic limiting factors determining the range of *E. angustifolia* in China are similar as that of in exotic ranges? (2) Where are the climatically suitable habitats of this species in China? These two questions may help to better understand the geographical and ecological characteristics of *E. angustifolia* in China, which could serve as a reference for policy makers and planners for afforestation using this species in China.

2. Materials and methods

2.1. Study area

The study area is located in China, which covers a land area of approximately 9.6 million km^2 (3°52′–53°33′N, 73°40′–135°2′E) and its topography descends in a three-step staircase-like manner from west to east (Hou, 1983). The hydrothermal condition of China is strongly affected by the monsoon climate and the continental climate (Fang et al., 2002). There are a large areas of desertification in northwest of China (Zhu, 1998). Therefore, a number of desertification control initiatives have launched since late 1970s, such as the Three-North Shelterbelt Development Program (1979–2050, widely known as the Great Green Wall), National Program on Combating Desertification (1991–2000), and Croplands to Forests or Grasslands Program (2000–2010). During the implementation of these initiatives, many plants with the characteristics of drought resistance and saline-alkaline tolerance, among which *E. angustifolia* is considered an important candidate plant, were used for revegetation and afforestation in arid and semi-arid deserts, saline-alkali wastelands, and bare mineral substrates. The current distribution of *E. angustifolia* with deserts in China is shown in Supplementary Material Fig. S1.

2.2. Species data and climate variables

The occurrence records of *E. angustifolia* in continental China were retrieved from the Chinese Virtual Herbarium (CVH, http://www.cvh.ac.cn/, last accessed on 20 February 2017), Chinese Academy of Sciences Node of Global Biodiversity Information Facility (GBIF-CAS, http://www.gbifchina.org, last accessed on 20 February 2017), and published literatures. CVH integrated the herbarium data from 35 institutes in China, including the leading and important museums of China, and more than 45,000 data records. GBIF-CAS was established in 2013, through which, one can visit the National Specimen Information Infrastructure (NSII) to access more than 8 million specimen records in China. The published literatures mainly included the relevant papers searched with the keyword of '*Elaeagnus angustifolia*' from the China National Knowledge Internet (CNKI http://www.cnki.net/) and Wanfang Data Knowledge Service Platform (http://www.wanfangdata.com.cn). We compiled the species location data from the above sources for a period spanning 1960 to 2016. During data collection, the distribution data for *E. angustifolia* var. *orientalis*, as a synonym of *E. angustifolia* (Sun and Lin, 2010), were also collected. The location data were accurate at the county level. Records without the location information, as well as the repetitive data, were deleted. Records in parks, botanical gardens and orchards were also removed, because there would be regular or irregular human maintenance management in these places, which can not reflect the adaptability of the species themselves to the environment. Then the remaining location data were converted to points by digitising the centroid of each county. The occurrence data of those points were located on a map of China with a grid cell spacing of 10 arc min. We assumed that a grid cell was suitable for *E. angustifolia* survival, if one or more specimens were present in the grid cell. Then, a binary grid map (presence/absence map) with a 10 arc min spatial resolution was converted into points by using the "raster-to-point" function in ArcGIS 9.3 (ESRI, Redlands, CA, USA). Finally, a total of 190 occurrences were identified (shown in Supplementary Material Fig. S2). The latitude and longitude coordinates for each record were stored in an Excel database for MaxEnt model building.

A set of climatic variables compiled from Bioclim system (http://www.worldclim.org/), Kira system (Kira, 1945) and Holdridge life zone system (Holdridge, 1947) was adopted to characterize the climatic niche of the species, which consisted of 13 climatic variables: annual mean temperature (AMT), max temperature of warmest month (MTWM), min temperature of coldest month (MTCM), annual range of temperature ($\mathrm{ART} = \mathrm{MTWM} - \mathrm{MTCM}$), annual precipitation (AP), precipitation of driest month (PDM), precipitation of wettest month (PWM), precipitation of seasonality (PSD = Monthly coefficient of variation of precipitation), annual biotemperature ($\mathrm{ABT} = \Sigma T/12$, $0\,^{\circ}\mathrm{C} < T < 30\,^{\circ}\mathrm{C}$, T is the mean monthly temperature), potential evapotranspiration rate ($\mathrm{PER} = 58.93 \times \mathrm{ABT}/\mathrm{AP}$), coldness index ($\mathrm{CI} = -\Sigma(5 - T)$, $T > 5\,^{\circ}\mathrm{C}$), warmth index ($\mathrm{WI} = \Sigma(T - 5)$, $T > 5\,^{\circ}\mathrm{C}$), humidity index ($\mathrm{HI} = \mathrm{AP}/\mathrm{WI}$). The first eight variables were

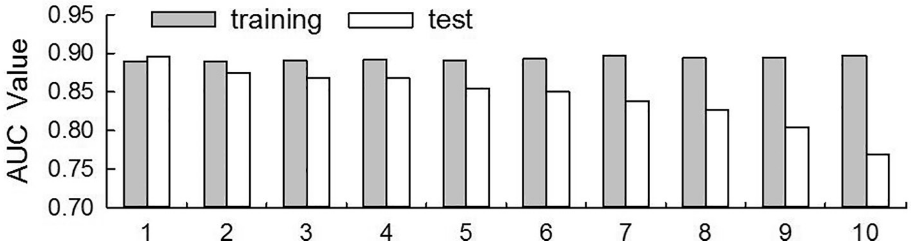

Fig. 1. Areas under the receiver operating characteristic curve (AUC) value of training data and test data, based on 10-fold cross-validation in descending order by the test AUC value. X-axis label 1–10 represents the model code. The mean training AUC value is 0.89 and the mean test AUC value is 0.84.

initially used on the BIOCLIM package (the first SDM model), which are generally used in ecological or other studies to evaluate the effect of climate on species distribution such as plant, pathogens, insect, etc. The remaining five variables were used in Holdridge life zone system and Kira index system, which are climate-vegetation models to describe the vegetation belts in the world and East Asia separately. These variables have been used to simulate the climatically suitable areas of other plants (*Platycladus orientalis*, *Pinus tabulaeformis*, *Robinia Pseudoacacia* L.) globally and nationally (Li et al., 2014, 2016a,b). All climatic layers were sourced directly or indirectly from the WorldClim database (http://www.worldclim.org/) at a spatial resolution of 10 arc-min, which were generated using thin-plate smoothing splines with latitude, longitude, altitude, and monthly temperature and precipitation records of 50-year averages (1950–2000) from climate stations around the world (Hijmans et al., 2005).

