Construction and Application of a Health Evaluation System for Artificial Haloxylon ammodendron Forests in the Lower Reaches of the Shiyang River: Postprint

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Abstract

Artificial Haloxylon ammodendron forests are the most extensively distributed and largest artificial sand-fixation forests in the lower reaches of the Shiyang River, possessing ecological functions including windbreak and sand fixation, soil amelioration, climate regulation, and carbon sequestration enhancement. In recent years, the widespread degradation of artificial Haloxylon ammodendron forests has posed a serious threat to the ecological security of the Minqin Oasis. Therefore, promptly assessing the health status of artificial Haloxylon ammodendron forests is of great significance for the sustainable management of artificial sand-fixation forests. Through literature review and expert consultation (questionnaire survey), a health evaluation system for artificial Haloxylon ammodendron forests was constructed, comprising 5 primary indicators and 19 secondary indicators, with the weight of each indicator determined using the Analytic Hierarchy Process (AHP) and entropy method. Based on field survey data, the ecological health comprehensive index (HI) was employed to evaluate the health status of artificial Haloxylon ammodendron forests. The results indicate that the artificial Haloxylon ammodendron forests in the lower reaches of the Shiyang River are generally in a sub-healthy state, with health index values ranging from 0.50 to 0.67 and a mean value of 0.617. The primary causes for the sub-healthy state include unreasonable community structure and the influence of habitat factors. It is recommended that tending and management measures such as thinning, stumping, and enclosure be implemented to enhance the stability of artificial Haloxylon ammodendron forests.

Full Text

Abstract

Artificial Haloxylon ammodendron forests represent the most extensive and widely distributed man-made sand-fixing forests in the lower reaches of the Shiyang River, providing critical ecological functions including windbreak and sand fixation, soil improvement, climate regulation, and carbon sequestration. In recent years, widespread degradation of these forests has seriously threatened the ecological security of the Minqin Oasis. Therefore, timely assessment of the health status of artificial H. ammodendron forests is essential for their sustainable management. Through literature review and expert consultation (via questionnaires), we constructed a health evaluation system for artificial H. ammodendron forests comprising five primary indicators and nineteen secondary indicators. The analytic hierarchy process (AHP) and entropy method were employed to determine indicator weights. Based on field survey data, we evaluated forest health status using the ecological health comprehensive index (HI). Results indicate that artificial H. ammodendron forests in the lower reaches of the Shiyang River are generally in a sub-healthy state, with HI values ranging from 0.50 to 0.67 and a mean value of 0.617. The primary causes of sub-health status include unreasonable community structure and habitat factor impacts. We recommend implementing tending measures such as thinning, stubble cutting, and enclosure to enhance forest stability.

Keywords: Lower reaches of Shiyang River; artificial Haloxylon ammodendron forest; health evaluation; analytic hierarchy process; entropy method; sustainable management

1. Introduction

Forest health assessment has long been a research focus worldwide. Forest health represents a state in which forest ecosystems maintain their diversity and stability while continuously meeting human demands for natural, social, and economic benefits, representing a necessary pathway for harmonious coexistence between humans and nature. Forest health evaluation employs appropriate indicator systems to diagnose forest ecosystem health status and assess comprehensive capabilities including productivity, structural condition, resistance to external disturbances, and service functions. Key to forest health assessment is understanding forest baseline conditions and the influence patterns of constructive species attributes and ecological factors on forest organisms.

Evaluation methods primarily include indicator species approach, index system methodology, health distance method, principal component analysis, analytic hierarchy process, fuzzy comprehensive evaluation, and artificial neural networks. Among these, the analytic hierarchy process (AHP) effectively integrates qualitative and quantitative information throughout the comprehensive evaluation process. Consequently, applying combined qualitative-quantitative methods to assess health status of artificial sand-fixing forests in arid regions provides important practical guidance for sustainable management of fragile desert ecosystems. AHP has been widely applied in health assessments of 20-30 year-old *Pinus tabuliformis* plantations in Xining' s north-south mountains, urban landscape trees, and black locust plantations in the Weibei Loess Plateau.

