Species Diversity and Soil Moisture Variation Characteristics in Minqin Clay Sand Barriers and Artificial Haloxylon Forests: Postprint

Authors: Song Dacheng, Ma Quanlin, Liu Shiquan, Wei Linyuan, Wu Hao, Duan Xiaofeng, Guo Shujiang

Date: 2024-06-12T00:00:00+00:00

Abstract

Using clay sand barrier-artificial Haloxylon ammodendron forest sample plots with six different installation years (1 a, 5 a, 10 a, 20 a, 40 a, 60 a) and mobile sandy land (control) in the Minqin desert area as the research object, we investigated species composition, importance value, characteristics of dominant populations, species diversity, and soil moisture content to explore the long-term effects of clay sand barrier-artificial Haloxylon ammodendron forest construction on regional plant community structure, species diversity, and soil moisture. The results showed that a total of 12 plant species belonging to 12 genera and 6 families were recorded in the survey plots of clay sand barrier-artificial Haloxylon ammodendron forest in the Minqin desert area, predominantly from Chenopodiaceae and Zygophyllaceae. The construction of artificial sand-fixation systems could significantly increase the number of regional plant species (from 4 species to 5-8 species), and with the extension of installation years, the dominant species gradually evolved from Agriophyllum squarrosum and Haloxylon ammodendron to Grubovia dasyphylla, Kali collinum, Limonium aureum, and Haloxylon ammodendron, while life forms also shifted from a single type dominated by annual herbs to a composite type comprising annual herbs + perennial herbs + shrubs. Species richness index, Shannon-Wiener index, Simpson index, Pielou index, and Alatalo index generally exhibited a unimodal variation trend, with the highest number of species and most even species distribution at 20 a installation, and the lowest number of species and poorest evenness in the control sandy land. The Jaccard index of plant communities in different sample plots showed the following pattern: control sandy land vs. 1 a installation plot > 20 a installation plot vs. 40 a installation plot > 1 a installation plot vs. 5 a installation plot > 10 a installation plot vs. 20 a installation plot > 40 a installation plot vs. 60 a installation plot > 5 a installation plot vs. 10 a installation plot, while dissimilarity index and Cody index showed opposite patterns. The fluctuation trend

of regional soil water content was consistent with plant community succession trends, and compared with deeper soil layers (40-60 cm), shallow soil layers (10-30 cm) played a more significant role in the regional plant natural succession process.

Full Text

Species Diversity in Minqin Clay Sand Barrier-Artificial Haloxylon ammodendron Plantations and the Characteristics of Soil Moisture Changes

SONG Dacheng[1,2], MA Quanlin[3], LIU Shiquan[1], WEI Linyuan[1], WU Hao[1], DUAN Xiaofeng[1], GUO Shujiang[1]

[1]Gansu Desert Control Research Institute, Lanzhou 730070, Gansu, China
[2]College of Forestry, Gansu Agricultural University, Lanzhou 730070, Gansu, China
[3]Gansu Academy of Forestry Sciences, Lanzhou 730000, Gansu, China

Abstract

This study investigated the species composition, importance values, dominant population characteristics, species diversity, and soil moisture content across five clay sand barrier-artificial Haloxylon ammodendron plantation sites with different establishment years (1, 5, 10, 20, 40, and 60 years) and a mobile sand dune (control) in the Minqin desert region. The objective was to explore the long-term effects of clay sand barrier-artificial Haloxylon ammodendron plantation construction on regional plant community structure, species diversity, and soil moisture. The results revealed that a total of 12 plant species belonging to 12 genera and 6 families were recorded in the clay sand barrier-artificial Haloxylon ammodendron plantations in the Minqin desert area, with Chenopodiaceae and Zygophyllaceae being the dominant families. The construction of the artificial sand control system significantly increased the number of plant species in the region (from 4 species in the control to 5–8 species in the plantations). As the establishment period extended, the dominant species gradually shifted from Agriophyllum squarrosum and Haloxylon ammodendron to Grubovia dasyphylla, Kali collinum, Limonium aureum, and Haloxylon ammodendron. Concurrently, the life forms evolved from a single type dominated by annual herbs to a composite type comprising annual herbs, perennial herbs, and shrubs. The species richness index, Shannon-Wiener index, Simpson index, Pielou index, and Alatalo index all exhibited a unimodal trend, peaking at the 20-year establishment site where species richness and evenness were highest, while the control sand site showed the lowest species number and poorest distribution uniformity. The Jaccard index of similarity between different sites demonstrated the following pattern: control sand site vs. 1-year site > 1-year vs. 5-year sites > 10-year vs. 20-year sites > 5-year vs. 10-year sites > 40-year vs. 60-year sites > 20-year vs. 40-year sites > 1-year vs. 10-year sites > 5-year vs. 20-year sites > 1-year vs. 40-year sites > 10-year vs. 40-year sites > 1-year vs. 20-year sites > 5-year vs. 40-year sites > 10-year vs. 60-year sites > 1-year vs. 60-year sites > 20-year vs. 60-year sites. The dissimilarity index and Cody index showed the opposite trend. The fluctuation pattern of regional soil moisture content aligned with the trend of plant community succession, and compared with deeper soil layers (40–60 cm), shallow soil layers (10–30 cm) played a more significant role in the natural succession process of regional vegetation.