2.3. Modeling methods and statistical analysis

We implemented MaxEnt using version 3.3.3 k of the software developed by Phillips et al. (Phillips et al., 2006; Phillips and Dudik, 2008). It was downloaded for free from the website of Princeton University (http://www.cs.princeton.edu/~schapire/maxent/). MaxEnt expresses the suitability of a grid cell as a function of the environmental or climatic layers at that grid cell in a landscape, together with a set of sample locations, where the plant species has been observed. The suitability distribution is estimated by the equation (Merow et al., 2013; Li et al., 2014; Li et al., 2016a): $P(x) = \exp(c_1 \times f_1(x) + c_2 \times f_2(x) + c_3 \times f_3(x) \ldots)/Z$. Here c_1, c_2, c_3, … are constants, f_1, f_2, f_3, … are the features, and Z is a scaling constant that ensures that P sums to 1 over all grid cells, with 0 being the lowest probability and 1 being the highest.

All occurrence points of *E. angustifolia* and 13 climatic variables were uploaded into the MaxEnt software. The feature parameters were settled as linear, quadratic, product, threshold and hinge in order to build non-linear response curves which were used to interpret how individual variables affect the probability of presence of this species. The regularization multiplier was set to 1 to prevent over-complexity and/or reduce overfitting by controlling the intensity of the chosen feature classes used to build the model (Elith et al., 2010). The method of 10-fold cross-validation was selected to evaluate the performance of MaxEnt. That is, the data were randomly divided into 10 subsamples, one of which was taken as the test data, and the remaining nine subsamples were taken as the training data; the program was then replicated 10 times. The prediction accuracy of the model was assessed by an area under the receiver operating characteristic curve (AUC), based on the 10-fold cross-validation method. Larger the average AUC value, higher is the prediction accuracy of the model. AUC values can range between 0.5 and 1.0, which could be divided into five classes (Swets, 1988): 0.5–0.6 (fail), 0.6–0.7 (poor), 0.7–0.8 (fair), 0.8–0.9 (good), and 0.9–1.0 (excellent).

The jackknife test (systematically leaving out each variable) were used to measure which were the dominant climatic factors determining potential distribution of the species (Phillips et al., 2006; Li et al., 2016a). Limiting factor mapping were also applied to explore spatially how the climatic factors most influencing predictions vary across study area. The limiting factor mapping is firstly described by Elith et al. (2010) and then has been successed used in case study of *Platycladus orientalis* around the world (Li et al., 2016a). A final distribution model was obtained based on the average logistic outputs of 10 replicated runs, which is used to estimate the probability of presence between 0 (not likely to occur) and 1 (most likely to occur) (Phillips et al., 2006). The threshold rule of maximum sensitivity plus specificity was chosen to change the probability map to binary map, which found a high degree of support when evaluated against other methods and was regarded as 'stringent' (Bystriakova et al., 2014). We have calculated the optimal threshold in the simulation process of this study (range from 0.279 to 0.421 with a mean value of 0.330 and standard deviation of 0.039). In order to preserve the maximum amount of forecast information and facilitate further analysis, we divided the habitat suitability in the map with four levels: unsuitable habitat (0–0.3), lowly suitable habitat (0.3–0.5), moderately suitable habitat (0.5–0.7), and highly suitable habitat (0.7–1).

3. Results

3.1. Model performance and the importance of climatic factors

The mean AUC values of test data and training data were 0.89 and 0.84, respectively, indicating that the model performed better than random and had good accuracy. The AUC values of 10-fold cross-validation are shown in descending order by the test AUC value (Fig. 1), and the coefficient of variation in the test AUC values was 3.7% among the 10 model simulations, indicating that the 10-fold cross-validation method hardly affected the predicted performance of the MaxEnt model. The simulated potential distribution of E. angustifolia was found to be similar with its occurrence points (as shown in Supplementary Material Fig. S3).

The relative contribution of each climatic factor was evaluated by a

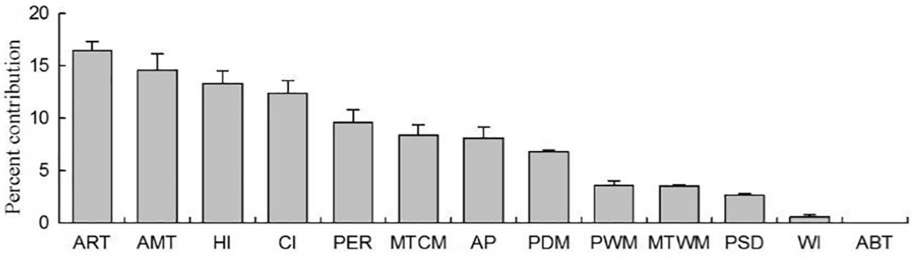

Fig. 2. Percent contribution rates for the climate factors affecting the distribution of *Elaeagnus angustifolia.* ART (annual range of temperature, °C), AMT (annual mean temperature, °C), HI (humidity index, mm/°C), CI (coldness index, °C), PDM (precipitation of the driest month, mm), PER (potential evapotranspiration rate, °C/mm), AP (annual precipitation, mm), MTCM (minimum temperature of coldest month, °C), PWM (precipitation of the wettest month, mm), PSD (precipitation of seasonality, %), MTWM (maximum temperature of warmest month, °C), WI (warmth index, °C), ABT (annual biotemperature, °C).

jack-knife test, and the percent contribution rates are shown in Fig. 2 and Table S1. The relative contribution rates of ART and AMT were 16.4% and 14.6%, respectively, which yielded them the top two ranks. They were followed by HI and CI, with contribution rates of 13.3% and 12.4%, respectively. These four factors (with individual contribution rates > 10%) can be considered the dominant climate factors that affect the potential distribution of *E. angustifolia* in China. The total contribution of the last four factors (MTWM, PSD, WI, ABT) was less than 10%, therefore, their effects can be considered very small. The other factors, in the decreasing order of contribution, were PER, MTCM, AP, PDM, and PWM, affecting climatically suitable habitats of this species to some extent.

