

Potential distribution of *Haloxylon ammodendron* in Central Asia under climate change (Postprint)

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Abstract

Understanding the spatial distribution of plant species and their dynamic changes in arid areas is crucial for addressing the challenges posed by climate change. *Haloxylon ammodendron* shelterbelts are essential for the protection of plant resources and the control of desertification in Central Asia. Thus far, the potential suitable habitats of *H. ammodendron* in Central Asia are still uncertain in the future under global climate change conditions. This study utilised the maximum entropy (MaxEnt) model to combine the current distribution data of *H. ammodendron* with its growth-related data to analyze the potential distribution pattern of *H. ammodendron* across Central Asia. The results show that there are suitable habitats of *H. ammodendron* in the Aralkum Desert, northern slopes of the Tianshan Mountains, and the upstream of the Tarim River and western edge of the Taklimakan Desert in the Tarim Basin under the current climate conditions. The period from 2021 to 2040 is projected to undergo significant changes in the suitable habitat area of *H. ammodendron* in Central Asia, with a projected 15.0% decrease in the unsuitable habitat area. Inland areas farther from the ocean, such as the Caspian Sea and Aralkum Desert, will continue to experience a decrease in the suitable habitats of *H. ammodendron*. Regions exhibiting frequent fluctuations in the habitat suitability levels are primarily found along the axis stretching from Astana to Kazakhskiy Melkosopchnik in Kazakhstan. These regions can transition into suitable habitats under varying climate conditions, requiring the implementation of appropriate human intervention measures to prevent desertification. Future climate conditions are expected to cause an eastward shift in the geometric centre of the potential suitable habitats of *H. ammodendron*, with the extent of this shift amplifying alongside more greenhouse gas emissions. This study can provide theoretical support for the spatial configuration of *H. ammodendron* shelterbelts and desertification

control in Central Asia, emphasising the importance of proactive measures to adapt to climate change in the future.

Full Text

Preamble

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Potential Distribution of *Haloxylon ammodendron* in Central Asia Under Climate Change

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Abstract

Understanding the spatial distribution of plant species and their dynamic changes in arid areas is crucial for addressing the challenges posed by climate change. *Haloxylon ammodendron* shelterbelts are essential for the protection of plant resources and the control of desertification in Central Asia. However, the potential suitable habitats of *H. ammodendron* in Central Asia under future global climate change conditions remain uncertain. This study utilized the maximum entropy (MaxEnt) model to combine current distribution data of *H. ammodendron* with growth-related data to analyze its potential distribution pattern across Central Asia. The results show that suitable habitats for *H. ammodendron* currently exist in the Aralkum Desert, northern slopes of the Tianshan Mountains, upstream of the Tarim River, and the western edge of the Taklimakan Desert in the Tarim Basin. The period from 2021 to 2040 is

projected to undergo significant changes in suitable habitat area, with a 15.0% decrease in unsuitable habitat area. Inland areas farther from the ocean, such as the Caspian Sea region and Aralkum Desert, will continue to experience decreases in suitable habitats. Regions exhibiting frequent fluctuations in habitat suitability levels are primarily found along the axis stretching from Astana to Kazakhskiy Melkosopochnik in Kazakhstan. These regions can transition into suitable habitats under varying climate conditions, requiring appropriate human intervention measures to prevent desertification. Future climate conditions are expected to cause an eastward shift in the geometric center of potential suitable habitats, with the extent of this shift amplifying alongside increased greenhouse gas emissions. This study provides theoretical support for the spatial configuration of *H. ammodendron* shelterbelts and desertification control in Central Asia, emphasizing the importance of proactive measures to adapt to climate change.

Keywords: *Haloxylon ammodendron*; potential suitable habitats; climate change; desertification; maximum entropy (MaxEnt) model; Central Asia; Aralkum Desert

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1 Introduction

Desertification involves rapid alterations in soil characteristics, vegetation patterns, and hydrological conditions that profoundly impact inland regions and present significant challenges for human societies (Rengasamy, 2006; Tarhouni et al., 2010; Paolo et al., 2013). In Central Asia, desertification has become a critical environmental issue under scrutiny, as biodiversity and ecological stability in this region are particularly vulnerable to climate change (Bohovic, 2016). Temperatures in Central Asia have been rising rapidly, which accelerates desertification processes (Hu et al., 2014; Davi et al., 2015; Jiang et al., 2017; Zhang et al., 2020). Currently, an effective measure to combat desertification is selecting suitable tree species to establish comprehensive shelterbelt systems (Fang et al., 2024). However, knowledge of shelterbelt construction based on Central Asian climate conditions remains insufficient (Wang et al., 2009; Shao et al., 2022; Fang et al., 2024; Xiao et al., 2024). Therefore, detailed analysis of suitable distribution areas for selected plant species represents a timely contribution to combating desertification in arid regions.