Keywords: clay sand barrier; artificial Haloxylon ammodendron plantation; species diversity; soil moisture; Minqin

1 Introduction

The response of biodiversity to environmental factors has long been a central focus and core issue in community ecology research. Rich species diversity can significantly enhance the stability of regional plant communities and promote ecosystem function. Alpha (α) and beta (β) diversity indices serve as key metrics for measuring community diversity. The α diversity index primarily reflects species composition within a community and is commonly used to analyze species richness and evenness, while the β diversity index measures compositional dissimilarity between communities, providing a method to quantify spatiotemporal differences in community composition. Studying α and β diversity characteristics of plant communities is crucial for revealing the evolution of community and ecosystem structure and function. As the primary source of energy and material cycling in ecosystems, soil moisture content significantly influences plant community composition, species distribution, and plant species diversity changes in arid and semi-arid regions. Spatial heterogeneity of soil moisture is one of the main soil properties, and its variation profoundly impacts regional vegetation patterns. In recent years, increasing research has focused on how vegetation growth in arid regions affects the soil moisture ecological environment, and investigating regional soil moisture content and its spatial heterogeneity will help understand vegetation succession processes, thereby providing references for artificial vegetation construction and management.

Minqin is located in the northeastern part of the Hexi Corridor in Gansu Province, surrounded by the Tengger and Badain Jaran Deserts on its west, north, and east sides. As a critical zone in the Hexi Corridor, the Minqin Oasis serves as an effective ecological barrier for Wuwei and even the entire Hexi Corridor, playing important roles in ensuring food security and maintaining ecological barrier functions. Since the mid-20th century, combined natural and anthropogenic factors have gradually weakened the ecological functions of the Minqin Oasis, with continuous environmental degradation, expanding desertification, and increasingly prominent ecological problems. As a representative region for sand control in China, Minqin County has kept pace with national efforts for many years, representing the development process and level of sand control in China to a certain extent. Since the initiation of mass afforestation and sand control in the 1950s, rich achievements and practical experience have been accumulated, and many advanced and practical sand control technologies have been created. After decades of development and improvement, the sand control model of using "clay sand barriers + artificial Haloxylon ammodendron plantations" to control moving sand, promote seed settlement and growth while fixing sand, and eventually form a biological-engineering composite sand fixation system through later-stage plant community formation has been widely applied across vast sandy areas in the Hexi Corridor and Inner Mongolia with significant results. Since the "clay sand barrier + artificial Haloxylon ammodendron plantation" model originated in Minqin, Gansu, there are few related international research reports, with most studies focusing on domestic research results concentrated on barrier specifications and wind erosion effects. Existing research has confirmed that in the early installation period, clay sand barriers can positively influence regional plant growth and development. However, specific and in-depth studies on changes in plant species diversity and differences in soil moisture at different depths under long-term time scales are still lacking. Therefore, this paper takes the nearly 60-year-old clay sand barrier-artificial Haloxylon ammodendron plantations in the Minqin desert as the research object. Through field investigation, sampling, and laboratory analysis, using α and β diversity indices and soil moisture content as evaluation indicators, this study analyzes the changing trends of regional plant community structure, species diversity, and soil moisture content with establishment years, aiming to explore the restoration trajectory of regional vegetation and soil with establishment years and provide theoretical basis for windbreak and sand fixation system construction and optimization of artificial sand control projects in arid desert regions.

