

Postprint: Distribution of *Caragana korshinskii* and Soil Carbon Storage Characteristics under Different Climate Scenarios in Huanxian County

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Abstract

Global climate change and land use transformation exert significant impacts on ecosystem carbon storage. Afforestation can enhance carbon sequestration, reduce emissions, and improve ecological environments. *Caragana korshinskii*, as one of the shrub species extensively planted in northwestern China, holds significant importance for determining afforestation areas and assessing carbon sequestration potential through the prediction of its potential suitable habitats. Based on 104 distribution point data of *Caragana korshinskii* and environmental factors in Huan County, Qingyang City, Gansu Province, this study employed an optimized MaxEnt model to predict its potential distribution patterns in Huan County for the contemporary period (2000s) and future periods (2030s, 2050s, 2070s), analyzed the primary environmental factors influencing its distribution, delineated priority and stable afforestation regions by integrating land use data, and estimated the soil carbon storage of *Caragana korshinskii* in Huan County for future periods. The results indicate: (1) The primary environmental factors influencing the distribution of *Caragana korshinskii* are monthly average radiation during the growing season, temperature seasonality coefficient, elevation, mean temperature of the warmest quarter, and isothermality. (2) The contemporary potential suitable habitats of *Caragana korshinskii* are mainly distributed in the western and northern regions of Huan County, with the total suitable area accounting for approximately 16.59% of Huan County's area. (3) Under future climate scenarios, the potential suitable habitats of *Caragana korshinskii* exhibit relatively rapid expansion under the low emission scenario (SSP126), whereas the expansion rate is slower under the high emission scenario (SSP585). (4) Under future climate scenarios, the retention areas of *Caragana korshinskii*'s potential distribution remain relatively stable, presenting as continuous and concentrated patches; expansion areas extend from the western and northern regions toward the central region, while loss areas become fragmented

and scattered; the spatial pattern of expansion and loss areas demonstrates an alternating trend of contraction and expansion. (5) Under the medium emission scenario (SSP370), the soil carbon storage of *Caragana korshinskii* increases more rapidly, reaching an increment of 1.017×10^6 t by the 2070s, representing a 2.1-fold increase, whereas the increase rate is slower under both the low emission scenario (SSP126) and the high emission scenario (SSP585).

Full Text

Characteristics of *Caragana korshinskii* Distribution and Soil Carbon Storage in Huan County under Different Climate Scenarios

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Abstract

Global climate change and land use transformation significantly impact ecosystem carbon storage. Afforestation enhances carbon sequestration, reduces emissions, and improves ecological environments. *Caragana korshinskii*, a widely planted shrub species in northwestern China, holds important implications for determining afforestation areas and assessing carbon sequestration potential through predicting its suitable habitats. Based on 104 distribution points of *C. korshinskii* and environmental factors in Huan County, Qingyang City, Gansu Province, this study employed the optimized MaxEnt model to predict its potential distribution patterns for the current period (2000s) and future periods (2030s, 2050s, 2070s). The study analyzed the major environmental factors influencing its distribution, identified priority and stable afforestation areas using land use data, and estimated future soil carbon storage for *C. korshinskii* in Huan County. The results indicate: (1) The primary environmental factors affecting *C. korshinskii* distribution are mean monthly radiation during the growing season, coefficient of seasonal temperature variation, elevation, mean temperature of the warmest quarter, and isothermality. (2) Current potential suitable areas for *C. korshinskii* are mainly distributed in the western and northern regions of Huan County, covering approximately 16.59% of the county's total area. (3) Under future climate scenarios, the low-emission scenario (SSP126) shows relatively rapid expansion of potential suitable areas, while the high-emission

scenario (SSP585) exhibits slower growth. (4) Stable distribution areas remain relatively stable, forming continuous and concentrated patches. Expansion areas extend from the west and north toward the central region, while lost areas become fragmented and scattered, showing an alternating contraction and expansion pattern. (5) Under the medium-emission scenario (SSP370), soil carbon storage of *C. korshinskii* increases rapidly, reaching 1.017×10^6 t by the 2070s—a 2.1-fold increase—while the increase is slower under the low-emission scenario (SSP126) and high-emission scenario (SSP585).