Vegetation in arid areas provides essential ecological benefits by sustaining livestock and wildlife survival while offering crucial functions such as preventing soil desertification (Lioubimtseva, 2015; Jiang et al., 2017; Tao et al., 2017). Consequently, vegetation responses to climate change in arid regions have become

a focal point of global research. *Haloxylon ammodendron* offers various ecological benefits, including increasing vegetation coverage, enhancing soil moisture retention, suppressing soil erosion, and improving carbon sequestration, and is widely distributed across arid areas (Abdi et al., 2019; Li et al., 2019). Its root system can tap deep groundwater, making it resilient to drought (Shao et al., 2022). The roots act as reinforcing bars that strengthen soil in desert regions, protect against dune encroachment, and help maintain soil fertility (Shao, 2008). Additionally, parasitized roots contain medicinal components that inhibit disease-related enzyme activity (Trampetti et al., 2019; Song et al., 2021). *H. ammodendron* forests in arid areas also create environments conducive to diverse flora and fauna, providing suitable habitats for various species (Wang et al., 2009). Assessing and predicting climate change impacts on suitable habitats of *H. ammodendron* is therefore essential for promoting sustainable development in Central Asia.

Current understanding of distribution prediction and suitable habitat identification for *H. ammodendron* relies heavily on model simulations. Several species distribution models have been developed and applied to explore habitat suitability and potential distribution, including the Mahalanobis distance (MD) model (Etherington, 2019), generalized linear model (GLM) (Guisan et al., 2002), support vector machine (SVM) (Betancourt, 2005), random forest (RF) (Mi et al., 2017), and maximum entropy (MaxEnt) model (Phillips et al., 2006). The potential of ensemble models to improve prediction accuracy has also been tested (Pecchi et al., 2020). Among these, MaxEnt is a machine-learning method that determines species ecological requirements based on distribution records and environmental factors (Kang et al., 2023). It employs a probability distribution function known as the MaxEnt principle to predict species occurrence probability across geographical spaces (Phillips et al., 2006). Compared with correlative and mechanistic models, MaxEnt achieves higher distribution accuracy with fewer sample points and is widely used in data-limited regions such as Central Asia (Gherghe et al., 2018; Sun et al., 2020).

Intergovernmental organizations have recognized the urgent need to combat desertification in Central Asia (Zhang et al., 2020). Drought stress can influence expression of drought-resistant genes in *H. ammodendron*, thereby altering its spatial distribution pattern (Xiao et al., 2006). Large areas of *H. ammodendron* shelterbelts have been planted in Central Asia, particularly in dry lake basins (Chen et al., 2022; Shao et al., 2022). However, some shelterbelts are unsustainable in fragile ecological environments (Jiang et al., 2017), leading to resource wastage and potential damage to existing arid area ecology. Climate change has been considered one of the most significant threats to global biodiversity since the 21st century began (Dawson et al., 2011). From 2011 to 2020, global surface temperature increased by 1.1°C compared with the 1850–1900 period (Intergovernmental Panel on Climate Change (IPCC), 2023). Against this backdrop, the future of existing *H. ammodendron* shelterbelts in Central Asia remains uncertain (Xiao et al., 2024), making investigation of *H. ammodendron* distribution in Central Asia essential. Therefore, we aimed to explore and

predict potential habitats of *H. ammodendron* in Central Asia. Based on historical climate data (1970–2000) and current *H. ammodendron* distribution, we systematically mapped suitable habitats and identified key factors influencing distribution. Utilizing climate data under four shared socioeconomic pathway (SSP) scenarios with varying greenhouse gas emission intensities for three future periods (2021–2040, 2041–2060, and 2061–2080), we projected future potential distribution patterns of *H. ammodendron* in Central Asia. This study may improve understanding of scientific shelterbelt construction in Central Asia, representing a timely contribution to formulation of local government environmental protection policies.

2.1 Study Area

Central Asia serves as a vital transportation link between Asia and Europe. The study area extends from the Caspian Sea in the west to the western China border in the east, encompassing Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan, Kyrgyzstan, and China's Xinjiang Uygur Autonomous Region (34°19'59"–55°27'15" N, 46°29'30"–96°23'15" E; Fig. 1 [Figure 1: see original paper]). Geographically, altitude gradually decreases from the Altay Mountains, Tianshan Mountains, and Pamirs in eastern Kazakhstan and Uzbekistan, traversing Kyrgyzstan and Tajikistan, to the Caspian Sea shores in western Kazakhstan and Turkmenistan. Characterized by a typical continental climate, spatial variation in precipitation and temperature follows gradients from mountainous areas to plains and from north to south (de Beurs et al., 2015). Apart from mountainous and hilly regions, average annual temperature ranges from 2.0°C in northern Kazakhstan to over 18.0°C in southern Turkmenistan (Mohammad et al., 2013). Against the backdrop of global temperature rise, this region is particularly sensitive to extreme climate events (Jiang et al., 2017; IPCC, 2023). Most deserts in Turkmenistan, Uzbekistan, southern Kazakhstan, and Xinjiang, China—including the Kyzylkum, Aralkum, Muyunkum, and Taklimakan (in the Tarim Basin) deserts—are characterized by sparse vegetation. The arid climate of these flatlands poses challenges for plant growth. According to statistical data since 1977, *H. ammodendron* is mainly distributed in Xinjiang, China, with some communities found in Kazakhstan and Uzbekistan (Fig. 1).

