Leaf Functional Traits of Typical Desert Plants in the Sand-Blocking and Sand-Fixing Belt of the Hexi Corridor (Postprint)

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Abstract

This study takes typical desert plants Haloxylon ammodendron and Nitraria tangutorum in the sand-blocking and sand-fixing belt of the Hexi Corridor as research subjects, and explores the adaptation strategies of desert plants to arid environments through a combination of field investigation, sample collection, laboratory analysis, and statistical methods. Therefore, we selected the sand-blocking and sand-fixing belts of Minqin Oasis and Gaotai Oasis, respectively from the upwind natural vegetation enclosure protection belt and the downwind arbor-shrub protection forest belt, with relatively consistent spatial structural characteristics, and established three 10 m × 10 m Haloxylon ammodendron quadrats and three 10 m × 10 m Nitraria tangutorum quadrats. By analyzing the spatial distribution characteristics and correlations of their main leaf parameters and environmental factors, this study aims to provide data support for evaluating the adaptation strategies of leaf functional traits of the two desert plants to arid environments. Typical desert plants can adapt to soil and climatic conditions in specific habitats by adjusting leaf functional traits. The results show that: (1) Leaf dry matter content (LDMC) and specific leaf area (SLA) showed significant differences ($P<0.05$), while leaf organic carbon (LOC), leaf nitrogen (LN), and leaf phosphorus content (LP) showed extremely significant differences in both habitats ($P<0.001$). (2) Principal component analysis indicated that the top three indicator factors affecting leaf functional traits of plants in Minqin were LN, C:N, and C:P; while those affecting leaf functional traits of plants in Gaotai were LP, C:N, and N:P. (3) Redundancy analysis indicated that soil water content (SWC), soil organic carbon content (SOC), and air dryness (AD) were the main limiting environmental factors affecting the variation in leaf functional traits of the two desert plants.

Full Text

Abstract

This study investigated the typical desert plants *Haloxylon ammodendron* and *Nitraria tangutorum* in the sand-blocking and sand-fixing belt of the Hexi Corridor through field surveys, sample collection, laboratory analysis, and statistical methods to explore adaptation strategies to arid environments. Sample plots were established in the sand-blocking and sand-fixing belts of Minqin Oasis and Gaotai Oasis, specifically in the natural vegetation conservation zone on the upwind side and the arbor-shrub shelterbelt on the downwind side where spatial structure characteristics were relatively consistent. Three 10 m × 10 m quadrats were set up for each species. The spatial distribution characteristics of key leaf parameters and environmental factors were analyzed to provide data support for evaluating the adaptation strategies of leaf functional traits in these two desert plants. The results showed that: (1) Leaf dry matter content (LDMC) and specific leaf area (SLA) showed significant differences ($P < 0.05$), while leaf organic carbon (LOC), leaf nitrogen (LN), and leaf phosphorus (LP) showed extremely significant differences ($P < 0.001$) between the two habitats. (2) Principal component analysis indicated that the top three indicator factors affecting leaf functional traits in Minqin were LN, C:P, and N:P, while for Gaotai they were LP, C:N, and N:P. (3) Redundancy analysis revealed that soil water content (SWC), soil organic carbon (SOC), and air dryness (AD) were the main limiting environmental factors affecting the functional traits of both desert plants.

Keywords: sand-blocking and sand-fixing belt; typical desert plants; leaf functional traits; environmental factors; Hexi Corridor

Introduction

1.1 Study Area Overview

The study areas were located in Minqin County, Wuwei City, and Gaotai County, Zhangye City. Meteorological data were obtained from national and regional meteorological stations. Minqin County is situated in the lower reaches of the Shiyang River, between the Badain Jaran and Tengger Deserts, while Gaotai County lies in the middle reaches of the Heihe River, adjacent to the southern edge of the Badain Jaran Desert. The average annual precipitation was 113.2 mm in Minqin and 131.5 mm in Gaotai; mean temperatures were 7.7 °C and 6.2 °C, respectively; dryness indices were 25.0 and 20.0; and wind speeds were 2.8 $\mathrm{m \cdot s^{-1}}$ and 2.5 $\mathrm{m \cdot s^{-1}}$, respectively. According to the Chinese National Standard "Names and Codes for Climate Regionalization—Climate Zones and Climate Regions" (GB/T 17297—1998), Minqin belongs to an extremely arid climate zone, while Gaotai belongs to an arid climate zone.

