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Simulation of suitable habitats of typical plants and quantification of water-resource-based vegetation carrying capacity in the wind-sand regions of northern China (postprint)

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Abstract

This study quantitatively reveals the distribution of suitable habitats for typical sand-fixing plants and the vegetation carrying capacity under water resource constraints in the aeolian desertification areas of northern China, determines reasonable thresholds for planting density, and provides a scientific basis for precise sand control. Taking Haloxylon ammodendron and Pinus sylvestris var. mongolica as the research objects, the study integrates the maximum entropy model (MaxEnt) with the classical soil water resource-based vegetation carrying capacity model. Using soil moisture data from 2008–2018 in combination with climate, soil, and topographic data, the suitable habitats and dominant environmental factors for the two species were analyzed, and the maximum vegetation carrying capacity based on regional water balance was calculated. The results show that: (1) the potential suitable habitat of H. ammodendron accounts for about 19% of the study area, concentrated in the desert steppe zone, with its distribution mainly controlled by precipitation in the coldest quarter and mean annual temperature; the suitable habitat of P. sylvestris var. mongolica accounts for 48%, with core areas in the eastern Horqin Sandy Land and the typical steppe zone, constrained by extreme precipitation in summer and winter and by soil rooting conditions. (2) There is pronounced spatial heterogeneity in water resource-based carrying capacity; for example, in the desert steppe zone west of the Yinshan Mountains, the carrying capacity for H. ammodendron exceeds 10.0\$$\times 10^4 plants \cdot km^-2, whereasinthewesternHorqinSandyLand, thepiedmontplainsonthesouthernflankoftheGreaterKhing$
plants • km^-2. (3) A zoned planting scheme is proposed: for the desert steppe zone, a spacing of 1.5 m × 2.0 m is recommended for H. ammodendron; in the typical steppe zone, P. sylvestris var. mongolica should be planted at 6.5 m

× 9.5 m; in constrained areas such as the Horqin Sandy Land, the spacing for P. sylvestris var. mongolica should be reduced to 10.5 m × 15.0 m, yielding small deviations from actual field practice. The findings provide quantitative data support for ecological restoration in northern aeolian desertification regions following the principles of “water-determined greening and site- and species-appropriate planting,” and highlight the need for further in-depth research on interspecific water competition mechanisms in mixed stands in the future.

Full Text

Simulation of Suitable Habitats for Typical Plants and Quantification of Water Resources Vegetation Carrying Capacity in the Wind-Sand Region of Northern China

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Abstract

This study quantitatively reveals the distribution patterns of suitable habitats for typical sand-fixing plants in the wind-sand region of northern China and the vegetation carrying capacity under water resource constraints, aiming to determine reasonable planting density thresholds and provide a scientific basis for precise desertification prevention and control. Haloxylon ammodendron and Pinus sylvestris var. mongolica were selected as research objects, integrating the MaxEnt model with the classical soil water resources vegetation carrying capacity model. By combining soil moisture data from 2008–2018 with climate, soil, and topography data, we analyzed the suitable habitats of the plants and the dominant environmental factors, and calculated the maximum vegetation carrying capacity based on regional water balance. The results showed that: (1) The potential suitable habitats for H. ammodendron account for approximately 19% of the study area, concentrated in the desert grassland zone, with distribution primarily controlled by precipitation in the coldest quarter and mean annual temperature. Suitable habitats for P. sylvestris cover 48% of the study area, with core areas in the eastern Horqin Sandy Land and typical steppe zone, constrained by extreme precipitation in summer and winter and soil rooting conditions. (2) Water resource carrying capacity exhibits significant spatial heterogeneity; for example, H. ammodendron shows values >10.0$×10^{4}$ trees · km^{-2} in the desert grassland zone west of the Yin Mountains, but <7.0$×10^{4}$ trees ·

km^{-2} in the western Horqin Sandy Land and the piedmont plain south of the Da Hinggan Mountains. (3) A zoned planting scheme is proposed: H. ammodendron in the desert grassland zone is recommended at a spacing of 1.5 m × 2.0 m; P. sylvestris in the typical steppe zone should adopt 6.5 m × 9.5 m; while in restricted areas such as the Horqin Sandy Land, P. sylvestris spacing should be reduced to 10.5 m × 15.0 m, showing minimal deviation from practical applications. The research findings provide quantitative data support for ecological restoration in the northern wind-sand region following the principles of "determining greening based on water availability" and "matching species to site conditions." Future research should focus on interspecific water competition mechanisms in mixed plantations.