Numerous forest ecosystem health evaluation indicator systems have been established, though variations in study regions, objects, and indicators limit operational practicality and applicability. Indicator systems for windbreak and sand-fixing forests must be based on sand fixation ecology theory, combined with natural conditions of sandy lands and specific forest characteristics, requiring continuous refinement to guide practice. Compared to humid regions, desert ecosystems in northwestern inland areas experience dry climates and severe physical weathering, with vegetation dominated by drought-tolerant and hyper-xerophytic trees, shrubs, and herbs. Overall, desert ecosystems feature simple structure, low vitality, significant stress, and unhealthy or at-risk status, necessitating further development of health assessment systems and methods.

Haloxylon ammodendron, a small tree in the Chenopodiaceae family, exhibits exceptional ecological adaptability, drought resistance, cold tolerance, salt-alkali tolerance, and resistance to soil infertility and wind erosion, making it the preferred species for windbreak and sand-fixing forests in arid regions. Since the late 1950s, large-scale afforestation using drought-resistant shrubs like H. ammodendron began along the Hexi Corridor oasis periphery. To date, artificial H. ammodendron forests in the Hexi Corridor exceed 2×10^{5} hm^{2}, with Minqin County covering 4.35×10^{4} hm^{2} as the earliest and largest planting area. These forests form 2-5 km wide sand-fixing belts around oases to improve soil, enhance biodiversity, modify microclimate, and increase carbon sinks.

Since the 1990s, many artificial H. ammodendron forests have experienced large-scale decline and mortality due to climate aridity, declining groundwater levels, excessive planting density, single species composition, and severe pest infestations, seriously threatening oasis ecological security and requiring restoration measures. Previous research has focused on decline causes, restoration techniques, self-thinning processes, photosynthetic physiology, community characteristics, net carbon exchange, natural regeneration soil conditions, soil seed banks, and succession mechanisms. Chang et al. applied fuzzy discriminant methods to assess health status of Minqin saxaul communities, establishing a degraded plant community evaluation system including plant status indicators, morbidity indicators, diversity indicators, and natural regeneration capacity indicators. However, this system focused only on population biological characteristics without considering habitat factors and human disturbance impacts. Furthermore, evaluation plots had limited spatial distribution and quantity, reducing representativeness. Therefore, this study focuses on artificial H. ammodendron forests in the lower Shiyang River reaches, constructing a health evaluation system through field surveys and data collection based on AHP and entropy methods, employing ecological health index models to assess forest health status and provide theoretical foundations for degraded forest restoration.

2. Study Area

The Minqin Oasis, located in the lower Shiyang River reaches, is surrounded by the Tengger and Badain Jaran deserts on three sides, featuring a typical temperate continental desert climate. The region has a mean annual temperature of 7.4°C ($ 10°Caccumulatedtemperatureof3248.8°C), meanannualprecipitationof113mm(concentratedinsumm
s^{-1}$ (northwest prevailing winds), with 25 annual sandstorm days (most frequent in spring). The lower Shiyang River lies in a transitional zone from arid steppe to desert, with 389 natural seed plant species comprising typical Gobi desert elements and some steppe-desert species. Artificial H. ammodendron forests dominate Minqin’ s windbreak and sand-fixing forests, accounting for 51.5% of total artificial forest area. Zonal soils are gray-brown desert soils, with azonal soils including aeolian sandy soils, meadow soils, and meadow swamp soils; irrigation-silt soils are the main cultivated soils.