2.2.1 Distribution Data

Distribution data for *H. ammodendron* were obtained from the Global Biodiversity Information Fund (GBIF; <http://www.gbif.org>) and field observations in the Aralkum Desert. Field observation data were collected during a scientific expedition conducted December 20–29, 2019. In total, 202 distribution records for *H. ammodendron* were collected, including 195 from GBIF and 7 from field observations (Fig. 1). Accurate longitude and latitude information was extracted

as inputs for the MaxEnt model. Although data from the same source typically exhibit stable and uniform resolution, mixing species distribution information from different sources is crucial for model construction given the requirement for sufficient data volume and prediction accuracy (Shao et al., 2022). To avoid sampling bias and overfitting caused by densely clustered points, we screened coordinate data and removed redundant entries. The “ENMeval” package in R software was used to perform these tasks, ensuring spatial resolution of recorded events matched that of environmental variables (Muscarella et al., 2015). ENMeval was designed for automated tuning and evaluation of ecological niche models (species distribution models) that estimate species distribution ranges and niche characteristics using species distribution and environmental data. In total, 167 valid records were retained for this study.

2.2.2 Predictor Variables

We selected 23 predictor variables to model the main factors affecting *H. ammodendron* distribution patterns in Central Asia under current climate conditions (1970–2000) and future shared climate change scenarios (2021–2080) (Table 1). Bioclimatic variables included 19 categories (BIO1–BIO19) obtained from the WorldClim database (<https://www.worldclim.org/>). Elevation data were derived from the WorldClim historical climate dataset (<https://worldclim.org/data/worldclim21.html>), a high-resolution global weather and climate database involving key vegetation growth parameters widely used to drive species distribution models (Yang et al., 2023; Fang et al., 2024). Soil represents a key limiting factor for vegetation growth, affecting plant species distribution (Shao et al., 2022). Topsoil sand content was obtained from the OpenLandMap dataset as a soil parameter driving the MaxEnt model, representing machine-learning predictions derived from comprehensive aggregation of global soil profiles and samples (Tomislav, 2018). Topsoil water content was downloaded from the OpenLandMap soil water content dataset, predicted at six standard depths (0, 10, 30, 60, 100, and 200 cm) at 250 m resolution for 33 and 1500 kPa suctions (Tomislav and Surya, 2019). Human activities are believed to influence *H. ammodendron* distribution in arid areas, particularly in northwestern China (Abdi et al., 2019). Population distribution data for Central Asia at 100 m resolution were obtained from the WorldPop global project (Sorichetta et al., 2015). Annual population distribution for 2020 was selected to quantify human activity impacts on *H. ammodendron* growth and distribution.

Topsoil sand content, topsoil water content, and population distribution were resampled using Google Earth Engine (GEE). Given the abundance of field survey data collected by our research team, *H. ammodendron* distribution data are relatively precise. Utilizing environmental variables with spatial resolutions matching distribution data accuracy can greatly enhance model precision and species distribution prediction accuracy (Sillero et al., 2014; Sofaer et al., 2019).

Future climate data utilized SSPs sourced from the Coupled Model Intercomparison Project (CMIP6) of the IPCC. To avoid uncertainty from using a single climate model, we derived future climate data by averaging results from three General Circulation Models (GCMs): INM-CM5-0, MIROC6, and MRI-ESM2-0. Each GCM was assessed for three periods (2021–2040, 2041–2060, and 2061–2080) under four shared climate change scenarios: SSP126, SSP245, SSP370, and SSP585. Elevation, soil variables, and population distribution were treated as constants.

Highly correlated environmental variables can severely impact model performance, causing overfitting and affecting acquisition of realistic variable response curves (De Marco Júnior et al., 2018). Traditional correlation methods often represent a compromise, whereas principal component analysis (PCA) can generate orthogonal variables that capture entire suites of response curves, transforming all variables into ecologically meaningful orthogonal components (Hirzel et al., 2002). This study employed PCA for variable reconstitution and selection to eliminate potential model overfitting from autocorrelation. PCA converts all environmental variables into distinct orthogonal components while preserving their ecological significance. The initial set of 23 environmental variables was transformed into eight restructured variables labeled PC1–PC8 (where PC denotes principal component), encapsulating over 95.0% of pertinent information considered essential for model construction. The top six variables contributing to each category in the PCA are listed in Table 1.

2.3 Model Framework

The MaxEnt model combines many highly regarded algorithms and is widely used to identify areas for plant protection (Guillera-Arroita et al., 2014). Particularly in background weighting and random processes, MaxEnt is recognized for producing highly comparable results and predictive performance in identifying test data, representing a practical approach for handling imbalanced biased data in species distribution models (Ahmadi et al., 2023). Ensemble methods are considered effective for reducing model uncertainty and increasing robustness in accurately simulating species distribution (Marmion et al., 2009). MaxEnt modeling involves two basic steps: (1) using all occurrence records of *H. ammodendron* in the study area and processing variables (PC1–PC8) to construct the MaxEnt model and generate species distribution, and (2) training the model using *H. ammodendron* distribution records to generate predicted distributions under different future climate change scenarios.

Traditional area-under-the-curve metrics have been widely used (Yang et al., 2023; Fang et al., 2024). However, previous studies indicate these metrics may not be entirely applicable for assessing performance of presence-only or presence-background ecological niche models (Leroy et al., 2018; Velasco and González-Salazar, 2019). Therefore, this study selected the continuous Boyce index to

evaluate model performance (Hirzel et al., 2002). The Boyce index ranges from -1 to 1 , where positive values signify alignment between predicted and observed distributions, while negative values imply poor predicted habitat quality.