Keywords: climate scenarios; MaxEnt model; potential suitable areas; soil carbon storage; *Caragana korshinskii*

1. Introduction

Climate warming represents a severe challenge facing global development today and constitutes a hot topic in ecological research and international concern. Carbon sequestration and emission reduction serve as crucial strategies for mitigating climate change. However, fossil fuels account for nearly 70% of China's total energy consumption, meaning that relying solely on emission reduction would adversely affect national economic development. Forest ecosystems annually absorb approximately 2.4 Pg C globally, equivalent to about one-third of CO₂ emissions from fossil fuel combustion. Consequently, forest carbon sequestration has become a strategic initiative for addressing climate change. Currently, young and middle-aged forests dominate China's forest composition, maintaining high carbon sequestration rates, but their capacity will weaken as forest age increases. Afforestation can enhance carbon sequestration by expanding plant biomass and soil carbon storage. Soil carbon storage is approximately three times that of atmospheric and vegetation carbon combined, with slower turnover rates and less disturbance impact, enabling long-term carbon maintenance. Therefore, soil carbon sequestration in forest soils represents an important pathway for future carbon sink enhancement.

Caragana korshinskii is a perennial shrub, commonly known as “ningtiao,” characterized by drought resistance, cold tolerance, and poor soil adaptability, while also providing soil and water conservation and carbon sequestration benefits. It is one of the most extensively planted shrub species in northwestern China. As global warming intensifies, the potential suitable areas for plants are changing, yet the shifts in *C. korshinskii*'s potential distribution remain unclear. Previous studies have shown contradictory results: some indicate that climate change will reduce suitable areas and shift them toward higher latitudes or elevations, while others project expansion of suitable areas in the Loess Plateau region. Given these divergent findings, the impact of climate change on *C. korshinskii*'s potential geographic distribution warrants further investigation.

Plant suitability refers to a plant's ability to adapt, survive, and develop in specific environments, encompassing adaptation to climatic, light, soil, and other

environmental factors. Different plants exhibit varying environmental requirements and adaptive capacities. Species distribution models (SDMs) can infer species' ecological requirements and predict potential geographic distributions using known distribution data and environmental factors. Among various algorithms, the Maximum Entropy model (MaxEnt) demonstrates high precision and spatial consistency, with superior reliability compared to other models. It has been widely applied for species suitable area prediction and validated across multiple spatial scales.

Huan County is located in the transitional zone from temperate semi-humid to semi-arid regions, featuring a pronounced continental monsoon climate. The county experiences an average annual temperature of 8.9°C, annual precipitation below 400 mm, annual evaporation of 1681 mm, and total annual sunshine hours of 2551 h. With severe wind erosion and desertification, over 90% of Huan County's area is covered by loess. Consequently, species such as *Pinus sylvestris* var. *mongolica*, *Pinus tabuliformis*, *Prunus davidiana*, and *Caragana korshinskii* have been extensively planted for sand fixation and ecological improvement. As a key battleground in the "Three-North" Shelter Forest Program's Yellow River Bend campaign, rational expansion of artificial afforestation in Huan County can simultaneously achieve ecological improvement goals and carbon sequestration through soil carbon storage. Therefore, this study predicts the potential distribution patterns of *C. korshinskii* in Huan County for current (2000s) and future (2030s, 2050s, 2070s) climate scenarios, analyzes spatial changes in potential suitable areas and major environmental factors, identifies priority afforestation areas using land use data, and estimates future soil carbon storage for *C. korshinskii*. The findings aim to provide theoretical references for rational planning of future afforestation areas in Huan County and scientific basis for assessing soil carbon sequestration potential in artificial forests.

2. Materials and Methods

2.1 Study Area

Huan County is located in northwestern Qingyang City, Gansu Province, comprising 20 towns and 4 townships with a total area of approximately 9236 km². The elevation ranges from 1122 to 2120 m. The county is situated on the southwestern edge of the Mu Us Sandy Land and connects with the Sichuan-Yunnan Loess Plateau ecological barrier zone. Its ecological environment directly affects the ecological security of surrounding regions.

2.2 Data Sources and Processing

2.2.1 Distribution Data *Caragana korshinskii* distribution data were obtained from two sources: (1) Field survey data from 2021-2023 recording survival coordinates, primarily in northern Huan County; (2) Artificial forest plantation

databases provided by local natural resources authorities, from which *C. korshinskii* coordinate points were selected. A total of 2000 distribution points were initially obtained. To avoid model overfitting caused by clustered distribution points, a 5 km × 5 km grid was applied, retaining one point per grid and removing duplicates or closely spaced points, resulting in 104 valid distribution points [Figure 1: see original paper].