Keywords: water resources vegetation carrying capacity; wind-sand region of northern China; potential suitable habitats; hydrothermal conditions; soil moisture; simulation

Introduction

China is one of the countries most severely affected by desertification worldwide, with land desertification seriously constraining environmental, social, and economic sustainable development. Under the dual influence of natural factors and human activities, the wind-sand region of northern China constitutes the primary sand source area within China and represents the main region for desertification development and reversal. To address desertification, the nation is vigorously advancing the three iconic campaigns of the "Three-North" Shelterbelt Program, coordinating integrated protection and systematic governance of mountains, waters, forests, farmlands, lakes, grasslands, and deserts, adhering to the principles of "determining greening based on water availability," "matching species to site conditions," and combining trees, shrubs, and grasses to promote afforestation and green expansion. Conducting scientific vegetation construction and restoration is a critical task, particularly in the water-scarce northern wind-sand region, where assessing suitable habitats for typical sand-fixing plants and simulating optimal vegetation coverage thresholds under soil moisture constraints holds important theoretical and practical significance for implementing the "determining greening based on water availability" principle and precisely enhancing the ecological stability of desertification control projects.

Plant suitability assessment represents a comprehensive evaluation of the adaptability of specific plants to environmental conditions such as climate, topography, and soil within a study area. Currently, research on plant suitable habitats primarily employs field surveys and ecological niche modeling. While field surveys offer low cost and high efficiency, they are limited by field conditions, suffer from insufficient spatial representativeness, limited sample data, and high equipment expenses. In contrast, ecological niche models represent an accurate, convenient, and efficient method for obtaining species distribution information, capable of simulating potential suitable habitats through limited distribution data. Common species distribution models include DOMAIN, BIOCLIM, and

MaxEnt, among which the MaxEnt model demonstrates stronger practicality. Based on maximum entropy theory, this distribution model estimates species distribution according to environmental constraints, yielding accurate predictions with high stability. Even with incomplete species distribution data and environmental variables, it can precisely predict potential distribution areas.

Soil water resources vegetation carrying capacity refers to the maximum quantity of indicator plant communities that can be maintained under healthy growth conditions when plant root water consumption equals soil water replenishment over extended periods and specific conditions. Numerous scholars have investigated soil water resources vegetation carrying capacity models, analyzing the effects of soil, groundwater depth, and climate zoning on typical northern vegetation such as Haloxylon ammodendron, Caragana korshinskii, and Medicago sativa. However, most simulations face challenges including difficult data acquisition, strong instability, and limited development of vegetation-coupled calculation models, preventing convenient application for large-scale single-species water resources vegetation carrying capacity estimation. The classical carrying capacity model requires only two factors—soil available water and individual plant water consumption—offering convenient data acquisition, efficient calculation, and high accuracy under existing theoretical data support.

This study integrates the MaxEnt model with the classical carrying capacity model to simulate water resources vegetation carrying capacity for typical plants in the northern wind-sand region. The MaxEnt model can precisely identify environmental constraints on suitable habitats, while the classical model quantifies water support capacity. Their integration enables coupled analysis of "suitable habitat" and "water carrying capacity," overcoming the limitations of single indicators. The research results provide computational methods for standardized determination of water resources vegetation carrying capacity for single species across large regions, offering references for desertification control and ecological restoration projects in the northern wind-sand region.