The above results indicate that the distribution of *E. angustifolia* was associated with both thermal (ART, AMT, CI, MTCM, MTWM, WI) and hydrological climatic factors (HI, PER, AP, PDM, PWM, PSD). However, among all factors, the cumulative contribution of the temperature-related climatic factors was 55.9%, being slightly larger than that of the hydrology-related climatic factors (Fig. 2Table S1). For the first four important factors, the cumulative contribution of the temperature-related climatic factors (ART, AMT, CI) was obviously larger compared to the hydrology-related climatic factors (HI) (Fig. 2Table S1). Therefore, the temperature-related climatic factors played a more important role than the hydrology-related climatic factors in controlling the potential distribution.

3.2. Response curves and limiting factors

Response curves to climatic suitability for the four dominant climate factors are shown in Fig. 3 and that of the remaining nine climatic factors are shown in Supplementary Material Fig. S4. Clearly, there were unimodal relationships between the habitat suitability and ART or AMT, and their response peaks were at 42.7 °C and 7.9 °C, respectively. The relationship between the habitat suitability values and HI was best described by exponential decay, and the response peak was at 1.3 mm/°C. The relationship between the habitat suitability values and CI was best described by exponential increase, and the response peak was at −8.5 °C.

The areas outside the potential distribution range of *E. angustifolia* were mainly shaped due to the limitation of CI, AMT, ART and PDM (Fig. 4). CI limited the potential distribution of this species across Northern China. Besides, it was also a limiting factor for Qinghai Tibet Plateau in Western China, as well as AMT. ART limited the distribution across Southern China. PDM was the main limiting factor both in Northwestern and Southeastern China, though it was not included in the four dominant climatic factors.

3.3. The potential distribution of E. angustifolia and climatic thresholds

Based on the average value of maps from 10-fold cross-validation, a climatically suitable habitat map for *E. angustifolia* was created (Fig. 5). The results showed that the climatically suitable habitats of *E. angustifolia* were mainly distributed from 1000 to 2000 m above sea level, crossing the northern regions of Kunlun, Altyn, Qilian and Qinling Mountains, including Funiu and Taihang Mountains and their surrounding areas. The highly suitable area accounted for approximately 2.0% (0.2×10^6 km^2) of the total land area and was mainly located in nine provinces or autonomous regions: Gansu (GS), Xinjiang (XJ), Ningxia (NX), Shaanxi (SAX), Inner Mongolia (NMG), Qinghai (QH), Shanxi (SX), Hebei (HEB), and Henan (HN). The moderately suitable areas accounted for approximately 10.2% (1.0×10^6 km^2) of the total land area and extended to Shandong (SD), Liaoning (LN), Tibet (XZ), Jiangsu (JS), and Anhui (AH). The lowly suitable areas accounted for approximately 14.2% (1.4×10^6 km^2), and in addition to the above provinces, there were also some small distribution areas in Hubei (HUB), Jilin (JL), Heilongjiang (HLJ), and Sichuan (SC) provinces. Other provinces or autonomous regions, mainly located in the very

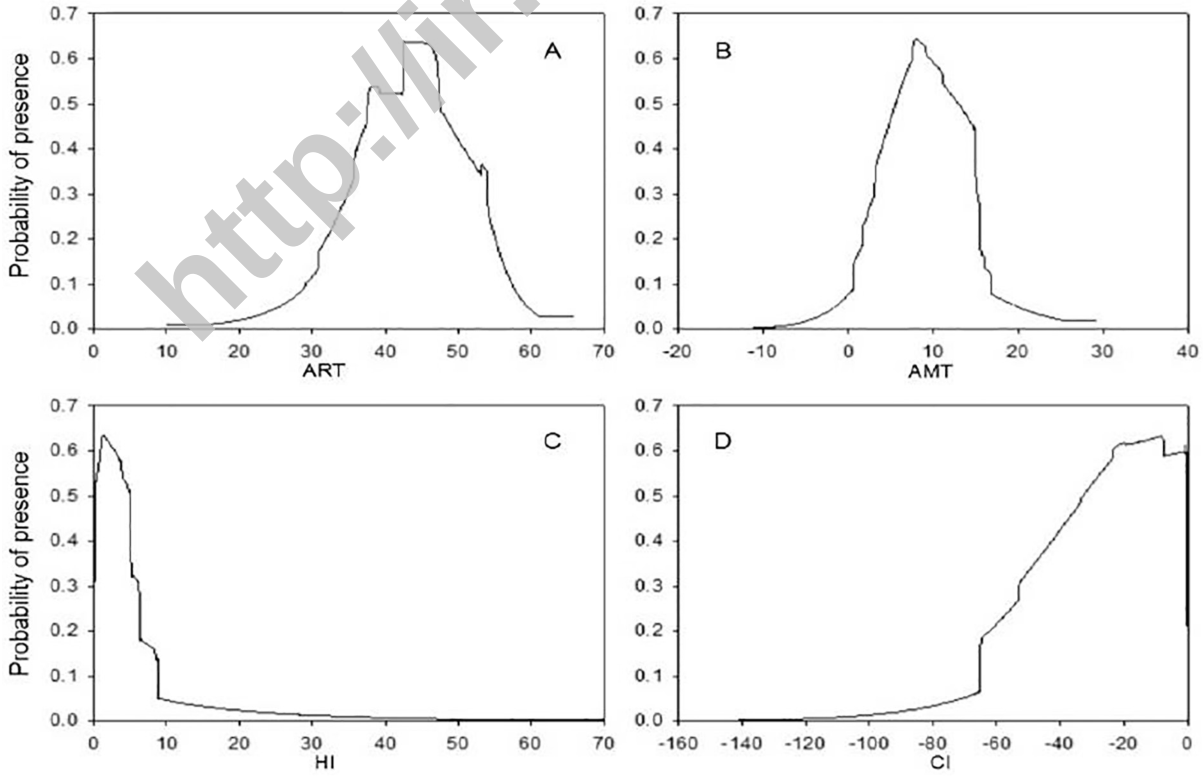

Fig. 3. The response curves of climatic suitability for the four most important climatic factors, which were simulated by MaxEnt model. (A) annual range of temperature (ART, °C); (B) annual mean temperature (AMT, °C); (C) humidity index (HI, mm/°C); (D) coldness index (CI, °C). Upward trends for variables indicated a positive relationship, while downward trends represented a negative relationship. The magnitude of these trends indicated the strength of the relationship.