2.2.2 Environmental Data Based on previous research and the ecological characteristics of *C. korshinskii*, 23 environmental factors with strong influence were selected for current (2000s) and future (2030s, 2050s, 2070s) suitable area prediction. Climate and light factors were obtained from WorldClim (<http://worldclim.org>) at 2.5 arc-minute resolution. Soil factors were sourced from the SoilGrids250m system (<https://soilgrids.org/>). Topographic factors were derived from Digital Elevation Model (DEM) data from the Geospatial Data Cloud (<http://www.gscloud.cn>). Land use data were obtained from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn>). All data were processed using ArcGIS for masking, resampling, and format conversion, with resolution unified to 1 km × 1 km for modeling and correlation calculations.

Future climate scenario data were selected from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), including three Shared Socio-economic Pathways: low-emission scenario (SSP126), medium-emission scenario (SSP370), and high-emission scenario (SSP585). Environmental variables for future periods were extracted assuming no changes in topography and solar radiation.

2.3 Methods

2.3.1 MaxEnt Model Optimization and Setting The MaxEnt model's regularization multiplier (RM) and feature combination (FC) parameters were optimized. RM values were tested from 0.5 to 5.0 at 0.5 intervals, and five FC types were evaluated: linear (L), quadratic (Q), hinge (H), product (P), and threshold (T). Using ENMeval package, 110 parameter combinations were tested. The optimal parameter combination was selected based on the corrected Akaike Information Criterion (delta.AICc), resulting in FC=LQHPT and RM=2.5, which improved model precision compared to default parameters.

For model construction, 104 *C. korshinskii* distribution points were used with 75% as training data and 25% as test data. Jackknife tests and response curves were enabled, with output format set to "Cloglog" and other parameters at default values. The model was run 10 times for robustness.

2.3.2 Model Evaluation and Output The Area Under the Receiver Operating Characteristic Curve (AUC) was used to evaluate model performance. AUC values were interpreted as: 0.9-1.0 (highly accurate), 0.8-0.9 (accurate), 0.7-0.8 (moderate), 0.6-0.7 (poor), and 0.5-0.6 (failing). The optimized model

achieved $AUC > 0.930$ for current conditions and $AUC > 0.910$ for future scenarios, indicating excellent performance.

To avoid overfitting from correlated environmental variables, variables were screened through pre-modeling to obtain contribution rates, followed by correlation analysis. Variables with contribution rate $< 1\%$ and correlation coefficient $> |0.85|$ were excluded, resulting in 11 environmental factors for final model construction.

The model output ASCII file represents the logistic suitability index. The minimum training presence threshold (0.21) was used to distinguish suitable from unsuitable areas. Suitable areas were further classified into low (0.21-0.4), medium (0.4-0.6), and high (0.6-1.0) suitability zones.

2.3.3 Priority Afforestation Area Selection Stable suitable areas were identified by overlaying total suitable areas across multiple periods under the same scenario. These were then overlaid with the 2020 land use map (assuming no land use type changes in future periods) to identify priority and stable afforestation areas. Based on land use maps, unused land was prioritized for afforestation, followed by sparse forest land, shrub land, and low-coverage grassland, while avoiding cultivated and forest land.

2.3.4 Soil Carbon Storage Estimation Soil carbon storage was calculated using soil carbon density and planting area:

$$M = A \times D$$

where M is soil carbon storage (t), A is the area of priority planting zones (hm^2), and D is soil carbon density ($\text{t} \cdot \text{hm}^{-2}$).

Soil carbon density values were modified from those of *C. korshinskii* in the loess hilly region, which shares similar climate, soil, and vegetation conditions. Since precipitation affects soil carbon density more than temperature, only precipitation impacts were considered. The relationship between mean annual precipitation and soil carbon density was calculated as:

$$SP = 3.3968 \times P + 3996.1 \quad (R^2 = 0.11)$$

where SP is soil carbon density ($\text{kg} \cdot \text{m}^{-2}$) and P is mean annual precipitation (mm). The ratio of soil carbon densities between Huan County and the loess hilly region under each climate scenario yielded a correction coefficient. Multiplying this coefficient by the loess hilly region's soil carbon density produced Huan County's soil carbon density values.

3. Results

3.1 MaxEnt Model Evaluation and Environmental Factor Analysis

Optimization results showed that the parameter combination FC=LQHPT with RM=2.5 produced delta.AICc values lower than default parameters, indicating improved model precision. Under this configuration, the model achieved AUC = 0.944 for current climate conditions and AUC > 0.930 for future scenarios, demonstrating excellent predictive reliability [Figure 2: see original paper].