1.1 Study Area Overview

The study area is located in the wind-sand region of northern China, a key ecologically vulnerable zone primarily in northwestern China, generally covering central and eastern Inner Mongolia, north of the Yulin wind-sand and Loess Plateau transition zone in Shaanxi Province, and mainly involving Xilingol League, Chifeng City, Ulanqab City, Baotou City, Bayannur City, Zhangjiakou City, and Chengde City (Fig. 1). The region spans 4.6$×10^{5}$ km^{2} and features a temperate arid and semi-arid climate with scarce precipitation, high evaporation, and frequent strong winds and sandstorms. Mean annual temperature ranges from 0-14°C, gradually decreasing from south to north, with the lowest temperatures in the northeast. Annual precipitation ranges from 150-642.1 mm, decreasing from south to north and from east to west, concentrated in June-August. Annual evaporation ranges from 1500-2700 mm. Vegetation is sparse and complex, with typical steppe, desert steppe, and sparse forest-shrub steppe as the main types, with forests locally distributed in high mountain areas. Soil types are diverse and vary significantly with longitude, dominated by aeolian sandy soil, brown desert soil, and chestnut soil. The region concentrates several major sandy lands including the Mu Us, Hunshandake, and Horqin sandy lands, with wind erosion dominating and water erosion coexisting locally, and prominent ecological problems including grassland degradation and land desertification.

Based on the desertified land distribution and geographic zoning characteristics shown in Fig. 1, the study area is divided into five main regions. The typical steppe region is mainly distributed in Xilingol League, where vegetation consists primarily of typical steppe communities, soil is relatively fertile but moisture conditions are moderate, representing a transition zone between grassland and sandy land ecosystems. The desert steppe region concentrates in Ulanqab City, Baotou City, Bayannur City, and surrounding areas, with a more arid climate, lower vegetation coverage dominated by drought-tolerant herbs and shrubs, and higher soil desertification. The Hunshandake Sandy Land, located in southern Xilingol League, is a typical sandy land distribution area in the study region, dominated by semi-fixed and fixed sandy lands with local mobile sands, and vegetation mainly consists of psammophytic shrubs and herbs. The Horqin Sandy Land, situated in Chifeng City and Tongliao City, features diverse sandy land types with comprehensive interlacing. The Yanshan region is distributed in Zhangjiakou City, Chengde City, and surrounding areas, with mountainous and hilly terrain, relatively rich vegetation types, and locally favorable moisture conditions due to topography. The southern Da Hinggan Mountains are located in northern Chaoyang City and western Chifeng City, belonging to mountainous terrain with relatively high elevation, dominated by forests and mountain steppes, forming a certain ecological barrier for surrounding sandy lands.

1.2 Data Sources and Processing

Research data include plant wilting coefficients, typical plant water requirements per plant, typical plant specimen coordinates, 19 climate variables, soil data, and topography data. Meteorological and topographic data were obtained from the WorldClim Global Climate Database (https://www.worldclim.org/) and Earth Science Data Website (https://www.earthdata.nasa.gov/), including 19 bioclimatic variables and elevation, slope, and aspect data at
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3}*.Thesedatashowstrongconsistencywithfieldmeasurements*(*R*^{2}$ > 0.78) and low unbiased root mean square error (ubRMSE < 0.05 $\mathrm{m}^3 \cdot \mathrm{m}^{-3}$), demonstrating good accuracy throughout the time series.

Typical plant specimen coordinates were sourced from the Chinese Virtual Herbarium and Global Biodiversity Information Facility (GBIF, https://www.gbif.org/). Plant wilting coefficients and water requirements were obtained from published literature data. The wilting coefficient for H. ammodendron is 0.87 $m^3 \cdot plant^{-1}$, with water consumption of 4.43 $m^3 \cdot plant^{-1}$; for P. sylvestris var. mongolica, the wilting coefficient is 0.824 $m^3 \cdot plant^{-1}$ with water consumption of 0.8-1.4 $m^3 \cdot plant^{-1}$. All experimental data were processed using ArcGIS, unified to 1 km × 1 km spatial resolution.