During model execution, 10,000 background points were randomly selected as pseudo-absences. Seventy-five percent of distribution records were used for training, with the remaining 25% used for testing. Cross-validation is essential for verifying model accuracy; therefore, we chose the hierarchical checkerboard2 method based on study area size and *H. ammodendron* distribution. As regional-scale distribution data are limited, assessing uncertainty associated with extrapolation after predictive training is necessary (Mannocci et al., 2017, 2018). In this phase, we utilized the “dsmExtra” package in R software to create two metrics: the extrapolation detection metric, which evaluates extrapolation in environmental space and model transferability, and the percentage of data nearby, which assesses extrapolation reliability in multivariate environmental space (Bouchet et al., 2020). Generally, low extrapolation detection or high percentage of data nearby indicates higher extrapolation reliability, whereas the opposite suggests lower reliability (Miller et al., 2013).

The measuring geographic distribution function of spatial statistical tools in ArcGIS 10.8 was used to estimate the geometric center of *H. ammodendron* distribution. Before processing, a reclassification procedure was applied to predicted spatial distributions under different climate change scenarios to derive spatial distribution polygons for further calculation.

3.1 Potential Suitable Habitats of *H. ammodendron* Under Current Climate Conditions

Figure 2 [Figure 2: see original paper] depicts the potential distribution of *H. ammodendron* in Central Asia under current climate conditions. Regions with highly suitable habitats (habitat class > 0.60) cover approximately 0.322×10^6 km², primarily located on the northern slopes of the Tianshan Mountains, upstream of the Tarim River, and the western edge of the Taklimakan Desert in the Tarim Basin. Scattered highly suitable habitats also occur within Uzbekistan and Kazakhstan, including the central Caspian coastal plain, Amu Darya River Delta, Aralkum Desert, western Kazakhstan, and southern coast of Balkhash Lake. Medium suitable habitats ($0.30 < \text{habitat class} \leq 0.60$) cover approximately 0.602×10^6 km², mainly distributed around highly suitable habitats. Unsuitable habitats (habitat class ≤ 0.15) are widely distributed in central and southern parts of the study area (approximately 3.620×10^6 km²), primarily located south of 50°N. These regions, including the Taklimakan Desert, Karakum Desert, and Uzbekistan, cannot support natural *H. ammodendron* growth due to arid climate.

The combined influence of multiple factors creates potential pattern variations in suitable habitats. Most areas around the Caspian Sea, Aralkum Desert,

Balkhash Lake, Ili River, and Tarim River are highly suitable for natural *H. ammodendron* growth. Inland lakes and rivers impact local climate, consequently affecting plant growth, with distribution patterns shifting depending on distance from water bodies. Furthermore, the potential distribution pattern in Xinjiang, China reflects distance dependence on mountains. PCA results show elevation and precipitation dominate factors (PC3, PC5, PC7, and PC8; Table 1) affecting *H. ammodendron* distribution, explaining decreasing suitable habitat areas with increasing distance from the Tianshan Mountains. Additionally, scattered suitable habitats occur within oases on the Taklimakan Desert edge, where favorable soil and water conditions sustain natural *H. ammodendron* growth.

3.2 Potential Suitable Habitats of *H. ammodendron* in Central Asia Under Future Climate Change Scenarios

Potential suitable habitats under 12 different future climate conditions (three periods: 2021–2040, 2041–2060, and 2061–2080; four scenarios: SSP126, SSP245, SSP370, and SSP585) are shown in Figure 3 [Figure 3: see original paper]. Under different future climate conditions, suitable habitat distribution remains similar but shows consistent shifting trends. Overall, suitable habitat areas in northern Central Asia, notably Kazakhstan, will increase under future climate change scenarios. The period 2021–2040 shows significant changes, with unsuitable habitat areas expected to decrease by approximately 15.0% and stabilize during 2041–2060. The total area of medium and highly suitable habitats is projected to increase to 1.55×10^6 km² during 2021–2040 before stabilizing thereafter. Increased highly suitable habitat area, such as in the Junggar Basin, is mainly distributed in northern Xinjiang, China. Compared with current distribution patterns, the highly suitable habitat area in the eastern Junggar Basin will increase by approximately 0.105×10^6 km². Inland areas farther from the ocean will continue experiencing decreases in suitable habitats. Meanwhile, the highly suitable habitat area in the Aralkum Desert will significantly decrease from 2021 to 2080, indicating that ecological issues in the Aralkum Desert may become even more severe in the future (Micklin, 2007).

3.3 Distribution Shifts in Suitable Habitats of *H. ammodendron*

Habitat transfer with different suitability classes during 2021–2040, 2041–2060, and 2061–2080 is shown in Figure 4 [Figure 4: see original paper]. Unsuitable habitat area in Central Asia will decrease in the future as climate change affects desertification processes. *H. ammodendron* exhibits characteristics of wide geographical distribution, strong climate tolerance, high fecundity, and short maturation time, enabling rapid response to climate change through spatial distribution shifts. Consequently, *H. ammodendron* is well-adapted to climate

change and will expand its distribution range. During 2021–2040, highly and moderately suitable habitats are projected to increase by 64.4% and 58.8%, respectively, while low ($0.15 < \text{habitat class} \leq 0.30$) and unsuitable habitat areas will decrease by 4.3% and 15.2%, respectively. From 2041–2060 to 2061–2080, suitable habitat areas will tend to stabilize, with conversion occurring only between adjacent suitability classes. Compared with current conditions, unsuitable habitat area will decrease by 15.7% by 2080.