Among the 11 environmental factors used in modeling [Figure 3: see original paper], those with high contribution rates to *C. korshinskii* distribution were: coefficient of seasonal temperature variation (16.1%), mean monthly radiation during growing season (14.5%), mean temperature of warmest quarter (13.6%), precipitation of wettest month (11.3%), and isothermality (10.6%), with a cumulative contribution of 75.4%. Jackknife tests identified coefficient of seasonal temperature variation, mean monthly radiation during growing season, mean temperature of warmest quarter, isothermality, elevation, and mean annual temperature as key factors. The intersection of contribution rates and Jackknife results identified the primary environmental factors: mean monthly radiation during growing season, coefficient of seasonal temperature variation, elevation, mean temperature of warmest quarter, and isothermality.

Response curves revealed optimal ranges for these factors [Figure 5: see original paper]. Mean monthly radiation < 17696 kJ · m⁻² · d⁻¹ was most suitable, with probability decreasing at higher values. The optimal coefficient of seasonal temperature variation was < 965.02. Elevation range of 1640.34-1993.32 m (optimal: 1955 m) was suitable. Mean temperature of warmest quarter range of 20.18-22.05°C was optimal. Isothermality range of 30.78-31.38 was most suitable. Overall, light and temperature strongly influenced *C. korshinskii* distribution.

3.2 Current Climate Distribution of Potential Suitable Areas

Under current climate conditions, *C. korshinskii*'s potential suitable areas in Huan County are primarily distributed in western and northern regions [Figure 6: see original paper], covering 1521.86 km² (16.59% of total county area). High-suitability areas (386.31 km², 4.21%) are concentrated in Luwan, Maojing, and Qintuanzhuang townships. Medium-suitability areas (399.63 km², 4.36%) scatter around high-suitability zones. Low-suitability areas (735.92 km², 8.02%) are distributed in Chedao, Maojing, and Xiaonangou townships, with sporadic presence in other towns.

3.3 Future Climate Distribution of Potential Suitable Areas

Under SSP126, total suitable area shows increasing trends across all three future periods, peaking in 2070s at 1736.32 km² (18.84%). Under SSP370, suitable area first increases then decreases then increases again, but remains higher than

current conditions. Under SSP585, suitable area increases slowly compared to current conditions.

Future suitable area distribution remains relatively stable [Figure 8: see original paper]. High-suitability areas are mainly in Luwan, Qintuanzhuang, Maojing, and Hedao townships. Medium-suitability areas surround high-suitability zones. Low-suitability areas are in Chedao, Xiaonangou, and Gengwan townships. The overall pattern shows extension from western and northern regions toward the center.

3.4 Changes in Potential Suitable Areas

Retention rates of potential suitable areas exceed 69.81% across all scenarios, with retained areas forming continuous, concentrated patches primarily in western and northern townships [Figure 9: see original paper]. Lost areas are fragmented and scattered, mainly in Maojing, Xiaonangou, Nanjiu, Luoshan, and Qintuanzhuang townships. The largest loss rates occur in 2050s-SSP370 (28.45%) and 2030s-SSP585 (28.29%). Expansion areas extend from west and north toward the center, concentrated in Chedao, Hedao, Hongde, and Gengwan townships. The largest expansion rates occur in 2030s-SSP126 (44.85%) and 2070s-SSP370 (40.19%). The pattern shows alternating contraction and expansion between gained and lost areas .

3.5 Soil Carbon Storage Estimation

Priority planting areas show consistent distribution, with the minimum area of 733.88 km² used for estimation. Assuming no *C. korshinskii* planting under current conditions, soil carbon storage was calculated as 0.484×10^6 t. Under SSP126, soil carbon storage values are 1.093×10^6 t (2030s), 1.517×10^6 t (2050s), and 2.027×10^6 t (2070s). Under SSP370, values are 1.101×10^6 t (2030s), 1.501×10^6 t (2050s), and 2.034×10^6 t (2070s). Under SSP585, values are 1.033×10^6 t (2030s), 1.550×10^6 t (2050s), and 1.498×10^6 t (2070s). The highest increase occurs under SSP370 in 2070s, reaching 1.017×10^6 t (2.1-fold increase). SSP126 shows moderate increase, while SSP585 shows slower increase .

4. Discussion

4.1 Primary Environmental Factors Influencing Distribution

Environmental variables critically determine plant growth and distribution. Contribution rates, AUC values, and response curves indicate that mean monthly radiation during growing season, coefficient of seasonal temperature variation, elevation, mean temperature of warmest quarter, and isothermality are the primary factors affecting *C. korshinskii* distribution.