1.2 Sample Plot Selection

In mid-August 2023, through literature review and field investigation, sand-blocking and sand-fixing belts with relatively consistent spatial structure were selected in both Minqin and Gaotai. These belts comprised a natural vegetation conservation zone on the upwind side and an arbor-shrub shelterbelt on the downwind side. In the natural vegetation conservation zone, three 10 m × 10 m quadrats were established for *N. tangutorum*, and in the *H. ammodendron* forest approximately 10 m from the upwind forest edge, three 10 m × 10 m quadrats were established for *H. ammodendron*. The characteristics of *H. ammodendron* and *N. tangutorum* sample plots are presented in Table 1.

1.3 Plant Leaf and Soil Sample Collection

To reduce water loss, the leaves of *Haloxylon ammodendron* have evolved into assimilative branches that minimize water dissipation and prevent sunburn, thereby enhancing survival in arid environments. For convenience, the term "leaves" in this study refers to these assimilative branches. Within each quadrat, healthy *H. ammodendron* and *N. tangutorum* plants were selected, and leafy twigs were cut from the east, south, west, and north directions using pruning shears. The samples were mixed, quickly placed in pre-labeled self-sealing bags, stored at low temperature in a thermostatic container, and transported to the laboratory for processing.

Soil samples were collected using the five-point method (east, west, south, north, and center) in each quadrat. Surface litter was cleared, soil profiles were excavated, and soil samples from 0–40 cm depth were uniformly collected with a soil auger, mixed, sealed in self-sealing bags, and brought back to the laboratory for physicochemical property analysis.

1.4 Measurement Methods

1.4.1 Leaf Functional Trait Measurement Plant samples brought back to the laboratory were weighed for fresh leaf mass using an electronic analytical balance with 0.001 g precision. Leaves were then completely immersed in deionized water in darkness until fully saturated. After controlled water removal, saturated fresh weight was measured. Leaves were placed in an oven at 105 °C for 30 minutes, after which the temperature was reduced to 65 °C and dried to constant weight for dry weight measurement. Leaf thickness (LT) was measured using a 0.02 mm precision vernier caliper. Leaf area (LA) was determined by scanning leaves to create digital images, which were then processed using ImageJ software. Leaf organic carbon (LOC) content was measured using the potassium dichromate oxidation external heating method. Leaf nitrogen (LN) content was determined using the semi-micro Kjeldahl method. Leaf phosphorus (LP) content was measured using the sodium bicarbonate extraction molybdenum-antimony anti-colorimetric method. The following formulas were used for calculations: Leaf water content (LWC) = (Leaf saturated fresh weight

- Leaf dry weight) / Leaf saturated fresh weight × 100%; Leaf dry matter content (LDMC) = Leaf dry weight / Leaf saturated fresh weight × 100%; Specific leaf area (SLA) = Leaf area / Leaf dry weight × 1000 ($cm^2 \cdot g^{-1}$).

1.4.2 Soil Physicochemical Property Measurement Soil physicochemical properties were measured following the methods in "Soil Agrochemical Analysis" [25]. Soil water content (SWC) was determined using the oven-drying method. Soil organic carbon (SOC) content was measured using the potassium dichromate oxidation heating method. Soil nitrogen (SN) content was determined using the semi-micro Kjeldahl method. Soil phosphorus (SP) content was measured using colorimetry. Soil pH was measured using a potentiometer, and electrical conductivity (EC) was determined using the conductivity method.

1.5 Data Processing and Analysis

Data were processed and statistically analyzed using Microsoft Excel 2021 and SPSS 23.0. Differences in plant leaf functional traits and environmental factors between the two habitats were compared using analysis of variance (ANOVA). Principal component analysis (PCA) was employed to identify the main indicator factors by ranking plant leaf functional traits. Pearson correlation analysis was used to examine correlations among leaf functional trait indices. Redundancy analysis (RDA) was applied to analyze the relationship between plant leaf functional traits and environmental factors under the two habitat conditions. Figures were generated using OriginPro 2024 and Canoco 4.5.