1.3 Research Methods

This study selected H. ammodendron and P. sylvestris var. mongolica as two excellent windbreak and sand-fixation species, employing the MaxEnt model and classical soil water resources vegetation carrying capacity model to simulate suitable habitats and water resources vegetation carrying capacity for these plants in the northern wind-sand region.

1.3.1 Extraction of Plant Suitable Habitats

This study analyzed the suitability of typical plants in the northern wind-sand region using the MaxEnt model. Climate, soil, topography, and evapotranspiration data were imported into the model, and the jackknife method in MaxEnt was used to evaluate the contribution rates of these factors to the distribution of suitable habitats. During model training, the test dataset was set at 25% of records, repeated ten times to verify stability. For each species, 25 specimen points and uniformly processed climate factor data were used to predict potential suitable habitats in the MaxEnt model until convergence. When the Area Under the Curve (AUC) > 0.9, the output was deemed accurate, and the contribution of each factor was analyzed. MaxEnt model predictions were classified using the natural breaks method into unsuitable, low-suitable, moderately-suitable, and highly-suitable zones.

1.3.2 Evaluation of Water Resources Vegetation Carrying Capacity

Moderately-suitable, highly-suitable, and very highly-suitable zones were selected as plantable suitable habitats. Based on the classical carrying capacity model, water resources vegetation carrying capacity for typical plants in the northern wind-sand region was calculated. It should be noted that the soil moisture vegetation carrying capacity calculated in this study based on the classical model refers specifically to the natural background state (i.e., without target artificial vegetation cover).

Literature indicates that arid region species absorb water at depths of approximately 100 cm. Therefore, this study used 100 cm soil layer moisture content to calculate soil volumetric available water. The classical carrying capacity model estimates the maximum carrying capacity of soil for tree species through the total amount of effective moisture supplied by soil and water consumption per plant. The calculation formula is:

$$SWCCV = \frac{ASWS}{W}$$

where $SWCCV$ is soil water carrying capacity for vegetation ($\text{trees} \cdot \text{km}^{-2}$); $ASWS$ is the soil effective water storage per grid cell ($\text{m}^3 \cdot \text{km}^{-2}$); and W is the water consumption of mature plants ($\text{m}^3 \cdot \text{tree}^{-1}$). $ASWS$ must be calculated from soil available water content, which is obtained by subtracting the plant wilting coefficient from the natural soil water content. The calculation formula is:

$$ASWS = V \times AWC$$

where AWC is soil available water content ($\text{m}^3 \cdot \text{m}^{-3}$); SWC is natural soil water content ($\text{m}^3 \cdot \text{m}^{-3}$); and WC is the plant wilting coefficient. $ASWS$ is calculated as:

$$ASWS = V \times (SWC - WC)$$

where V is the grid soil volume (m^3), and S is the grid area (km^2). It should be noted that this maximum carrying capacity does not consider soil evaporation effects, as surface soil moisture decreases during dry seasons, changes in soil porosity nearly halt capillary movement, making it difficult for roots to extract water from the soil. Therefore, evaporation effects on water consumption in deeper soil layers are much smaller than plant transpiration consumption.

2.1 Analysis of Typical Plant Suitable Habitats

MaxEnt model results based on 25 H. ammodendron and 25 P. sylvestris distribution points and 19 environmental variables showed an average AUC of 0.989, indicating high credibility of the suitable habitat analysis results.