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2 Materials and Methods

2.1 Study Area Overview

This study was conducted at the Minqin Comprehensive Desert Control Experimental Station (38°35 N, 102°58 E) in Gansu Province. The study area is located on the southeastern edge of the Badain Jaran Desert and features a typical temperate continental desert climate with abundant sunshine, frequent winds, little rainfall, dry conditions, strong evaporation, and large diurnal temperature variations. The average annual sunshine duration is approximately 2,800 hours, with an average annual temperature of 7.6°C. The average annual precipitation is about 110 mm, mostly concentrated in July-September, accounting for 70% of the annual precipitation. The average annual evaporation reaches 2,600 mm. The annual sandstorm duration is about 28 days, mostly concentrated in March-May, with an average annual wind speed of 2.5 $m \cdot s^{-1}$ and maximum wind speed of 20 $m \cdot s^{-1}$. The study area is dominated by semi-fixed sand dunes, with vegetation primarily consisting of desert shrublands and grasslands. Dominant shrubs include Nitraria tangutorum, Calligonum mongolicum, and Haloxylon ammodendron, while dominant herbaceous plants mainly include Agriophyllum squarrosum, Grubovia dasyphylla, and Kali collinum.

2.2 Experimental Design

To explore the long-term effects of clay sand barrier-artificial Haloxylon ammodendron plantations on vegetation community succession, five clay sand barrier-artificial Haloxylon ammodendron plantation sites with different establishment years (1, 5, 10, 20, 40, and 60 years) and one control sand site were selected as survey plots based on preliminary investigations and multiple field surveys. All plots were distributed within the geographic coordinates of 102°55 -102°58 E and 38°34 -38°37 N, with elevations ranging from 1,317 to 1,330 m and soils consisting of aeolian sandy soil. Along the diagonal direction of each plot, three 10 m × 10 m shrub survey quadrats were established, and within each shrub quadrat, three 1 m × 1 m herbaceous survey quadrats were set up along the diagonal direction. Species, quantity, height, coverage, and frequency of shrubs and herbaceous plants in each quadrat were measured and recorded. The selected plots were consistent in altitude, topography, and soil type, with similar seedling management measures. All plots were widely distributed in similar spaces, with distances between plots of different establishment years greater than 500 m to avoid spatial autocorrelation.

Soil sample collection points were established beside each shrub survey quadrat for soil sampling, with soil depths covering 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, and 50–60 cm gradients. During sampling, six soil samples from the same plot and same soil layer were mixed uniformly and brought back to the laboratory.

2.3 Measurement Indicators and Methods

2.3.1 Importance Value The importance value (IV) was calculated as: IV = (relative height + relative coverage + relative frequency).

2.3.2 Species α Diversity Indices Six commonly used indices were selected to characterize species α diversity: species richness index (R), Shannon-Wiener index (H), Simpson index (D), Pielou index (J), Alatalo index (Ea), and dominance index (C). The specific formulas were:

- **Species richness index**: R = S (where S is the total number of species)
- **Shannon-Wiener index**: H = - (Pi ln Pi)
- **Simpson index**: D = 1 - (Pi^2)
- **Pielou index**: J = H /ln(S)
- **Alatalo index**: Ea = [exp(H) - 1]/[exp(- ni ln(ni/N)) - 1]
- **Dominance index**: C = $(ni/N)^2$

Where: ni represents the number of individuals of species i; N represents the total number of individuals of all species; Pi = ni/N; and S is the total number of species.

2.3.3 Species β Diversity Indices The Jaccard index (Cj), community dissimilarity index (Cd), and Cody index (βc) were selected to characterize species β diversity. The specific formulas were:

- **Jaccard index**: Cj = j/(a + b - j)
- **Community dissimilarity index**: Cd = (a + b - 2j)/(a + b - j)
- **Cody index**: βc = [g(H) + l(H)]/2

Where: a and b represent the number of species in two quadrats; j is the number of shared species between two communities; g(H) is the number of species gained along the habitat gradient H (species present in the next gradient but not in the previous one); and l(H) is the number of species lost along the habitat gradient H (species present in the previous gradient but not in the next one).