To clarify evolutionary patterns of suitable habitats, we identified regions with different variation characteristics based on temporal transfer sequences (Fig. 5 [Figure 5: see original paper]). In northern Kazakhstan, the Taklimakan Desert, Junggar Basin, and eastern Turkmenistan, suitable habitat levels are increasing steadily. Simulation results for 2021–2080 in these regions show no decline, only differences in magnitude of increase across locations. For instance, habitat suitability in the Taklimakan Desert under future climate conditions will increase compared with current conditions, though remaining within the low suitable habitat zone. Regions with frequent habitat suitability fluctuations during 2021–2080 are mainly distributed along the axis from Astana to Kazakhskiy Melkosopchnik in Kazakhstan. These regions have better soil and water conditions than Central Asian core areas, and habitat suitability levels for *H. ammodendron* may change in various ways under different future climate change scenarios.

Regions where suitable habitat levels continue to decline are primarily along the northern Caspian Sea coast, Aralkum Desert, southern Kazakhskiy Melkosopchnik, and northern Tianshan foothills. Geographically, regions between 45°N and 55°N covering approximately $0.503 \times 10^6 \text{ km}^2$ are anticipated to experience greater habitat reductions under future climate change scenarios, possibly due to climate change decreasing *H. ammodendron*'s climate adaptability and competitiveness, leading to distribution range contraction.

3.4 Spatial Pattern Changes in Potential Suitable Habitats of *H. ammodendron* Under Future Climate Change Scenarios

The geometric center of potential suitable habitat regions tends to migrate eastward under future climate change scenarios (Fig. 6 [Figure 6: see original paper]). Under SSP126, the geometric center will migrate 147 km southeast during 2021–2040, followed by 80 km eastward displacement in the 2050s, and finally 45 km westward shift in the 2070s. Geometric centers under SSP245, SSP370, and SSP585 scenarios exhibit gradual eastward movement, with movement distance increasing alongside greenhouse gas emission levels. For instance, geometric center movement under SSP126 is only 176 km, whereas it reaches 405 km under SSP585. Climate change could intensify desertification in Central Asian core regions, gradually shifting the geometric center toward areas closer

to the ocean. Alternatively, this phenomenon may be explained by precipitation influence, as larger precipitation values in SSP scenarios typically imply higher carbon emissions and temperatures, leading to increased aridity in Central Asia. Nevertheless, under future climate conditions, the MaxEnt model predicts a gradual decrease in potential suitable habitats in the Central Asian hinterland, leading to westward geometric center shift.

4.1 Effects of Environmental Factors on Spatial Distribution of *H. ammodendron* in Central Asia

Plant species distribution is primarily influenced by climate, with hydrothermal conditions playing crucial roles (Dillon et al., 2010). PCA can generate all possible model parameter settings through cross-validation and feature selection, choosing optimal models based on maximum Boyce index to elucidate key environmental factors influencing spatial distribution (Shao et al., 2022). In this study, precipitation-related climate conditions dominate PC1, PC3, and PC8 (Table 1), with variance explanation rates of 37.63%, 17.84%, and 2.39%, respectively. For example, in the Junggar Basin north of the Tianshan Mountains, the terrain is not completely enclosed, allowing prevailing westerly winds from the Atlantic Ocean and airflow from the Arctic Ocean to lift onto northern Tianshan slopes, forming orographic precipitation. Consequently, moisture conditions on northern Tianshan slopes are better than southern slopes, creating suitable habitats for *H. ammodendron* growth. Temperature-dominated influencing factors (PC4) contribute approximately 5.83% to spatial distribution. Hydrothermal condition-related factors thus account for a cumulative 63.69% of total variance in *H. ammodendron* spatial distribution. Temperature-related factors such as annual mean temperature (BIO1), temperature seasonality (BIO4), and temperature annual range (BIO7) can also impact distribution through other PCA categories.

Elevation influences spatial distribution through PC5 and PC7, with a cumulative contribution of 7.10%. Notably, the factor dominated by population density (PC2) contributes approximately 22.42% among PC1–PC8, possibly related to utilization of *H. ammodendron* roots for producing *Cistanche deserticola* in Xinjiang, China (Shao et al., 2022). This discrepancy may be attributed to the multifaceted nature of plant survival, which is influenced by multiple environmental factors.

4.2 Layout of *H. ammodendron* Shelterbelts in Central Asia Under Future Climate Conditions

H. ammodendron is an important species for desertification control (Li et al., 2022). Its root system can stabilize sandy soils and reduce wind erosion (Shao,

2008). Adjusting shelterbelt coverage and density may be necessary to cope with more frequent extreme climate events such as drought, high temperatures, and wind erosion. The fluctuated zone of suitable habitats is expected to become susceptible to desertification under future climate conditions. Maintaining ecological stability in these regions will be a priority for Central Asian desertification control, reducing desertification spread, safeguarding local ecological environments, and supporting sustainable human livelihoods. Transitional zones composed of drought-resistant plants should also be established at region edges to provide stable transitional environments for local ecosystems.