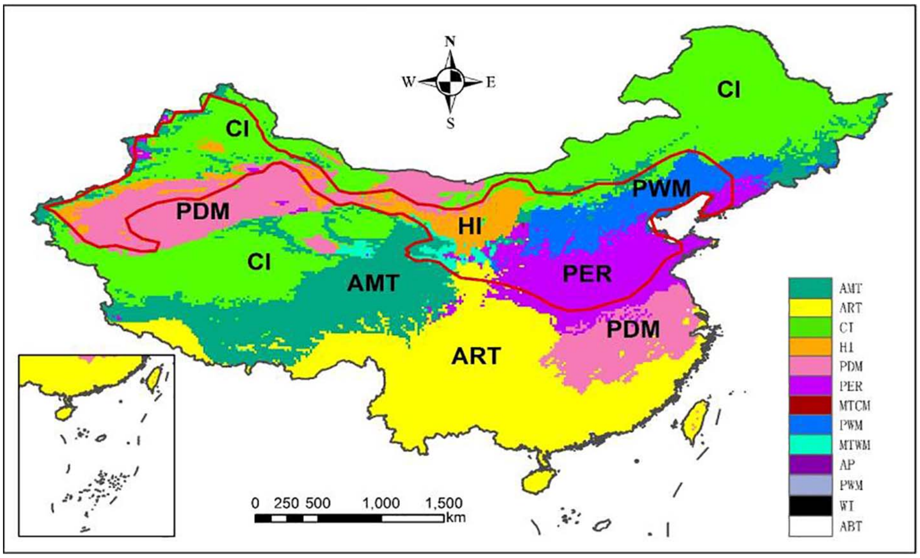

Fig. 4. Spatial distribution of limiting factors for *Elaeagnus angustifolia*, indicating how the variables with the most effect on predictions vary across China. Coarse red polygon represents potential distribution range of E. angustifolia. ART (annual range of temperature, °C), AMT (annual mean temperature, °C), HI (humidity index, mm/°C), CI (coldness index, °C), PDM (precipitation of the driest month, mm), PER (potential evapotranspiration rate, °C/mm), AP (annual precipitation, mm), MTCM (min temperature of coldest month, °C), PWM (precipitation of the wettest month, mm), PSD (precipitation of seasonality, %), MTWM (max temperature of warmest month, °C), WI (warmth index, °C), ABT (annual biotemperature, °C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

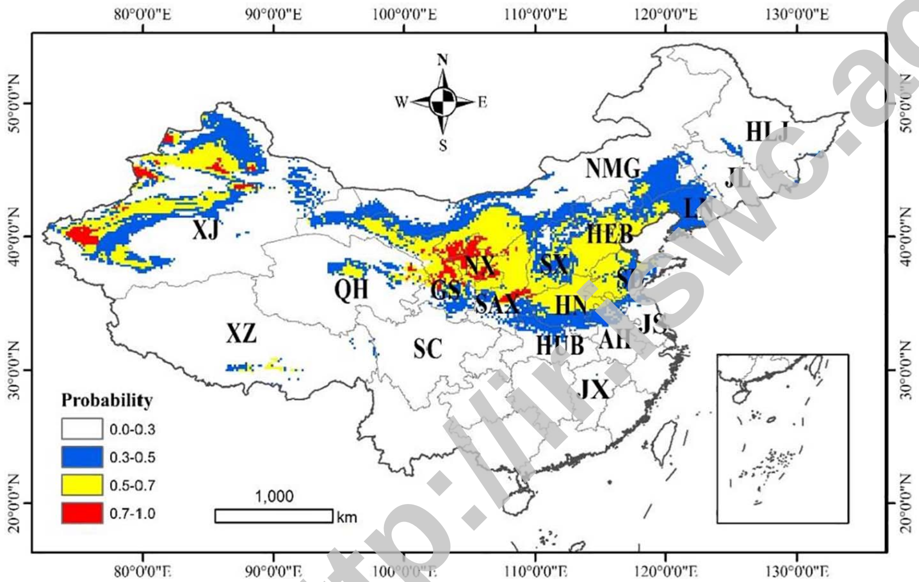

Fig. 5. Potential distribution of *Elaeagnus angustifolia* in China. XJ (Xinjiang), GS (Gansu), QH (Qinghai), XZ (Tibet), NX (Ningxia), SAX (Shanaxi), SC (Sichuan), SX (Shanxi), HN (Henan), HUB (Hubei), NMG (Inner Mongolia), HEB (Hebei, Beijing, Tianjin), SD (Shandong), JS (Jiangsu), AH (Anhui), JX (Jiangxi), LN (Liaoning), JL (Jilin), HLJ (Heilongjiang).

northeast and the south of China, and the Qinghai Tibet Plateau, were potentially unsuitable areas.