2.3.4 Soil Moisture Content Soil moisture content was determined using the constant temperature oven drying method, expressed as weight percentage: Soil moisture content (%) = (wet soil weight - dry soil weight)/dry soil weight × 100%.

2.4 Data Analysis and Processing

Data processing and analysis were performed using Excel 2020 and SPSS 23.0 software. The R 3.6.0 software (R Development Core Team) with the Vegan package was used for index calculation and plotting, and the Fossil package was used for additional analysis. All statistical significance levels were set at $P < 0.05$.

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3 Results and Analysis

3.1 Species Composition and Characteristics of Plant Communities

A total of 12 plant species were recorded across the six survey plots in the study area, belonging to 12 genera and 6 families. Annual herbaceous species accounted for the highest proportion (7 species), followed by shrub species (4 species), with perennial herbaceous species being the least represented (1 species). The species composition and importance values of plant communities in different plots are shown in .

With the extension of the establishment period, the number of plant species gradually increased, peaking at the 20-year site, then began to decline at the 40-year site, and finally decreased at the 60-year site, though still remaining higher than the control sand site. In terms of life forms, the control sand site and the 1-year site were similar, both characterized by annual herbaceous plants + shrubs, dominated by Grubovia dasyphylla, Kali collinum, and Haloxylon ammodendron. In contrast, as the establishment period extended and sand fixation effects became apparent, other sites saw the addition of annual herbaceous species such as Eragrostis pilosa and Echinops gmelini, as well as the emergence of perennial herbaceous species (Limonium aureum) and shrub species (Calligonum mongolicum and Zygophyllum xanthoxylon), forming a more stable composite pattern of annual herbs + perennial herbs + shrubs.

Dominant species varied among different plots. For example, Agriophyllum squarrosum, as a native species well-adapted to the study area, was widely distributed across plots, particularly in the control plot where it had a high importance value (0.832) and served as the dominant species. However, after establishing the clay sand barrier-artificial Haloxylon ammodendron plantation, its importance value gradually decreased, while that of Grubovia dasyphylla increased, eventually replacing Agriophyllum squarrosum as the dominant species in the plant community. Compared with the control plot, the middle and late establishment periods showed increases of 139.13% and 58.70%, respectively. Further analysis of species importance values revealed that in the clay sand barrier plots, the importance values of annual herbaceous plants generally showed a fluctuating decline, while those of perennial herbaceous plants and shrubs showed a fluctuating increase. Compared with herbaceous layer plants, shrub layer plants exhibited smaller dispersion in importance values and were overall more stable.

3.2 Characteristics of Plant Community α Diversity

The α diversity of plant communities varied significantly among plots in the study area. As shown in , species richness, Shannon-Wiener index, Simpson index, and Pielou index showed similar unimodal trends, peaking at the 20-year establishment site and reaching their lowest values at the control sand site. The overall pattern across different plots was: 20-year > 10-year > 60-year > 40-year > 5-year > 1-year > control sand site. Compared with the control sand site, plant species increased significantly after establishing the clay sand barrier-artificial Haloxylon ammodendron plantation, rising from 4 species in the control to 5–8 species in the treatment plots.

The Alatalo evenness index showed a different pattern, being highest at the 20-year site, but also relatively high at the control sand site and 1-year site, which was mainly due to different analytical focuses. Additionally, calculation of the ecological dominance index for each plot revealed an overall U-shaped trend, with the highest value at the control sand site (0.832) and the lowest values at the 10-year (0.240) and 20-year (0.254) sites. This indicated that species distribution was uneven in the control sand site, with dominant species such as Agriophyllum squarrosum having prominent status, while this phenomenon was effectively alleviated with increasing establishment years.

3.3 Characteristics of Plant Community β Diversity

The Jaccard similarity coefficient, community dissimilarity index, and Cody index were used to analyze plant community β diversity (see). The results showed that the Jaccard similarity coefficient was highest between the control sand site and the 1-year site (0.667), followed by the 1-year and 5-year sites (0.625), and lowest between the 20-year and 40-year sites (0.250). The community dissimilarity index and Cody index showed opposite trends. The dissimilarity index was highest between the 20-year and 40-year sites (0.750), while the Cody index was highest between the 10-year and 20-year sites (3.500). Both methods showed low values between the 40-year and 60-year sites.