Considering that hydrothermal conditions may dominate *H. ammodendron* spatial distribution, desertification control in Central Asia should also be based on terrain characteristics and hydrothermal distribution (Jiang et al., 2017). Strategically locating *H. ammodendron* shelterbelts in river valleys and foothills can utilize surface water and groundwater resources to provide necessary moisture for growth and enhance soil retention capacity. Additionally, constructing shelterbelts requires considering ecosystem connectivity by establishing ecological corridors that connect shelterbelts, facilitating flora and fauna migration and genetic exchange, thereby enhancing ecosystem stability and resilience.

4.3 Sustainable Recommendations for Establishment of *H. ammodendron* Shelterbelts in Response to Future Climate Change

Human activities significantly affect *H. ammodendron* habitats and contribute to desertification processes in Central Asia (Shao et al., 2022). Unsustainable water resource utilization, such as excessive diversion for irrigation, can further reduce downstream water availability (Chen et al., 2022). Changes in hydrological regimes alter soil moisture levels, influencing plant growth and survival (Micklin, 2007). Considering that the Uzbekistan government is currently implementing afforestation measures in the Aralkum Desert to mitigate salt-dust disasters, the sustainability of these measures requires further evaluation under future climate conditions. Therefore, greater efforts should focus on these areas through strengthened shelterbelt management and minimized climate change impacts on afforestation.

Moreover, suitable habitat area in the western Junggar Basin will decrease under future climate conditions. To mitigate human activity impacts on *H. ammodendron* habitats, integrated land management approaches are essential (Qi et al., 2023). In-situ conservation should focus on preserving and restoring natural habitats conducive to *H. ammodendron* growth, protecting existing stands and associated ecosystems, and restoring degraded habitats through sustainable practices such as reforestation, soil conservation, and water management (Abdi et al., 2019). Community engagement and stakeholder participation are vital components for shelterbelt protection.

H. ammodendron also provides important ecosystem services and economic values in arid and semi-arid areas. It can absorb and store atmospheric carbon dioxide, enabling local governments to facilitate carbon sequestration in desert areas through systematic planting, thereby supporting international sustainable land management efforts. The parasitic roots are widely used in traditional Chinese medicine to treat various ailments due to antimicrobial, anti-inflammatory, and antioxidant properties (Trampetti et al., 2019; Song et al., 2021). Appropriate planning for cultivating *H. ammodendron* and increasing parasitic root yield can generate economic benefits and increase incomes for residents in desertified areas. In summary, implementing a comprehensive approach integrating in-situ and ex-situ conservation measures while engaging local communities and stakeholders can effectively conserve *H. ammodendron* and ensure its survival amid climate change. Climate change will inevitably cause global warming and increased droughts (Yang et al., 2023), requiring appropriate artificial interventions to prevent desertification in affected regions.

5 Conclusions

This study applied *H. ammodendron* growth-related data to the MaxEnt model to analyze spatial distribution of potential suitable habitats in Central Asia under current and future climate conditions. The highly suitable habitat area is approximately 0.322×10^6 km² under current conditions, primarily distributed in the Aralkum Desert, northern Tianshan slopes, upstream Tarim River, and western Taklimakan Desert edge. The unsuitable habitat area covers approximately 3.620×10^6 km², widely distributed south of 50°N. Under future climate change scenarios, suitable habitat area will decrease in regions far from the ocean, with highly suitable area in the Aralkum Desert expected to decrease significantly. The geometric center of potential suitable habitat area shows an eastward shift tendency, with movement distance increasing alongside greenhouse gas emissions. By 2080, geometric center movement can reach up to 405 km, gradually shifting suitable habitats toward regions closer to the ocean. While this study analyzed potential future spatial distribution of *H. ammodendron* in Central Asia, actual shelterbelt construction still requires reasonable incorporation of other plant species to achieve better ecological service functions.

Conflict of Interest

LEI Jiaqiang is an editorial board member of *Journal of Arid Land* and was not involved in editorial review or the decision to publish this article. All authors declare no competing interests.

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Author Contributions

Conceptualization: CHEN Zhuo, SHAO Minghao; Methodology: CHEN Zhuo, SHAO Minghao, HU Zihao; Investigation: CHEN Zhuo; Writing - original draft preparation: CHEN Zhuo, SHAO Minghao; Writing - review & editing: GAO Xin, LEI Jiaqiang; Supervision: GAO Xin, LEI Jiaqiang; Funding acquisition and resources: GAO Xin, LEI Jiaqiang. All authors approved the manuscript.

References

- Abdi E, Saleh H R, Majnonian B, et al. 2019. Soil fixation and erosion control by *Haloxylon persicum* roots in arid lands, Iran. *Journal of Arid Land*, 11(1): 86–96.
- Ahmadi M, Hemami M R, Kaboli M, et al. 2023. MaxEnt brings comparable results when the input data are being completed: Model parameterization of four species distribution models. *Ecology and Evolution*, 13(2): e9827, doi: 10.1002/ece3.9827.
- Bohovic R, Dobrovolny P, Klein D. 2016. The spatial and temporal dynamics of remotely-sensed vegetation phenology in Central Asia in the 1982–2011 period. *European Journal of Remote Sensing*, 49(1): 279–299.
- Bouchet P J, Miller D L, Roberts J J, et al. 2020. Dsmextra: Extrapolation assessment tools for density surface models. *Methods in Ecology and Evolution*, 11(11): 1464–1469.
- Chen Z, Gao X, Lei J Q. 2022. Dust emission and transport in the Aral Sea region. *Geoderma*, 428: 116177, doi: 10.1016/j.geoderma.2022.116177.
- Davi N K, D'Arrigo R, Jacoby G C, et al. 2015. A long-term context (931–2005 C.E.) for rapid warming over Central Asia. *Quaternary Science Reviews*, 121: 89–97.
- Dawson T P, Jackson S T, House J I, et al. 2011. Beyond predictions: biodiversity conservation in a changing climate. *Science*, 332(6025): 53–58.
- de Beurs K M, Henebry G M, Owsley B C, et al. 2015. Using multiple remote sensing perspectives to identify and attribute land surface dynamics in Central Asia 2001–2013. *Remote Sensing of Environment*, 170: 48–61.