The potential distribution of *E. angustifolia* was overlaid with the maps of dry and wet divisions, and the temperature zones in China (Hou, 1983), using ArcGIS (Fig. 6). The potential areas were distributed mainly in the extremely arid, arid and semi-arid regions in

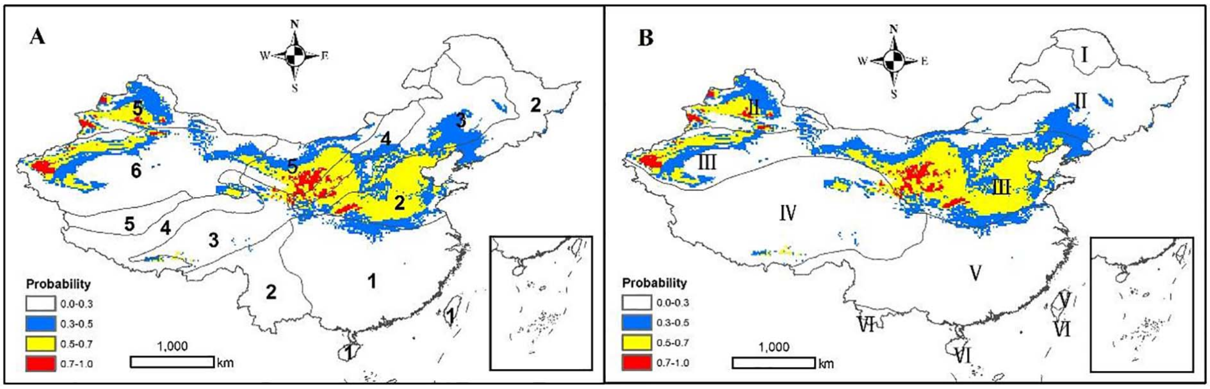

Fig. 6. Potential distribution of *Elaeagnus angustifolia* in China and its relationships with (A) dry and wet divisions and (B) temperature zones. 1: Humid region with non-distinct dry season, 2: humid region with distinct dry season, 3: semi-humid region, 4: semi-arid region, 5: arid region, 6: extremely arid region. I: Cold temperate zone, II: middle temperature zone, III: warm temperate zone, IV: plateau climate zone, V: subtropical zone, VI: tropical zone.

Northwestern China, semi-humid region and humid region with distinct dry in Northern China, but sparsely in these regions in Southwestern China and Northeastern China (Fig. 6A). In addition, there were sparsely suitable areas in the humid region with distinct dry season, whereas there was hardly any suitable area in the humid region with non-distinct dry season in Southern China. The boundary of *E. angustifolia* distribution was roughly consistent with the dividing line of the temperature zones (Fig. 6B). The suitable areas were mainly distributed in the warm temperature zone, and partly in the middle temperate zone. Besides, there were a small number of suitable areas in the subtropical zone and the plateau climate zone, whereas there was hardly any suitable area in the tropical zone and the cold temperate zone.

The climatic thresholds of different suitable habitats can quantitatively describe the climatic characteristics of *E. angustifolia* (Supplementary Material Table S2), in which, the thresholds of the four dominant climatic factors of highly suitable habitats are as follows: ART 35.8–54.2 °C, AMT 1.8–15.4 °C, HI 0.1–8.6 mm/°C, and CI −42.2 to 0.0 °C.

4. Discussion

4.1. The temperature-related limiting factors of geographical boundary

ART is the main temperature-related limiting factor that determines the boundary of *E. angustifolia* in Southern China (Fig. 4), where the minimum temperature is usually above 0 °C. These results can reflect the effect of lacking low temperature on the southern boundary of this specie, which is consistent with previous studies from United States and Canada (Friedman et al., 2005; Guilbault et al., 2012; Collette and Pither, 2015a,b) that the southern boundary of this species is limited by insufficient chilling temperature. It appears that the accumulation of chilling temperatures are very necessary to break seed and bud dormancy for *E. angustifolia* (Katz and Shafroth, 2003).

AMT and CI are the main limiting factors for Qinghai Tibet Plateau (Fig. 4), where exists a cold high-mountain climate (the annual average temperature is less than 5 °C and no summer in the southeastern part, ranges from −8 °C to −10 °C in the northwestern part) and it is characterized by the most extreme type of climate (Hou, 1983). CI is also the main limiting factor across Northern China (Fig. 4). Both AMT and CI can reflect that chronically and/or extremely low temperature is unfavorable to form self-sustaining populations of this species in those regions. Similarly, in the perspective of the response curve of AMT and CI (Fig. 3B, D), the gradual decrease in probability of presence below 7.9 °C and −25 °C, respectively, can also reflect that this species cannot endure continuously or extremely low temperature. The limit of *E. angustifolia* in Qinghai Tibet Plateau and across Northern China appears to result mainly from its inability to undergo full fruit maturation or tolerate extremely low temperature, based on the previous observation that the fruits of this species are mainly formed in the midsummer with the average temperature above 20 °C (Guo and Wang, 2008), and the previous controlled-freezing experiments that its killing temperature is −55 °C (Gusta et al., 1983).

4.2. The hydrology-related limiting factors of geographical boundary

HI is the only hydrology-related factor included in the four dominant climatic factors. It is a climatic factor that reflects the hydrothermal conditions, and the higher value of HI represents the more humid climate (Xu, 1985). The highest probability of *E. angustifolia* presence occurs when HI is 1.3 mm/°C (Fig. 3) (This value signifies that there is little surplus of rainfall in addition to the water needed to satisfy evaporation); however, a rapid declining trend is seen in the probability of occurrence after this value (Fig. 3), which indicates that a very wet climate is not suitable for this species.

PDM is also a hydrology-related factor that limit the suitable distribution areas of *E. angustifolia* in the extremely arid and arid regions of Northwestern China, and additionally in humid areas of Southeastern China where the driest months occurs usually in winter (Figs. 4 and 6), although its contribution rate is low. However, the underlying reasons are diferent. The distribution of *E. angustifolia* appears to be limited by too little precipitation in the arid area of Northwestern China, whereas it appears to be limited by excessive precipitation in winter in the humid areas of Southeast China. Consequently, high rainfall is also the important climatic limiting factor and it mainly affects the suitable habitats in the southeast of China, which provides a validation for the hypothesis by Guilbault et al. (2012) that the effects of insufficient chilling need not be absolute to limit distribution. It is possible that *E. angustifolia* needs a certain period of dryness in the process of growth, especially during the dormant period. Otherwise, it gets outcompeted by more tree species when the rainfall is enough.