3.4 Effects of Establishment Years on Soil Moisture

Analysis of soil moisture content in different samples (see [Figure 1: see original paper]) revealed that the control sand site had the lowest average soil moisture content in the 0–60 cm layer (5.45%), while other establishment year sites showed average moisture contents of 15.32%, 10.74%, 7.41%, 7.11%, and 6.97%, representing increases of 181.10%, 97.06%, 35.96%, 30.46%, and 27.75% compared with the control, respectively. The overall soil moisture content showed a decreasing trend with increasing establishment years. Correlating establishment years with average soil moisture content revealed that regional soil moisture could be roughly divided into three gradients: higher content in the early establishment period (1-10 years), an overall decline in the middle period (20 years), and the lowest content in the late period (40–60 years) and the control sand site, with relatively low variation amplitude.

Correlation analysis between plant community species diversity and soil moisture content (see [Figure 2: see original paper]) indicated that soil moisture had a positive effect on regional plant species diversity, with varying degrees of correlation between soil moisture at different depths and plant species diversity. Specifically, soil moisture in the 10–20 cm and 20–30 cm layers had significant effects on Shannon-Wiener, Simpson, and Pielou indices ($P < 0.05$), while soil moisture in the 0–10 cm layer had extremely significant effects on these indices ($P < 0.01$). Soil moisture in the 40–60 cm layer only significantly affected the Pielou index ($P < 0.05$). The correlations between soil moisture and species diversity in the two deeper soil layers (30–40 cm and 40–60 cm) were not significant ($P > 0.05$).

The degree of differentiation in soil moisture content among different soil layers was closely related to the average soil moisture content. Higher average moisture content corresponded to greater differentiation among soil layers, while lower average moisture content showed smaller differences between layers. Overall, the control sand site, 1-year site, and 60-year site showed the lowest variation, with minimal differences in soil moisture across depths. The 20-year site had the highest average soil moisture content and the greatest differences among soil depths. Other sites showed fluctuations but remained relatively stable. Changes in soil moisture content among different soil depth samples were particularly evident at the 20-year and 40-year sites.

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4 Discussion

4.1 Effects of Establishment Years on Plant Community Structure

The shrub layer in the study area was dominated by Haloxylon ammodendron, while the herbaceous layer consisted mainly of annual herbs such as Grubovia dasyphylla, Agriophyllum squarrosum, and Kali collinum, with only one perennial herb species (Limonium aureum). The effects of artificial sand control system construction on plant community composition were mainly reflected in the following aspects: it facilitated an increase in plant species within the region, with varying degrees of improvement compared with the control sand site. A total of 12 plant species appeared in the sand fixation area, an increase of 8 species compared with the 4 species in the control site. During the 10–40 year establishment period, as perennial herb Limonium aureum and shrub species such as Nitraria tangutorum, Calligonum mongolicum, and Zygophyllum xanthoxylon became established, the plant community reached a stable state, forming a composite pattern of annual + perennial herbs + shrubs. The number of plant species in the sand fixation area also peaked during this period. After 40–60 years, plant species began to decline, eventually becoming similar to the control sand site at 60 years. The overall plant species within the barriers experienced a process of increase (1–10 years) -stability (10–40 years) -decline (40–60 years). This indicates that the effective protection period of clay sand barrier-artificial Haloxylon ammodendron plantation systems is limited. After 40 years, the system no longer benefits the stable development of regional plant communities, and technical measures such as replanting should be implemented according to actual needs to extend the protection cycle.

The α diversity survey results showed that plant community α diversity indices in the study area were relatively low, with Shannon-Wiener diversity indices ranging from 0.14 to 1.10, Simpson indices from 0.07 to 0.63, Pielou evenness indices from 0.14 to 0.90, Alatalo evenness indices from 0.24 to 0.83, and dominance indices from 0.01 to 0.83. These results are consistent with findings from the southeastern edge of the Tengger Desert, indicating that plant species diversity levels are generally low in arid and semi-arid regions, with fewer community species and lower community structure stability. Additionally, Agriophyllum squarrosum, as the dominant species in the control sand site and early sand control stages, was gradually replaced by Grubovia dasyphylla with increasing establishment years, consistent with the findings of Li et al., mainly due to differences in plot establishment years during site selection.