- De Marco Júnior P, Nóbrega C C. 2018. Evaluating collinearity effects on species distribution models: An approach based on virtual species simulation. *PLoS ONE*, 13(9): e0202403, doi: 10.1371/journal.pone.0202403.
- Dillon M E, Wang G, Huey R B. 2010. Global metabolic impacts of recent climate warming. *Nature*, 467(7316): 704–706.
- Etherington T R. 2019. Mahalanobis distances and ecological niche modelling: correcting a chi-squared probability error. *PeerJ*, 7: e6678, doi: 10.7717/peerj.6678.
- Fang J Q, Shi J F, Zhang P, et al. 2024. Potential distribution projections for *Senegalia senegal* (L.) Britton under climate change scenarios. *Forests*, 15(2): 379, doi: 10.3390/f15020379.
- Guillera-Arroita G, Lahoz-Monfort J, Elith J. 2014. MaxEnt is not a presence-absence method: a comment on Thibaud et al. *Methods in Ecology and Evolution*, 5(11): 1192–1197.
- Guisan A, Edwards Jr T C, Hastie T. 2002. Generalized linear and generalized additive models in studies of species distributions: setting the scene. *Ecological Modelling*, 157(2–3): 89–100.
- Hirzel A H, Hausser J, Chessel D, et al. 2002. Ecological-niche factor analysis: how to compute habitat-suitability maps without absence data? *Ecology*, 83(7): 2027–2036.
- Hu Z Y, Zhang C, Hu Q, et al. 2014. Temperature changes in Central Asia from 1979 to 2011 based on multiple datasets. *Journal of Climate*, 27(3): 1143–1167.
- Intergovernmental Panel on Climate Change (IPCC). 2023. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC.
- Jiang L L, Jiapaer G, Bao A M, et al. 2017. Vegetation dynamics and responses to climate change and human activities in Central Asia. *Science of the Total Environment*, 599–600: 967–980.
- Kang J F, Liu M S, Qu M K, et al. 2023. Identifying the potential soil pollution areas derived from the metal mining industry in China using MaxEnt with mine reserve scales (MaxEnt_{MRS}). *Environmental Pollution*, 329: 121687, doi: 10.1016/j.envpol.2023.121687.
- Leroy B, Delsol R, Huguény B, et al. 2018. Without quality presence–absence data, discrimination metrics such as TSS can be misleading measures of model performance. *Journal of Biogeography*, 45(9): 1994–2002.
- Li C J, Han H, Ablimiti M, et al. 2022. Morphological and physiological responses of desert plants to drought stress in a man-made landscape of the Taklimakan Desert shelter belt. *Ecological Indicators*, 140: 109037, doi: 10.1016/j.ecolind.2022.109037.

- Li J Y, Chang H, Liu T, et al. 2019. The potential geographical distribution of *Haloxylon* across Central Asia under climate change in the 21st century. *Agricultural and Forest Meteorology*, 275: 243–254.
- Lioubimtseva E. 2015. A multi-scale assessment of human vulnerability to climate change in the Aral Sea basin. *Environmental Earth Sciences*, 73: 719–729.
- Mannocci L, Roberts J J, Miller D L, et al. 2017. Extrapolating cetacean densities to quantitatively assess human impacts on populations in the high seas. *Conservation Biology*, 31(3): 601–614.
- Mannocci L, Roberts J J, Halpin P N, et al. 2018. Assessing cetacean surveys throughout the Mediterranean Sea: A gap analysis in environmental space. *Scientific Reports*, 8(1): 3126, doi: 10.1038/s41598-018-19842-9.
- Marmion M, Parviainen M, Luoto M, et al. 2009. Evaluation of consensus methods in predictive species distribution modelling. *Diversity and Distributions*, 15(1): 59–69.
- Mi C R, Huettmann F, Guo Y M, et al. 2017. Why choose Random Forest to predict rare species distribution with few samples in large undersampled areas? Three Asian crane species models provide supporting evidence. *PeerJ*, 5: e2849, doi: 10.7287/peerj.preprints.2517v1.
- Micklin P. 2007. The Aral Sea disaster. *Annual Review of Earth and Planetary Sciences*, 35: 47–72.
- Miller D L, Burt M L, Rexstad E A, et al. 2013. Spatial models for distance sampling data: recent developments and future directions. *Methods in Ecology and Evolution*, 4(11): 1001–1010.
- Mohammad A, Wang X H, Xu X T, et al. 2013. Drought and spring cooling induced recent decrease in vegetation growth in Inner Asia. *Agricultural and Forest Meteorology*, 178–179: 21–30.
- Muscarella R, Galante P J, Soley-Guardia M, et al. 2015. Enmeval: an R package for conducting spatially independent evaluations and estimating optimal model complexity for maxent ecological niche models. *Methods in Ecology and Evolution*, 5(11): 1198–1205.
- Paolo D, Bhattachan A, Kyle F, et al. 2013. Global desertification: Drivers and feedbacks. *Advances in Water Resources*, 51: 326–344.
- Pecchi M, Marchi M, Moriondo M, et al. 2020. Potential impact of climate change on forest coverage and spatial distribution of 19 key forest tree species in Italy under RCP4.5 IPCC trajectory for 2050s. *Forests*, 11(9): 934, doi: 10.3390/f11090934.
- Phillips S J, Anderson R P, Schapire R E. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190(3–4): 231–259.