4.3. The uncertainty of the simulation and its applications

Our simulation of the potential distribution of *E. angustifolia* is only based on occurrence data in native regions rather than occurrence data in exotic areas, which indicates that the climatic niche of the species we have simulated is realized niche instead of fundamental niche (Soberon and Nakamura, 2009; Booth et al., 1988, Booth, 2017). Soberon and Arroyo-Pena (2017) suggest that realized niche is always smaller than the fundamental niche. Therefore, we speculated that our simulated climatically suitable habitat and climatic thresholds may be only applicable native ranges rather than exotic areas. Many studies suggested when species are introduced outside their native ranges, the competition factors may be have changed in exotic areas, which will make the realized niche shift to new climatic conditions (Ancillotto et al., 2016; Li et al., 2018). When our simulated MaxEnt model is projected into world map (shown in Supplementary Material Fig. S5), we found there are only median and marginal climatic suitable habitat instead of core climatic suitable habitat in North America region, where faced a serious problem of invasion of *E. angustifolia* (Reynolds and Cooper, 2010; Collette and Pither, 2015a,b). The most likely explanation is that the climatic niche of the species has shifted or evolved in North America compared with the native ranges, leading to changes in its adaptability to climate conditions. We suggested this assumption should be further studied.

Our simulation of the potential distribution of *E. angustifolia* is only based on climatic variables rather than other abiotic factors, such as soil factors. Some previous studies have shown that *E. angustifolia* can tolerate more severe drought conditions in introduced ranges (Katz and Shafroth, 2003; Reynolds and Cooper, 2010), which is attributed to its well developed root system that can absorb stable groundwater sources or reach the underground aquifer to absorb moisture in deep soil (> 200 cm) (Zhang, 1981; Cui et al., 2015; Dubovyk et al., 2016)). Our study did not include hydro-geological characteristics due to data limitations and we highly recommended it should be further studied when these data become available in China. It is noteworthy that the seedling of *E. angustifolia* is primary rely on rainfall or irrigation until 15 years of age before utilizing groundwater (Reynolds and Cooper, 2010). Therefore, climatic factors may remains the most crucial factors controlling the regeneration and spread of natural populations. It also suggests that the potential distribution of *E. angustifolia* we have simulated is the climatically suitable habitats or areas that can be introduced.

Our simulation of the potential distribution of *E. angustifolia* mainly locates from extremely arid to semi-arid regions of Northwestern China between 30°N and 50°N, which accounted for approximately 26.4% (2.6×10^6 km^2) of the total land area in China. Here are ecologically fragile areas in China with serious degradation of vegetation and desertification of land. Given the favorable climatic conditions in these areas, the implement of extensive afforestation with *E. angustifolia* to rehabilitate degraded land and control desertification would be efficient and feasible. A number of practices of afforestation have been proved that *E. angustifolia* forest can play an effective on windbreak and sand-fixing (Fu, 2016) and enhance regional ecosystem services for local society (Liang, 2016). But we should know that when land degradation persist, these or other soil factors may significantly restrict the introduction of *E. angustifolia* even under favorable climatic conditions. It should be acknowledged that our simulation map is often a good start, but it is desirable to include more information from other limiting factors (e.g. soil) if they are available. Besides, as an ornamental plant, this species is paid more attention to its ornamental value than the ability of forming self-sustaining populations, thereby it is well suited for planting in wasteland for hedgerows, windbreaks, other horticultural purpose under human intervention (Katz and Shafroth, 2003; Wang et al., 2009).

It is noteworthy that *E. angustifolia* has been reported as an invasive species in its exotic regions and cased great damage to local natural ecosystem to many countries (Reynolds and Cooper, 2010; Collette and Pither, 2015a,b). It was reportedly first brought to the U.S. in the 1800s by Russian Mennonites who planted it in hedgerows and orshade (Hansen, 1901; Katz and Shafroth, 2003). Thereafter, as a multi-purpose, salt-tolerant and fast-growing species, it was encouraged for planting in windbreaks and horticultural settings (Olson and Knopf, 1986; Haber, 1999; Nagler et al., 2011). However, it escaped cultivation and now become frequently occurring riparian tree species in the western United States (Friedman et al., 2005). Therefore, introduction the species to other non-native region for large-scale ecological restoration project purpose should be strict restrictions. However, planting this species in its native ranges should be not facing such problem, because native species are the result of natural selection under local environment in a long-term evolution history and the ecosystem composed of native species are very stable and does not invading other ecosystem in native ranges (Vila and Weiner, 2004; Strauss et al., 2006; Marsh-Matthews et al., 2011). Besides, native species have local cultural characteristics as well as great economic benefits to local soceity. Therefore, we suggest that *E. angustifolia* would contribute greatly to control and rehabilitate degraded land and enhancing the ecosystem service in Northwest of China without risking invasion as other non-native ecosystems.

5. Conclusions

Our work is the first study to simulate the potential distribution of *E. angustifolia* and evaluate its limiting climatic factors in China. It demonstrates that low temperature is the main limiting climatic factor that determine the southern and northern boundaries of this species, which is consistent with that of exotic population in North American regions. More importantly, our research confirms that high rainfall is another limiting climatic factor that determine the southern boundary of *E. angustifolia*, which has not been reported before for this species. The climatically suitable habitats of *E. angustifolia* are mainly distributed in the warm temperate and middle temperate zones with cold and dry winters, and in the arid and semi-arid regions of China between 30°N and 50°N. This species should be an excellent species for afforestation and desertification control in those regions in view of its ability to pioneer saline soils and degraded lands in China. The method used in this study will also be useful in evaluating limiting climatic factors and simulating potential distribution of other species around the world.

Acknowledgments

The authors acknowledge two anonymous reviewers for their constructive comments, which significantly improved the manuscript. The project was supported financially by the National Key Research and Development Program of China (2017YFC0504601), National Nature Science Foundation of China (No. 31300407) and Key Cultivation Project of Chinese Academy of Sciences “The promotion and management of ecosystem functions of restored vegetation in Loess Plateau, China”.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2018.01.009.