2.1.1 Haloxylon ammodendron Suitable Habitats

The main suitable habitats for H. ammodendron are in the desert steppe region (Fig. 2), with patchy distribution in the Hunshandake and Horqin sandy lands, scattered distribution in the southern Da Hinggan Mountains and Yanshan region, and unsuitable conditions in the typical steppe region. Overall, potential suitable habitats for H. ammodendron occupy 19% of the northern wind-sand region, including 8.74$×10^{4}$ km^2 of highly-suitable habitats, 1.21$×10^{5}$ km^2 of moderately-suitable habitats, and 1.95$×10^{5}$ km^2 of low-suitable habitats. Detailed analysis across geographic zones reveals that all highly-suitable habitats for H. ammodendron in the northern wind-sand region are located in the desert steppe region (accounting for 21.3% of the desert steppe area). Moderately-suitable habitats are distributed in both the desert steppe region and Hunshandake Sandy Land (accounting for 16.7% and 8.9% of their respective zones). Low-suitable habitats are distributed across all regions except the typical steppe region, comprising 18.5% of the desert steppe region, 12.3% of the Yanshan region, 9.8% of the southern Da Hinggan Mountains, 11.2% of the Hunshandake Sandy Land, and 8.7% of the Horqin Sandy Land.

MaxEnt model analysis (Table 1) shows that precipitation in the coldest quarter, mean annual temperature, precipitation in the wettest quarter, precipitation in the warmest quarter, mean temperature in the coldest quarter, and mean annual precipitation have contribution rates of 16.3%, 15.7%, 12.8%, 11.4%, 11.4%, and 10.9%, respectively. The cumulative contribution rate of precipitation- and temperature-related factors reaches 78.2%, demonstrating the importance of climatic factors in H. ammodendron distribution. Among topographic data, elevation (4.2%), slope (3.1%), and aspect (2.8%) contribute to H. ammodendron suitable habitats, reflecting the influence of local microclimate and soil moisture redistribution. High-altitude or steep-slope areas may restrict growth due to insufficient heat or soil erosion.

Analysis of H. ammodendron distribution probability response curves reveals that the highest distribution probability occurs when precipitation in the coldest quarter is $ $3.9 mm, precipitation in the warmest quarter is 40.9–76.8 mm, mean temperature in the coldest quarter is -9.3 to -4.9°C, mean annual precipitation is 42.4–127.4 mm, and precipitation in the wettest quarter is 40.4–76.1 mm. In the northern wind-sand region, precipitation in the warmest quarter and wettest quarter often occur in the same season (summer), so their optimal precipitation ranges are similar.

2.1.2 Pinus sylvestris var. mongolica Suitable Habitats

The main suitable habitats for P. sylvestris are located in the eastern part of the northern wind-sand region, including the Horqin Sandy Land, typical steppe region, and central Hunshandake Sandy Land, with scattered habitats in the Yanshan region and desert steppe region (Fig. 2). Overall, P. sylvestris suitable habitats occupy 48% of the northern wind-sand region, including 2.21$×10^{4}$ km^2 of highly-suitable habitats, 4.85$×10^{4}$ km^2 of moderately-suitable habitats, and 1.53$×10^{5}$ km^2 of low-suitable habitats. Detailed geographic analysis shows that highly-suitable habitats are mainly distributed in the Horqin Sandy Land, accounting for 18.5% of the region' s total area and 16.3% of the typical steppe region, but less than 5% in the southern Da Hinggan Mountains. Moderately-suitable habitats are distributed across all geographic zones, primarily in the typical steppe region (accounting for 15.2% of the region), with less than 8% in the desert steppe region. Low-suitable habitats are distributed across all regions.

MaxEnt model analysis shows that both climatic and soil factors dominate P. sylvestris distribution, with soil factors having a stronger determining effect than for H. ammodendron. Precipitation in the coldest quarter (cumulative contribution 16.2%), precipitation in the warmest quarter (15.7%), temperature seasonality (12.8%), precipitation variation coefficient (11.4%), rooting conditions (11.4%), and precipitation in the wettest month (10.9%) are the most influential factors, reflecting the critical constraints of precipitation spatiotemporal distribution and temperature periodic fluctuations on P. sylvestris growth. Precipitation in the warmest quarter directly relates to growing season water supply, while temperature seasonality may regulate phenological processes through accumulated temperature and dormancy low-temperature requirements. Among soil data, the high contribution rate of rooting conditions indicates that suitable soil physical structure (loose, aerated, deep layers) is crucial for P. sylvestris root expansion and water absorption, while nutrient availability and salt accumulation have relatively weaker effects.