Results

2.1 Leaf Functional Trait Characteristics in Two Habitats

Two-way ANOVA revealed that *H. ammodendron* and *N. tangutorum* showed significant differences ($P < 0.05$) in leaf functional traits between the two habitats. As shown in Figures 1 and 2, in Minqin, the LWC of *H. ammodendron* and *N. tangutorum* was slightly lower than in Gaotai. However, LDMC was significantly lower in Minqin than in Gaotai. These findings indicate that environmental conditions with low precipitation and high evaporation profoundly influence plant leaf functional traits, likely resulting from the combined effects of climate aridity and soil factors.

Leaf chemical traits also showed extremely significant differences ($P < 0.001$) between habitats. In Minqin, LOC, LN, and LP of both species were lower than in Gaotai. However, C:N, C:P, and N:P ratios were higher in Minqin than in Gaotai. This demonstrates that leaf chemical traits of both species differed markedly between habitats, possibly because different arid climates and soil water deficits led to varying plant growth rates, resulting in differences in leaf chemical element composition.

2.2 Correlations Among Leaf Functional Traits and Principal Component Analysis

Correlation analysis revealed that in Minqin, LWC was extremely significantly negatively correlated with LDMC ($P < 0.01$) and significantly positively correlated with SLA ($P < 0.05$). LDMC was extremely significantly negatively correlated with SLA ($P < 0.001$). Both C:N and C:P ratios were extremely significantly negatively correlated with LN and LP contents ($P < 0.01$). In Gaotai, similar correlation patterns were observed, with LWC extremely significantly negatively correlated with LDMC ($P < 0.01$) and significantly positively correlated with SLA ($P < 0.05$). LDMC was extremely significantly negatively correlated with SLA ($P < 0.001$). Both C:N and C:P ratios were extremely significantly negatively correlated with LN and LP contents ($P < 0.01$), while N:P was significantly positively correlated with LN ($P < 0.05$) and extremely significantly negatively correlated with LP ($P < 0.01$).

Principal component analysis (Table 4) identified the main indicators of leaf functional traits varying with habitat. For Minqin, the first three principal components had eigenvalues of 2.398, 1.825, and 1.418, with contribution rates of 34.266%, 26.070%, and 20.263%, respectively, and a cumulative contribution rate of 80.599%. For Gaotai, the first three principal components had eigenvalues of 2.446, 1.663, and 1.506, with contribution rates of 34.943%, 23.751%, and 21.512%, respectively, and a cumulative contribution rate of 80.206%. The cumulative contribution rates exceeded 80% in both habitats, indicating that these three principal components represent the main factors driving variation in leaf functional traits of *H. ammodendron* and *N. tangutorum*.

The top three indicator factors affecting leaf functional traits in Minqin were LN, C:P, and N:P, while for Gaotai they were LP, C:N, and N:P. Notably, N:P was a common top-three indicator factor for both species in both habitats, suggesting it is a key leaf functional trait.

2.3 Soil Factors in Two Habitats

As shown in Figure 3, soil factors differed between Minqin and Gaotai. SOC content ranged from 0.553 to 0.443 $\mathrm{mg \cdot g^{-1}}$ in Minqin and 0.532 to 0.426 $\mathrm{mg \cdot g^{-1}}$ in Gaotai. Soil pH was slightly higher in Minqin than in Gaotai, with both habitats being alkaline. Soil phosphorus content was lower in Minqin (0.0026 $\mathrm{mg \cdot g^{-1}}$) than in Gaotai (0.0031 $\mathrm{mg \cdot g^{-1}}$). Soil water content showed significant differences between habitats ($P < 0.05$), with Minqin at 0.75% and Gaotai at 1.30%.