References

Ancillotto, L., Strubbe, D., Menchetti, M., Mori, E., 2016. An overlooked invader? ecological niche, invasion success and range dynamics of the *Alexandrine parakeet* in the invaded range. Biol. Invasions 18, 583–595.

Asgarzadeh, M., Vandati, K., Lotfi, M., Arab, M., Babaei, A., Naderi, F., Soufi, M.P., Rouhani, G., 2014. Plant selection method for urban landscapes of semi-arid cities (a case study of Tehran). Urban Forest. Urban Green. 13, 450–458.

Booth, T.H., 2016. Estimating potential range and hence climatic adaptability in selected tree species. Forest Ecol. Manage. 366, 175–183.

Booth, T.H., 2017. Assessing species climatic requirements beyond the realized niche: some lessons mainly from tree species distribution modelling. Clim. Change 145, 259–271.

Booth, T.H., Nix, H.A., Hutchinson, M.F., Jovanovic, T., 1988. Niche analysis and tree species introduction. Forest. Ecol. Manag. 23, 47–59.

Booth, T.H., Nix, H.A., Busby, J.R., Hutchinson, M.F., 2014. BIOCLIM: the first species distribution modelling package, its early applications and relevance to most current MAXENT studies. Divers. Distrib. 20, 1–9.

Bystriakova, N., Ansell, S.W., Russell, S.J., Grundmann, M., Vogel, J.C., Schneider, H., 2014. Present, past and future of the European rock fern Asplenium fontanum: combining distribution modelling and population genetics to study the effect of climate change on geographic range and genetic diversity. Ann. Bot.-London 113, 453–465.

Collette, L.K.D., Pither, J., 2015a. Modeling the potential North American distribution of Russian olive, an invader of riparian ecosystems. Plant Ecol. 216, 1371–1383.

Collette, L.K.D., Pither, J., 2015b. Russian-olive (*Elaeagnus angustifolia*) biology and ecology and its potential to invade northern North American Riparian ecosystems. Invas. Plant Sci. Mana. 8, 1–14.

Cui, Y.Q., Ma, J.Y., Sun, W., Sun, J.H., Duan, Z.H., 2015. A preliminary study of water use strategy of desert plants in Dunhuang. China. J. Arid Land. 7, 73–81.

Dubovyk, O., Menz, G., Khamzina, A., 2016. Land suitability assessment for afforestation with *Elaeagnus Angustifolia* L. in degraded agricultural areas of the lower Amudarya River basin. Land Degrad. Dev. 27, 1831–1839.

Elith, J., Graham, C.H., Anderson, R.P., Dudik, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L.G., Loiselle, B.A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J.M., Peterson, A.T., Phillips, S.J., Richardson, K., Scachetti-Pereira, R., Schapire, R.E., Soberon, J., Williams, S., Wisz, M.S., Zimmermann, N.E., 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29, 129–151.

Elith, J., Kearney, M., Phillips, S., 2010. The art of modelling range-shifting species. Methods Ecol. Evol. 1, 330–342.

Elith, J., Leathwick, J.R., 2009. Species distribution models: ecological explanation and prediction across space and time. Annu. Rev. Ecol. Evol. S. 40, 677–697.

Fang, J.Y., Song, Y.C., Liu, H.Y., Piao, S.L., 2002. Vegetation-climate relationship and its application in the division of vegetation zone in China. Acta Bot. Sin. 44, 1105–1122.

Friedman, J.M., Auble, G.T., Shafroth, P.B., Scott, M.L., Merigliano, M.F., Preehling, M.D., Griffin, E.K., 2005. Dominance of non-native riparian trees in western USA. Biol. Invasions 7, 747–751.

Fu, G., 2016. A study of evaluating the health of windbreak and sand-fixation forest in Minqin (Master of Professional Degree). Chinese Academy of Forestry.

Guilbault, K.R., Brown, C.S., Friedman, J.M., Shafroth, P.B., 2012. The influence of chilling requirement on the southern distribution limit of exotic Russian olive (*Elaeagnus angustifolia*) in western North America. Biol. Invasions 14, 1711–1724.

Guisan, A., Tingley, R., Baumgartner, J.B., Naujokaitis-Lewis, I., Sutcliffe, P.R., Tulloch, A.I.T., Regan, T.J., Brotons, L., McDonald-Madden, E., Mantyka-Pringle, C., Martin, T.G., Rhodes, J.R., Maggini, R., Setterfield, S.A., Elith, J., Schwartz, M.W., Wintle, B.A., Broennimann, O., Austin, M., Ferrier, S., Kearney, M.R., Possingham, H.P., Buckley, Y.M., 2013. Predicting species distributions for conservation decisions. Ecol. Lett. 16, 1424–1435.

Guo, L.J., Wang, Y.T., 2008. Conservation research and prospects of *Elaeagnus* germplasm resources and utilization values. Chin. Wild Plant Resour. 27, 32–34.

Gusta, L.V., Tyler, N.J., Chen, T.H., 1983. Deep undercooling in woody taxa growing north of the -40 °C isotherm. Plant. Physiol. 72, 122–128.

Haber, E., 1999. Invasive Exotic Plants of Canada Fact Sheet No. 14: Russian Olive. National Botanical Services, Ottawa, Ontario, Canada.

Hansen, N.E., 1901. Ornamentals for South Dakota. U. S. Experiment Station, Brookings, SD, USA. Bulletin 72.

Heywood, V.H.E., 1993. Flowering Plants of the World. Oxford University Press, New York, NY, USA.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.

Hirzel, A.H., Le Lay, G., 2008. Habitat suitability modelling and niche theory. J. Appl. Ecol. 45, 1372–1381.

Holdridge, L.R., 1947. Determination of world plant formations from simple climatic data. Science 105, 367–368.

Hou, X.Y., 1983. Vegetation of China with reference to its geographical distribution. Ann. Mo. Bot. Gard. 70, 509–549.

Huang, J., Maimaitijiang, Yang, Yang, C., Wang, C., 2005. Present situation and prospect about the study of *Elaeagnus angustifolia* L. Chinese Wild Plant Resour. 24, 26–28.