Analysis of P. sylvestris distribution probability response curves shows that the optimal growth environment occurs when precipitation in the coldest quarter is 15.7 ± 6 mm, precipitation in the warmest quarter is 288.4-403.9 mm, temperature seasonality is 15.2-16.9, precipitation variation coefficient is 0.02-0.76, precipitation in the wettest month is 117.2-174.5 mm, and precipitation in the driest month is 107.9-123.2 mm, where P. sylvestris distribution probability is highest.

2.2 Water Resources Vegetation Carrying Capacity in the Northern Wind-Sand Region

Analysis of H. ammodendron water resources vegetation carrying capacity (Fig. 5) reveals that high carrying capacity areas (>10.0$\times10^{4}$ trees · km^{-2}) are mainly distributed in the desert steppe zone west of the Yin Mountains, including northwestern Bayannur City and northern Ulanqab City, primarily in mobile, semi-mobile, and semi-fixed sandy lands where continuous patchy high-density shrub distribution can form. Medium carrying capacity areas (7.0-10.0$\times10^{4}$ trees · km^{-2}) are concentrated in the northeastern Ordos Plateau and southwestern Xilingol League, where H. ammodendron grows in scattered shrub communities due to surface water evaporation constraints. Low carrying capacity areas (<7.0$\times10^{4}$ trees · km^{-2}) are sporadically found in the western Horqin Sandy Land, the piedmont plain south of the Da Hinggan Mountains, and the Yanshan region. Although these areas have relatively high annual precipitation (>250 mm), higher relative humidity somewhat restricts H. ammodendron distribution.

P. sylvestris high carrying capacity core areas (>14.0$\times10^{4}$ trees · km^{-2}) are mainly distributed in the transition zone between the southern Da Hinggan Mountains and typical steppe region (Xing' an League-Xilingol League line). This zone has abundant precipitation in the warmest quarter, fertile soil, and deep soil water supporting dense forest distribution. Influenced by terrain slope, soil moisture redistribution results in significantly higher carrying capacity on shady slopes than sunny slopes. Medium carrying capacity areas (8.0-14.0$\times10^{4}$ trees · km^{-2}) extend to the typical steppe region and central Horqin Sandy Land, surrounding the Hunshandake Sandy Land and northern Yanshan region, with sporadic distribution in the desert steppe region. Although the Horqin Sandy Land shows extremely high suitability in MaxEnt analysis, the sandy matrix' s limited water-holding capacity reduces carrying capacity, resulting in patchy P. sylvestris distribution that can form forest-grass mosaic patterns with grassland vegetation. Low carrying capacity areas (<8.0$×10^{4}$ trees · km^{-2}) are distributed in the Yanshan region and margins of the Horqin Sandy Land, including central Hunshandake Sandy Land, suitable only for shelterbelt-style planting.

3.1 Key Factors Influencing Plant Distribution

Plant suitable habitat distribution results from the comprehensive effects of multiple environmental factors. The MaxEnt model reveals the dominant roles of hydrothermal conditions and soil topographic characteristics on H. ammodendron and P. sylvestris distribution, with significant differences in response mechanisms between the two species. The model demonstrates high performance in suitable habitat prediction, with AUC = 0.989, proving the reliability of factor analysis. The MaxEnt model results show that H. ammodendron is highly suitable when precipitation in the coldest quarter is $ $3.9 mm, precipitation in the wettest quarter is 40.9–76.8 mm, mean temperature in the coldest quarter is -9.3 to -4.9°C, mean annual precipitation is 42.4–127.4 mm, and mean annual temperature is 6.6–9.7°C. These findings align with previous studies by Fu Guiquan et al. and Chang Hong et al., which identified annual mean temperature of 2–8°C, annual precipitation of 80–200 mm, and wettest quarter precipitation of <100 mm as suitable habitats for H. ammodendron. Our results meet previous research standards with more detailed factor data. For P. sylvestris, the limiting factors are precipitation in the coldest quarter of 15.7 ± 6 mm, precipitation in the warmest quarter of 288–404 mm, temperature seasonality of 15.2–16.9, precipitation variation coefficient of 0.02–0.76, and wettest month precipitation of 117.2–174.5 mm. These results are basically consistent with predictions by Li Gan et al. For example, in Zhanggutai, Liaoning, a typical P. sylvestris distribution area, winter precipitation is about 15–35 mm and annual precipitation is 469.4 mm, matching regional reality and confirming the accuracy of MaxEnt model predictions.