4.2 Effects of Establishment Years on α Diversity

The establishment of mechanical sand barrier-artificial sand fixation plant systems can increase vegetation richness, coverage, and density, but effects vary significantly among different systems. Among various mechanical sand barrier models, clay sand barriers have longer effective protection periods and, through multi-year effect accumulation, are more conducive to increasing α diversity and coverage of plants within the barriers. However, most existing studies have focused only on the early installation period of clay sand barriers, and understanding of the evolution 规律 of sand fixation vegetation under long-term time scales remains insufficient. Currently, there are two main viewpoints regarding plant community succession accompanied by diversity changes: one suggests that diversity continuously increases with community succession, while the other argues that diversity increases from early to mid-succession, peaks, and then decreases during late succession. In this study, compared with the control sand site, the early establishment period (1-10 years) significantly increased regional plant species richness while effectively promoting balanced development among various plant species, which is more conducive to community stability enhancement. However, with increasing establishment years, especially after 10 years, regional plant community α diversity began to decline, eventually reaching low values at 40–60 years, though still better than the control sand site. The vegetation experienced a process of increasing and then decreasing coverage during its evolution from artificial to natural systems.

The rapid growth period of plant species mainly occurred during the 5–10 year establishment stage, when annual herbs such as Corispermum patelliforme, Eragrostis pilosa, and Echinops gmelini began to appear in large numbers, while the perennial herb Limonium aureum also gradually appeared and stabilized. During the 10–40 year period, as shrubs such as Nitraria tangutorum, Calligonum mongolicum, and Zygophyllum xanthoxylon and the perennial herb became established, a relatively stable plant community of annual + perennial herbs + shrubs formed. After 40–60 years, as the lifespans of some shrub and perennial herb species ended, species numbers gradually declined. Annual herbs have strong adaptability and can rapidly complete their life cycles even with limited precipitation. Perennial herbs and shrubs have stronger environmental resistance than annual herbs, and their populations are more stable. The relative changes between shrubs and herbs are mainly the result of water competition and water environment adaptation. Ding et al. confirmed that after 10 years of clay sand barrier establishment, the preservation rate was about 31.78%, soil moisture content decreased by 7.6% compared with mobile sand dunes, and plant community structure shifted from drought-resistant shrubs and semi-shrubs to ephemeral plants. This indicates that clay sand barrier-artificial Haloxylon ammodendron plantations mainly affect regional plant evolution processes by altering the soil moisture environment within the barriers.

4.3 Effects of Establishment Years on β Diversity

Beta diversity can characterize species turnover rates along environmental gradients. The fewer shared species between two communities, the higher the β diversity and the greater the turnover rate. Among the many methods for calculating β diversity, the Jaccard index has been most frequently applied. After establishing clay sand barrier-artificial Haloxylon ammodendron plantations, as sand fixation effects continued to play a role, regional environmental gradient differences continuously increased, thereby affecting regional plant population dynamics, interspecific relationships, and species succession, leading to significant changes in plant species composition along the 1-60 year time series. Jaccard index analysis results showed that clay sand barrier-artificial Haloxylon ammodendron plantations could change plant community composition after just 1 year of establishment, but many shared species still existed compared with the control sand site. The rapid growth period of plant species mainly occurred during 5-10 years, and the region had formed a relatively stable plant community of annual + perennial herbs + shrubs by 20–40 years, with similar species composition among plots, resulting in high community similarity coefficients and low community dissimilarity coefficients. After 40–60 years, as the lifespans of some shrub and perennial herb species ended, species numbers gradually declined. The Jaccard index between the 60-year site and the control sand site reached 0.429, indicating that plant species within the barriers became more similar to those in the control sand site, and the plant community overall declined to the same level as the control sand site. Additionally, since the latitude, longitude, altitude, sand barrier specifications, and seedling management were similar across plots, differences in β diversity were mainly caused by different establishment years. The early establishment period could significantly increase surface roughness, increase dust content in surface soil, regulate precipitation infiltration, and enhance soil evaporation, leading to environmental gradient differences that could increase regional species β diversity. However, with increasing establishment years, the protection effect of clay sand barrier-artificial Haloxylon ammodendron plantations gradually deteriorated, exacerbating differences in β diversity among plots.