3. Methods

3.1 Field Survey Design

Taking typical artificial H. ammodendron forests at the ecotone between Minqin Oasis and Badain Jaran Desert as the study object, we conducted comprehensive ecological surveys of community structure, habitat conditions, human disturbance, and pest damage using a combination of transect and quadrat methods [Figure 1: see original paper]. Along the groundwater depth gradient from the oasis periphery to Qingtu Lake, we established 6 survey transects (Table 1), with 7-8 random 100 m × 100 m sample plots at 500 m intervals along each transect (41 total plots). Within each plot, we established three 10 m × 10 m shrub quadrats, and within each shrub quadrat, three 1 m × 1 m herb quadrats along diagonals. We measured tree/shrub height and crown diameter using measuring rods and steel tapes, herb density through 1 m × 1 m sub-quadrats, vegetation layer structure, and calculated species richness, diversity, and evenness indices. Habitat factor surveys recorded plot latitude, longitude, and elevation. Wind prevention efficiency was calculated using Esh = (Vh - Vsh)/Vh × 100%, where Esh represents wind prevention efficiency at distance s and height h behind the forest belt, Vh is the average wind speed at height h in the control area, and Vsh is the average wind speed at distance s and height h behind the forest belt (s = 1.5 m, h = 0.5 m during surveys). Sand fixation capacity was represented by sand fixation efficiency ($\mathrm{kg \cdot plant^{-1}}$), calculated as sand dune volume per unit fresh weight of H. ammodendron branches. Soil and water conservation was measured through wind erosion status using erosion pins.

3.2 Evaluation Indicators Acquisition

Soil physicochemical properties: Soil water content was measured using the oven-drying method; soil organic matter by potassium dichromate volumetric method; total nitrogen by Kjeldahl method; available phosphorus by molybdenum-antimony colorimetry; soil mechanical composition by Malvern laser particle size analyzer; soil pH by potentiometric method; water-soluble calcium and magnesium by EDTA complexometric titration; and water-soluble salt by double indicator method.

Health risk survey: Pest damage incidence, dead branch degree, and disease severity were obtained through field investigation.

External disturbance survey: Human management and livestock damage were obtained through interviews with local residents.

3.3 Indicator System Construction

Forest health evaluation methods vary by country, evaluation principles, and region. All factors affecting artificial H. ammodendron forest health should be considered while avoiding indicator redundancy. No unified evaluation system currently exists for saxaul forests. Based on relevant research and Minqin' s actual conditions, we initially determined evaluation indicators through literature review, distributed questionnaires to 10 experts (receiving 8 valid responses), adjusted the indicator system based on expert feedback, and redistributed questionnaires (10 sent, 9 valid). Experts quantified indicator grades and weights, ultimately establishing a systematic evaluation framework under five primary indicators: community structure, community function, health risk, habitat factors, and external disturbance [Figure 2: see original paper]. Combined with field survey data, we assessed forest health status using mathematical statistics.

Community structure: Healthy artificial H. ammodendron forests should have relatively complex community structure, typically including species diversity, vegetation layer structure, species richness index, and evenness index.

Community function: Community function is crucial for sustainable production and ecological environment maintenance in arid sandy regions. Windbreak and sand fixation functions are vital for stable, high-yield farmland in these areas. Soil crusts within H. ammodendron forests reduce wind erosion and protect against sand burial, but also limit water infiltration, accelerate soil drought, and consequently accelerate population decline. Additionally, soil crusts affect annual plant establishment and growth, altering species composition despite no significant difference in species numbers compared to mobile dunes.

Health risk: Rodent damage poses the greatest threat to artificial H. ammodendron forests. *Rhombomys opimus* damage includes: branch gnawing affecting plant growth; root hollowing and severing, which is fatal to saxaul; and burrowing that loosens sand layers, disrupts soil water flow, accelerates dune drying, and cuts water supply. Additionally, pest and disease outbreaks, primarily powdery mildew (covering green shoots with white mycelium in summer-autumn) and noctuid moth infestations and galls, significantly impact forest health by slowing growth.

Habitat factors: Insufficient soil water supply is a primary cause of artificial H. ammodendron forest decline in Minqin. Soil physicochemical properties including total nitrogen, organic matter, and pH also substantially affect forest growth by influencing physiological-ecological balance.

External disturbance: Overgrazing and fuelwood collection are the primary external disturbances affecting artificial H. ammodendron forest health.

3.4 Weight Determination

Analytic Hierarchy Process (AHP): We invited 10 ecology and forestry experts to score indicator weights (10 questionnaires distributed, 9 valid responses). Using yaahp software, we obtained weight judgment matrices, calculated maximum eigenvectors, and derived indicator weights.

Entropy method: The entropy method objectively describes indicator importance based on concentration within the model, offering relatively high accuracy suitable for fragile arid environment evaluation.