Solar radiation directly affects plant growth and development. Adequate light enables effective photosynthesis, while excessive radiation can damage leaves and cause soil water deficiency, slowing or halting growth. Our results show mean monthly radiation $< 17696 \text{ kJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ is optimal, consistent with Wang Ziting et al.'s finding that light intensity is a primary limiting factor for young *C. korshinskii* in semi-arid loess regions. The optimal mean temperature of warmest quarter (20.18–22.05°C) aligns with Yang Hui et al.'s finding of 10–25°C as optimal for *C. korshinskii* germination. Elevation affects plant distribution through water-heat redistribution, with our optimal range of 1640.34–1993.32 m consistent with Zhou Zhenzhao et al.'s results on site factors affecting understory shrub biomass. These environmental relationships provide valuable references for rational planting layout and efficient management.

4.2 Spatial Distribution Patterns and Changes

Monoculture artificial forests have unstable structures vulnerable to climate change. Our results show *C. korshinskii*'s potential suitable areas are in northern and western Huan County, consistent with Xu Hao et al.'s identification of medium-confidence potential afforestation areas and Xu Jinyong et al.'s mapping of potential forest land quality. Total suitable area increases from current (2000s) to future (2070s) periods across all scenarios, indicating good adaptability to climate change, consistent with Chen Meilin et al.'s findings. Deng Di et al. also projected increased suitable habitat in northern Qingyang under future scenarios, validating our results.

The SSP585 scenario shows slower suitable area growth, likely because intense temperature and precipitation changes increase extreme events affecting distribution. Many studies confirm SSP585 has the greatest impact on species distribution, consistent with our findings. Conversely, SSP126 shows the fastest suitable area growth, possibly because moderate temperature and precipitation increases convert previously unsuitable areas. Retained areas remain stable as continuous patches, while lost areas fragment and expansion areas extend centrally, showing alternating contraction and expansion patterns.

4.3 Soil Carbon Storage Changes under Future Climate

Soil carbon storage shows increasing trends across all future scenarios, rising from $0.484 \times 10^6 \text{ t}$ (2000s) to $1.033 \times 10^6 \text{ t}$ (2070s-SSP370). Precipitation and temperature increases affect soil organic carbon storage. While warming may accelerate decomposition short-term, this effect diminishes over time, showing adaptation. Guo Guangfen found future temperature changes would reduce soil carbon in Ningxia and Gansu, but increased precipitation would raise it, with net increase under combined effects. Xu Xiaofeng indicated soil carbon pools in mid-low latitudes may remain stable or slightly increase with warming. Wei Yunyan noted warming changes plant growth rates, enhances vegetation carbon sequestration, and increases carbon input to soils. Cui Xie et al. found warming and precipitation increases benefit plant growth and organic

matter accumulation, increasing carbon storage. Our results align with these findings, suggesting modest temperature and precipitation increases will benefit vegetation growth and long-term soil carbon storage.

4.4 Uncertainty Analysis

Our prediction did not consider surface cover, human disturbance, government policies, or economic development factors, which could reduce potential distribution ranges if included. Integrating these constraints represents a future direction for improving species distribution models. We assumed constant solar radiation and topographic factors, though solar radiation will likely change under global climate change. Short-term solar radiation fluctuations may have relatively minor but non-negligible impacts on vegetation ranges. As solar radiation increases, surface temperatures rise, potentially expanding the range of heat- and drought-tolerant species like *C. korshinskii*. Carbon density values were modified using precipitation only, which may introduce minor biases. More precise data in future studies would significantly improve reliability.

5. Conclusion

- 1) The primary environmental factors influencing *Caragana korshinskii* distribution are mean monthly radiation during the growing season, coefficient of seasonal temperature variation, elevation, mean temperature of the warmest quarter, and isothermality.
- 2) Current potential suitable areas for *C. korshinskii* are concentrated in western and northern Huan County, covering approximately 16.59% of the county's total area.
- 3) Under future climate scenarios, SSP126 shows relatively rapid expansion of potential suitable areas, while SSP585 shows slower growth.
- 4) Stable distribution areas remain relatively stable, forming continuous patches. Expansion extends from west and north toward the center, while lost areas fragment and scatter, showing alternating contraction and expansion trends.
- 5) Soil carbon storage of *C. korshinskii* will increase under all future scenarios, reaching 1.017×10^6 t by 2070s under SSP370 (2.1-fold increase). The increase is slower under SSP126 and SSP585.

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