3.2 Practical Significance of Zoned Afforestation Schemes

This study employs overlay analysis to overcome the limitations of single-factor decision-making. Relying solely on suitable habitat data might lead to blind high-density planting in highly-suitable but low-carrying-capacity areas, causing excessive soil water consumption and subsequent vegetation decline. Conversely, relying only on carrying capacity data might result in forced planting in high-carrying-capacity but unsuitable areas, causing high seedling mortality and low ecological benefits. Through overlay analysis, this study precisely identifies areas where ecological suitability and water support capacity match, providing spatial positioning basis for determining density thresholds while strictly following the "determining greening based on water availability" and "matching species to site conditions" principles.

Based on overlay analysis of water resources vegetation carrying capacity and suitable habitats, this study proposes a zoned planting scheme that achieves quantitative implementation of "determining greening based on water availability." Considering regional water characteristics and engineering practice requirements, differentiated planting schemes are proposed (Table 2). In high carrying capacity areas for H. ammodendron (>10.0$×10^{4}$ trees · km^{-2}), a spacing of 1.5 m × 2.0 m is recommended, which matches the actual community density in Minqin area (80,000–100,000 trees · km^{-2}). In high carrying capacity areas for P. sylvestris (>14.0$×10^{4}$ trees · km^{-2}), a spacing of 6.5 m × 9.5 m is recommended, satisfying dense distribution supported by deep soil water while avoiding growth limitations from insufficient water-holding capacity of sandy substrates.

It should be clarified that the water resources vegetation carrying capacity and corresponding recommended planting densities calculated in this study are based on natural backgrounds (natural grassland or desert), assuming no existing P. sylvestris or H. ammodendron vegetation cover in the study area, and calculating the maximum theoretical support capacity based on natural soil water balance. These results can directly serve as reasonable density upper limits for artificial establishment of target vegetation in non-afforested areas. Actual planting should strictly control density not to exceed the corresponding regional carrying capacity threshold to avoid initial density-induced soil water deficit. For already afforested areas, overload assessment can be conducted by comparing existing target species actual density with regional water resources vegetation carrying capacity. If existing density exceeds the carrying capacity threshold, it is judged as "water overload," requiring density reduction through thinning or transplanting to prevent vegetation decline and death due to water stress. If existing density is below the carrying capacity threshold, moderate supplementary planting within the threshold range can be implemented as needed in ecological restoration practice to enhance vegetation coverage and ecological benefits while ensuring soil water balance.

Comparison with existing research shows that the recommended P. sylvestris planting density in this study is slightly lower than experimental values in related studies. This difference may stem from: (1) This study's model calculation is based on the theoretical maximum carrying capacity of long-term soil water balance, focusing on ecological stability under non-irrigation conditions relying on natural precipitation and soil water storage, while field experiments often focus on growth performance and survival rates during specific periods (e.g., young forest stage). (2) The model-recommended density considers water competition after forest maturity and sustainability, 倾向于更保守（即密度更低）的方案以避免未来水分胁迫导致的衰退。Therefore, the slightly lower density recommended in this study compared to some field experiments' "optimal early growth" density conforms to the final mature forest density and aligns with the principle of ensuring long-term forest health and stability, providing important water-constraint-based references for scientific establishment of P. sylvestris plantations in the northern wind-sand region.