Combined weighting: Since AHP and entropy methods have distinct characteristics, combining them provides more realistic weights using the formula: $Q = aQ_1 + (1\text{-}a)Q_2$, where Q represents combined weight, Q_1 represents AHP weight, and Q_2 represents entropy weight. Results showed consistent trends between methods, with vegetation layer structure, tree height, species richness index, dead branch degree, shrub crown diameter, soil water content, diversity index, and tree crown diameter receiving higher weights. Vegetation layer structure achieved the highest combined weight at 0.12, while herb height, herb density, and livestock damage received lower weights, with livestock damage at only 0.02.

3.5 Evaluation Model Construction

We adapted the ecosystem health index model HI = V × O × R, calculating artificial H. ammodendron forest health index using:

$$HI = \sum_{i=1}^{5} W_i \left(\sum_{j=1}^{n} W_{ij} \times S_{ij} \right)$$

where HI represents the artificial H. ammodendron forest health comprehensive index; O, f, r, S, and U represent community structure, community function, health risk, habitat factor, and external disturbance indices, respectively; S represents scores of secondary indicators; W represents weights of secondary indicators; and W represents weights of primary indicators.

We also calculated primary indicator health values (X) as the sum of products between secondary indicator weights and scores:

$$X = \sum_{j=1}^{n} W_{ij} \times S_{ij}$$

3.6 Health Status Classification

Following forest health classification by Lu et al., we divided artificial H. ammodendron forest health status in the lower Shiyang River into five grades .

4. Results

4.1 Health Status of Artificial H. ammodendron Forests

Community structure: Among 41 sample plots, 29 scored above 0.6, primarily distributed in Qingtu Lake and Fu Gong, accounting for 70.73% of total plots; 10 plots scored 0.6-0.7; and 2 plots scored below 0.6, mainly in Longwangmiao and Zhisha Station.

Community function: Twenty-three plots scored above 0.6, primarily in Qingtu Lake, accounting for 56.10% of total plots; 15 plots scored 0.6-0.7, mainly in Songhe; and 3 plots scored below 0.6, distributed in Sanjiaocheng.

Health risk: Thirty-four plots scored above 0.6, primarily in Qingtu Lake, accounting for 82.93% of total plots; 5 plots scored 0.6-0.7; and 2 plots scored below 0.6, distributed in Sanjiaocheng.

Habitat factors: Thirty plots scored above 0.6, primarily in Qingtu Lake, accounting for 73.17% of total plots; 9 plots scored 0.6-0.7, mainly in Zhisha Station and Songhe; and 2 plots scored below 0.6, distributed in Sanjiaocheng.

External disturbance: Twenty-five plots scored above 0.6, primarily in Qingtu Lake and Fu Gong, accounting for 60.98% of total plots; 12 plots scored 0.6-0.7; and 4 plots scored below 0.6, distributed in Songhe and Longwangmiao [Figure 4: see original paper].

Primary indicator weights ranked as: community structure > habitat factors > health risk > community function > external disturbance, indicating community structure most significantly affects forest health while external disturbance has minimal impact. Based on the ecological health index model, artificial H. ammodendron forest health indices ranged 0.50-0.70, with 13 plots in unhealthy condition (31.71%) and the remainder in sub-health condition. No plots achieved healthy or excellent health status [Figure 5: see original paper].

4.2 Causes of Sub-health Status

Analysis of transect health status showed Qingtu Lake transect had the best quality (HI = 0.6-0.7), while Zhisha Station had the poorest (HI = 0.5-0.6). Among 6 transects, 2 were unhealthy (33.33%) and 4 were sub-healthy. Unhealthy plots at Zhisha Station and Longwangmiao scored above 0.6 only for health risk and community function, with all other primary indicators below 0.6, particularly habitat factors at only 0.4. Research indicates long-term soil drought is the primary cause of H. ammodendron forest decline in the lower Shiyang River. Although Qingtu Lake transect has relatively abundant water sources (possibly contributing to higher HI), habitat factor weight was not the highest among primary indicators, suggesting soil drought is not the most critical factor. However, water cannot be ignored—large-scale well drilling for irrigation should be halted to prevent further groundwater decline.