Katz, G.L., Shafroth, P.B., 2003. Biology, ecology and management of *Elaeagnus angustifolia* L. (Russian olive) in western North America. Wetlands 23, 763–777.

Khamzina, A., Lamers, J.P.A., Vlek, P.L.G., 2009. Nitrogen fixation by *Elaeagnus angustifolia* in the reclamation of degraded croplands of Central Asia. Tree Physiol. 29, 799–808.

Kira, T., 1945. A New Classification of Climate in Eastern Asia as the Basis for Agricultural Geography. Horticultural Institute, Kyoto University, Kyoto.

Li, G.Q., Xu, G.H., Guo, K., Du, S., 2014. Mapping the global potential geographical distribution of black locust (*Robinia Pseudoacacia* L.) using herbarium data and a maximum entropy model. Forests 5, 2773–2792.

Li, G.Q., Du, S., Wen, Z.M., 2016a. Mapping the climatic suitable habitat of oriental arborvitae (*Platycladus orientalis*) for introduction and cultivation at a global scale. Sci. Rep UK 6.

Li, G.Q., Xu, G.H., Guo, K., Du, S., 2016b. Geographical boundary and climatic analysis of *Pinus tabulaeformis* in China: insights on its afforestation. Ecol. Eng. 86, 75–84.

Li, G.Q., Zhang, X.Q., Huang, J.H., Wen, Z.M., Du, S., 2018. Afforestation and climatic niche dynamics of black locust (*Robinia pseudoacacia*). Forest Ecol. Manag. 407, 184–190.

Liang, L.Y., 2016. Application and Extension of Cultivation Techniques on *Elaeagnus augustifolia* L. (Master of agricultural extension). Beijing Forestry University.

Liu, Z.X., Zhang, H.X., Yang, X.Y., Liu, T., Di, W.B., 2014. Growth, and cationic absorption, transportation and allocation of *Elaeagnus angustifolia* seedlings under NaCl stress. Acta Ecol. Sinica 34, 1530–1544.

Marsh-Matthews, E., Matthews, W.J., Franssen, N.R., 2011. Can a highly invasive species re-invade its native community? the paradox of the red shiner. Biol. Invasions 13, 2911–2924.

Merow, C., Smith, M.J., Silander, J.A., 2013. A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. Ecography 36, 1058–1069.

Nagler, P.L., Glenn, E.P., Jarnevich, C.S., Shafroth, P.B., 2011a. Distribution and abundance of saltcedar and Russian Olive in the Western United States. Crit. Rev. Plant Sci. 30, 508–523.

Olson, T.E., Knopf, F.L., 1986. Agency subsidization of a rapidly spreading exotic. Wildl. Soc. Bull. 4, 492–493.

Pearson, R.G., Raxworthy, C.J., Nakamura, M., Peterson, A.T., 2007. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. J. Biogeogr. 34, 102–117.

Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Model. 190, 231–259.

Phillips, S.J., Dudik, M., 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography 31, 161–175.

Phillips, S.J., Dudik, M., Schapire, R.E., 2004. A maximum entropy approach to speciesdistribution modeling. In: Proceedings of the Twenty-First International Conference on Machine Learning, South Banff, Alberta, Canada, 4–8 July, pp. 655–662.

Reynolds, L.V., Cooper, D.J., 2010. Environmental tolerance of an invasive riparian tree and its potential for continued spread in the southwestern US. J. Veg. Sci. 21, 733–743.

Shah, J.J.F., Harner, M.J., Tibbets, T.M., 2010. *Elaeagnus angustifolia* elevates soil inorganic nitrogen pools in Riparian ecosystems. Ecosystems 13, 46–61.

Soberon, J., Arroyo-Pena, B., 2017. Are fundamental niches larger than the realized? Testing a 50-year-old prediction by Hutchinson. Plos One 12.

Soberon, J., Nakamura, M., 2009. Niches and distributional areas: concepts, methods, and assumptions. Proc. Natl. Acad. Sci. U.S.A. 106, 19644–19650.

Strauss, S.Y., Webb, C.O., Salamin, N., 2006. Exotic taxa less related to native species are more invasive. Proc. Natl. Acad. Sci. U.S.A. 103, 5841–5845.

Sun, M.A., Lin, Q., 2010. A revision of *Elaeagnus* L. (Elaeagnaceae) in mainland China. J. Syst. Evol. 48, 356–390.

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science 240, 1285–1293.

Toledo, M., Poorter, L., Pena-Claros, M., Alarcon, A., Balcazar, J., Leano, C., Licona, J.C., Llanque, O., Vroomans, V., Zuidema, P., Bongers, F., 2011. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. J. Ecol. 99, 254–264.

Vila, M., Weiner, J., 2004. Are invasive plant species better competitors than native plant species? evidence from pair-wise experiments. Oikos 105, 229–238.

Wang, B.Q., Minxia, L., YaoHui, W., 2009. Study on introduction and plantation of *Elaeagnus angustifolia* L. Agri. Sci. Technol. 10, 72–75.

Wisz, M.S., Hijmans, R.J., Li, J., Peterson, A.T., Graham, C.H., Guisan, A., Distribut, N.P.S., 2008. Effects of sample size on the performance of species distribution models. Divers. Distrib. 14, 763–773.

Xu, W.D., 1985. Kira's temperature indices and their application in the study of vegetation. Chinese J. Ecol. 3, 35–39.

Yildiz, O., Altundag, E., Cetin, B., Guner, S.T., Sarginci, M., Toprak, B., 2017. Afforestation restoration of saline-sodic soil in the Central Anatolian Region of Turkey using gypsum and sulfur. Silva Fenn 51.

Yu, W.W., Yan, G.R., 2009. Resources and research situation of Elaeagnus spp. J. Tianjin Agric. Univ. 16, 46–50.

Zhang, Y.J., 1981. A preliminary study on the eco-physiological characteristics of *Elaeagnus angustifolia* L. in Min-Qin region of Gansu Province. Acta Bot. Sin. 23, 393–400.

Zhu, Z.D., 1998. Concept, cause and control of desertification in China. Quat. Sci. 18, 145–155.