- Qi K, Zhu J J, Zheng X, et al. 2023. Impacts of the world's largest afforestation program (Three-North Afforestation Program) on desertification control in sandy land of China. *GIScience & Remote Sensing*, 60(1): 2167574, doi: 10.1080/15481603.2023.2167574.
- Rengasamy P. 2006. World salinization with emphasis on Australia. *Journal of Experimental Botany*, 57(5): 1017–1023.
- Ruan X, Wang Q, Chen Y, et al. 2006. Physio-ecological response of *Haloxylon persicum* photosynthetic shoots to drought stress. *Frontiers of Forestry in China*, 1: 176–181.
- Shao M H, Wang L, Li B W, et al. 2022. Maxent modeling for identifying the nature reserve of *Cistanche deserticola* Ma under effects of the host (*Haloxylon Bunge*) forest and climate changes in Xinjiang, China. *Forests*, 13(2): 189, doi: 10.3390/f13020189.
- Shao Y. 2008. *Physics and Modelling of Wind Erosion*. Dordrecht: Springer Netherlands, 456, doi: 10.1007/978-1-4020-8895-7.
- Sillero N, Gonçalves-Seco L. 2014. Spatial structure analysis of a reptile community with airborne LiDAR data. *International Journal of Geographical Information Science*, 28(8): 1709–1722.
- Sofaer H, Jarnevich C, Pearse I S, et al. 2019. Development and Delivery of Species Distribution Models to Inform Decision-Making. *BioScience*, 69(7): 544–557.
- Song Y L, Zeng K W, Jiang Y, et al. 2021. Cistanches Herba, from an endangered species to a big brand of Chinese medicine. *Medicinal Research Reviews*, 41(3): 1539–1577.
- Sorichetta A, Hornby G M, Stevens F R, et al. 2015. High-resolution gridded population datasets for Latin America and the Caribbean in 2010, 2015, and 2020. *Scientific Data*, 2: 150045, doi: 10.1038/sdata.2015.45.
- Sun J J, Qiu H J, Guo J H, et al. 2020. Modeling the potential distribution of *Zelkova schneideriana* under different human activity intensities and climate change patterns in China. *Global Ecology and Conservation*, 21: e00840, doi: 10.1016/j.gecco.2019.e00840.
- Tao Y, Wu G L, Zhang Y M. 2017. Dune-scale distribution pattern of herbaceous plants and their relationship with environmental factors in a saline–alkali desert in Central Asia. *Science of the Total Environment*, 576: 473–480.
- Tarhouni M, Salem F B, Belgacem A O, et al. 2010. Acceptability of plant species along grazing gradients around watering points in Tunisian arid zone. *Flora-Morphology, Distribution, Functional Ecology of Plants*, 205(7): 454–461.
- Tomislav H. 2018. Sand content in % (kg/kg) at 6 standard depths (0, 10, 30, 60, 100 and 200 cm) at 250 m resolution (v0.2) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.2525662>.

Tomislav H, Surya G. 2019. Soil water content (volumetric %) for 33 kPa and 1500 kPa suctions predicted at 6 standard depths (0, 10, 30, 60, 100 and 200 cm) at 250 m resolution (v0.1) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.2784001>.

Trampetti F, Pereira C, Rodrigues M J, et al. 2019. Exploring the halophyte *Cistanche phelypaea* (L.) Cout as a source of health promoting products: *In vitro* antioxidant and enzyme inhibitory properties, metabolomic profile and computational studies. *Journal of Pharmaceutical and Biomedical Analysis*, 165: 119–128.

Velasco J A, González-Salazar C. 2019. Akaike information criterion should not be a “test” of geographical prediction accuracy in ecological niche modelling. *Ecological Informatics*, 51: 25–32.

Wang L J, Zhao C Y, Li J, et al. 2009. Study on species diversity in early-spring in *Haloxylon* desert in north Fukang region, Xinjiang. *Arid Zone Research*, 26(4): 574–581. (in Chinese)

Xiao F J, Liu Q F, Qin Y. 2024. Predicting the potential distribution of *Haloxylon ammodendron* under climate change scenarios using machine learning of a maximum entropy model. *Biology*, 13(1): 3, doi: 10.3390/biology13010003.

Yang W J, Sun S X, Wang N X, et al. 2023. Dynamics of the distribution of invasive alien plants (Asteraceae) in China under climate change. *Science of the Total Environment*, 903: 166260, doi: 10.1016/j.scitotenv.2023.166260.

Zhang X X, Claiborn C, Lei J Q, et al. 2020. Aeolian dust in Central Asia: Spatial distribution and temporal variability. *Atmospheric Environment*, 238: 117734, doi: 10.1016/j.atmosenv.2020.117734.

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