Community structure scores for unhealthy Zhisha Station and Longwangmiao plots were 0.4-0.5. These plots had the highest forest densities, causing insufficient nutrients and water per tree. Since community structure carries the highest weight among primary indicators, maintaining appropriate planting density is crucial for forest health. Additionally, external disturbance scores averaged below 0.6 across all transects. Continuous overgrazing has caused vegetation degradation and desertification, disrupting natural succession processes. Fixed dunes now feature numerous annual plants but fewer perennials, with mesic and xeric species coexisting and original mesic species becoming xerophytic. Management should enhance ecological awareness, strengthen human management and protection, and reduce livestock damage including malicious cutting and grazing.

5. Discussion

Indicator system scientific validity: First, the constructed indicator system is applicable for evaluating artificial H. ammodendron forests in the lower Shiyang River. The single evaluation object enhances scientific validity of results. Second, explicit weight allocation reflects importance and evaluation priorities of primary indicators. Combined subjective-objective weighting reduces subjectivity from expert scoring while reflecting each indicator' s importance. Finally, following AHP hierarchical structure requirements, indicators selected from five aspects form an organic whole that scientifically evaluates forest health status.

Systematic nature and applicability: The comprehensive indicator system includes five primary aspects, greatly improving operational feasibility and providing technical support for health evaluation. Indicators were selected based on relevant research and Minqin forest degradation characteristics, including wind prevention efficiency, dead branch degree, rodent damage incidence, pest/disease proportion, and groundwater level. This system targets small-scale evaluation; applicability should be fully considered for county-level or larger assessments.

Health standard values: Due to climate condition variations (e.g., rainfall, wind force) in the lower Shiyang River, health standard values are not uniform. Results represent overall quality scores. To expand application scope and applicability, we distributed a second questionnaire to experts, dividing thresholds into five grades based on actual district/county conditions (10 questionnaires sent, 90% valid). Artificial H. ammodendron forest health index values reaching 0.70-0.75 indicate healthy status, while 0.65-0.70 represents sub-health. Introducing different natural conditions into the evaluation system allows assessment of forest health across Hexi Corridor districts/counties for better construction and management.

Data limitations: Research data derive from short-term surveys lacking long-term monitoring and evaluation, preventing accurate predictions of health trends and sustainability. Long-term regional monitoring is needed for future direction and sustainability studies. Additionally, some indicator data acquisition has limitations—for example, soil and water conservation was measured indirectly through wind erosion status rather than directly obtaining soil erosion modulus.

6. Conclusions

Through ecological field surveys and laboratory analysis, we obtained baseline indicator data and constructed an artificial H. ammodendron forest health evaluation system based on previous research. Using combined AHP and entropy methods for weighting and the HI model for health index calculation, we evaluated forest health status in the lower Shiyang River to inform management and achieve sustainable development. Conclusions are:

1) Based on literature review and field surveys, we constructed a health evaluation system specific to the lower Shiyang River artificial H. ammodendron forests, incorporating five primary indicators (community structure, community function, health risk, habitat factors, external disturbance) and secondary indicators including diversity index, evenness index, rodent damage incidence, and pest/disease degree. The system combines subjective and objective weighting methods, integrates wind prevention function, forest health status, and external disturbances, features strong data accessibility, simple calculation, and good operational feasibility.

2) Artificial H. ammodendron forests in the lower Shiyang River are generally sub-healthy (mean HI = 0.617), with 31.71% of plots unhealthy and 68.29% sub-healthy. No plots achieved healthy or excellent status. Sub-health causes include unreasonable community structure and habitat factor impacts. Management should enhance ecological awareness, strengthen protection, reduce livestock damage and malicious cutting, halt large-scale well drilling, prevent groundwater decline, and maintain appropriate planting density in future afforestation.

3) To expand the indicator system' s application scope and applicability, we classified health index values into five grades based on wind force and precipitation indicators, corresponding to different natural conditions across districts/counties, thereby providing more reliable scientific support for artificial H. ammodendron forest construction and management.

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Note: Figure translations are in progress. See original paper for figures.