3.3 Research Limitations and Future Prospects

This study integrates the MaxEnt model with the classical carrying capacity model to efficiently quantify water resources vegetation carrying capacity for H. ammodendron and P. sylvestris. The data results are reliable, with MaxEnt model-predicted suitable habitats (AUC = 0.989) highly consistent with field conditions. However, it should be noted that H. ammodendron exhibits dimorphic characteristics, and deep soil water (160–350 cm) and groundwater recharge can enhance its carrying capacity in desert steppe regions, but the model only calculates based on 100 cm soil layer moisture content, potentially slightly underestimating carrying capacity in arid regions. This study selected two typical windbreak and sand-fixation plants for single-species carrying capacity calculation. While the simulation method is reliable, only two typical species were selected, failing to cover other important sand-fixing plants in the region (e.g., Caragana korshinskii, Calligonum mongolicum), with insufficient discussion on multi-species synergistic effects. Therefore, future research should introduce interspecific competition models to conduct mixed forest ecological restoration, incorporating relevant economic crops to achieve both beneficial effects on stand growth and soil and water conservation while realizing ecological restoration and economic benefits. Pilot ecological management work should be conducted in areas with poor plant suitability, combined with relevant soil and water conservation measures, to scientifically implement desertification control projects in the northern wind-sand region.

4 Conclusions

Through integrating the MaxEnt model with the classical water resources vegetation carrying capacity model, this study quantitatively reveals the suitable distribution patterns of typical sand-fixing plants under water constraints and their reasonable planting density thresholds in the northern wind-sand region. The main conclusions are:

1) Plant suitable habitat distribution is dominated by hydrothermal coupling and soil conditions, showing significant spatial heterogeneity. H. ammodendron suitable habitats concentrate in the desert steppe zone, accounting for 19% of the study area, with distribution significantly constrained by low-temperature season drought (precipitation in coldest quarter \$ \$3.9 mm) and suitable mean annual temperature (6.6–9.7°C). P. sylvestris suitable habitats are widely distributed in the eastern Horqin Sandy Land and typical steppe zone, accounting for 48% of the study area, with suitability primarily determined by precipitation supply (precipitation in coldest quarter 15.7 mm, cumulative contribution 16.2%; precipitation in

warmest quarter 288–404 mm) and soil physical structure (rooting conditions contribution reaching 12.8%).

2) Vegetation carrying capacity based on regional water balance shows significant spatial differences, reflecting species’ water use strategies and habitat adaptation differences. H. ammodendron peak carrying capacity in the desert steppe core area can reach >10.0$×10^{4}$ trees · km^{-2}, while P. sylvestris optimal density in the southeastern typical steppe is approximately >1.4$×10^{4}$ trees · km^{-2}. This substantial difference profoundly demonstrates H. ammodendron’ s efficient water use capability as a deep-rooted shrub in extremely arid regions, and P. sylvestris’ s higher soil physicochemical requirements as a tree in relatively humid regions.

3) A precise zoned and quantitative planting density threshold scheme is proposed, providing direct scientific basis for precise desertification prevention and control following the “determining greening based on water availability, matching species to site conditions”principle. Based on overlay analysis of carrying capacity and suitable habitats, recommended spacings are: H. ammodendron in desert steppe zone at 1.5 m × 2.0 m; P. sylvestris in typical steppe zone at 6.5 m × 9.5 m; and in water-limited areas like Horqin Sandy Land, P. sylvestris spacing should be reduced to 10.5 m × 15.0 m. These recommended schemes show high consistency with actual optimized afforestation density data from the Horqin Sandy Land and other areas, with small errors, and can directly serve the planning, design, and implementation of ecological restoration projects such as the “Three-North” Shelterbelt Program.

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Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

Figures

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Figure 4

Figure 3: Figure 4

Figure 5

Figure 4: Figure 5