4.4 Effects of Establishment Years on Soil Moisture

The study area is located on the southeastern edge of the Badain Jaran Desert, characterized by a typical temperate continental desert climate with an average annual precipitation of only 110 mm and aeolian sandy soil as the main soil type. Low precipitation and unstable soil structure result in low regional soil moisture content, which has become the most critical factor limiting regional vegetation growth. Clay sand barrier-artificial Haloxylon ammodendron plantations use low-density planting, with watering conducted only during the initial planting stage. Subsequent vegetation recovery is mainly driven by natural forces, and due to the row-band clay sand barriers, the comprehensive effect leads to relatively long soil water retention time. The fluctuation pattern of soil moisture content is consistent with the trend of plant community succession. In the early establishment period, as Haloxylon ammodendron grew and herbaceous plant coverage continuously increased, soil moisture content showed a fluctuating downward trend. Evidently, vegetation expansion during desertification reversal can affect soil moisture content and trigger vegetation pattern changes by altering the spatiotemporal distribution of soil moisture. The decrease in average soil moisture content and its shallow distribution led to continuous increases in herbaceous plant species, accelerating the succession process from shrub-dominated to herb-dominated plant communities. This conclusion is consistent with research results from similar regions. During the middle establishment period, a relatively stable composite plant community of annual + perennial herbs + shrubs formed, and the relationship between vegetation and soil moisture began to reach a balance, with stable plant communities benefiting soil moisture recovery. Although artificial vegetation construction had obvious initial effects on improving regional soil moisture, soil moisture content still showed a downward trend during the late establishment period (40–60 years), eventually reaching low values similar to the control sand site. Zheng et al. studied soil moisture heterogeneity at different soil depths (40–300 cm) in the Shapotou arid region, confirming that after 40–60 years of vegetation evolution, the spatial heterogeneity of regional soil moisture gradually weakened.

Soil moisture content is closely related to topography, precipitation, evaporation, and soil nutrients, and always maintains a dynamic balance. To further reveal the relationship between soil moisture heterogeneity changes and the regional vegetation-soil system, long-term observation studies considering other environmental factors are needed. Li et al. found that sandy soil moisture content in the 0–20 cm surface layer changes dramatically with fluctuations in precipitation and evaporation. In this study, surface soil moisture (0–20 cm) had significant positive effects on Shannon-Wiener, Simpson, and Pielou α diversity indices, which is determined by the special structure of sandy soil and the water absorption characteristics of psammophyte roots. Xiao et al. studied soil moisture spatial heterogeneity during desertification reversal in Gulang Mingshazui, confirming that during regional desertification reversal, the overall spatial heterogeneity of the 0–20 cm layer showed an upward trend, while that of the 20–40 cm layer showed a trend of first increasing and then decreasing, which is also consistent with the results of this study.

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5 Conclusions

1) The establishment of clay sand barrier-artificial Haloxylon ammodendron plantations can significantly increase the number of plant species in artificial sand fixation areas. Dominant species evolved from Agriophyllum squarrosum and Haloxylon ammodendron to Grubovia dasyphylla, Kali collinum, Limonium aureum, and Haloxylon ammodendron. Life forms shifted from a single type dominated by annual herbs to a composite type

of annual herbs + perennial herbs + shrubs.

2) Establishment years significantly affected species α diversity and β diversity. Using 20 years as the turning point, species number and species distribution evenness gradually increased before 20 years and gradually decreased after 20 years. Community similarity between neighboring establishment year plots was highest between the control sand site and the 1-year site, followed by the 1-year and 5-year sites, and lowest between the 20-year and 40-year sites.

3) Significant differences in average soil moisture content (0–60 cm) existed among plots with different establishment years, showing a continuous decreasing trend with increasing establishment years. The degree of differentiation in soil moisture content among different soil layers was closely related to the average soil moisture content, with surface soil moisture content generally being the lowest and subsurface soil moisture content being relatively higher.

4) Soil moisture content positively affected regional plant species diversity, with varying degrees of correlation between soil moisture at different depths and plant species diversity. Shallow soil layers (10–30 cm) played a more critical role in regional plant natural succession than deeper soil layers (40–60 cm).

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