2.4 Relationship Between Leaf Functional Traits and Environmental Factors

Redundancy analysis showed that the first, second, third, and fourth axes explained 34.943%, 23.751%, 21.512%, and 12.134% of the variation in leaf functional traits, respectively. The cumulative contribution rate exceeded 92.339%

for both habitats, indicating that the first two axes adequately reflected the correlation between leaf functional traits and environmental factors. Leaf functional traits were positively correlated with soil water content (SWC) and soil organic carbon (SOC), and negatively correlated with air dryness (AD). The positive correlation between SOC and leaf functional traits was the strongest. Air dryness was negatively correlated with leaf nitrogen (LN) and leaf phosphorus (LP) contents, while soil phosphorus was positively correlated with LP.

The RDA ordination axis showed that as air dryness increased and soil water content decreased, habitats deteriorated and plant nutrient contents declined. Plants in Gaotai had significantly higher nutrient contents than those in Minqin, and the decline in nutrient content was more pronounced closer to the desert and farther from the oasis. This may be due to soil water and nutrient limitations under extremely arid habitat conditions.

Discussion

3.1 Differences in Leaf Functional Traits of *H. ammodendron* and *N. tangutorum* Between Habitats

Leaf functional traits represent long-term adaptive strategies of plants to environmental factors and their variations. In arid desert regions, water is the dominant factor influencing plant distribution and growth. Leaf functional traits, including leaf water content, are constrained not only by soil moisture but also by environmental temperature, humidity, light intensity, wind speed, and other factors. Based on precipitation, both Gaotai and Minqin are located in arid zones, but Minqin has much higher evaporation than Gaotai. According to the dryness index, Gaotai belongs to an arid climate, while Minqin belongs to an extremely arid climate. These differences in climate aridity inevitably affect leaf transpiration rates and leaf water content, which are reflected in leaf thickness, dry matter content, specific leaf area, and nutrient content. Previous studies have shown that plants growing in arid regions tend to have thicker leaves, lower leaf dry matter content, and smaller specific leaf area.

Our study found that under the influence of low soil water content and high air dryness, *H. ammodendron* in Minqin had significantly lower LWC and higher LDMC compared to Gaotai. However, unlike *H. ammodendron*, *N. tangutorum* in Minqin had higher LWC and lower LDMC than in Gaotai. The C:N and C:P ratios in Minqin were significantly higher than in Gaotai. As air dryness increased, plants stored more C content in their leaves to withstand harsh environments. Studies have shown that when plant leaf N:P ratio is less than 14, growth is primarily limited by nitrogen, and when greater than 16, primarily by phosphorus [25]. In this study, the N:P ratios of both species in both habitats were less than 14, indicating that growth of these two plants may be mainly limited by nitrogen rather than phosphorus.

3.2 Correlations Among Leaf Functional Traits of *H. ammodendron* and *N. tangutorum*

Under natural conditions, plants have evolved to adapt to environmental heterogeneity through coordination and trade-offs among functional traits. Consequently, leaf functional traits are closely interrelated, with trait combinations adjusting to suit different habitats. SLA directly affects the construction of protective tissues or mesophyll density to improve water use efficiency, and is closely related to water conservation, resource acquisition, and assimilation. In both habitats of this study, LDMC was negatively correlated with LWC ($P < 0.05$) and positively correlated with SLA ($P < 0.05$), consistent with previous research [20]. The positive correlation between LWC and SLA ($P < 0.05$) reflects the balance between water retention and photosynthetic area in desert plants.

Leaf organic carbon, nitrogen, and phosphorus are essential elements for plant physiological activities and play crucial roles in biogeochemical cycles. In this study, leaf nutrient contents were significantly positively correlated with each other ($P < 0.001$) in both habitats. LN and LP contents were significantly lower in Minqin than in Gaotai ($P < 0.05$), likely because the harsher environment in Minqin, with stronger evaporation and higher dryness index, constrains plant growth and inhibits synthesis of N and P contents. Under the drier and more nutrient-poor conditions in Minqin, both species first reduce LWC and photosynthesis to decrease nutrient demand and improve nutrient use efficiency.

The N:P ratio reflects nutrient limitation on plant growth. When $N:P < 14$, growth is primarily N-limited; when $N:P > 16$, P-limited [25]. In this study, N:P ratios of both species in both habitats were less than 14, indicating N limitation. The C:N and C:P ratios were significantly higher in Minqin than in Gaotai, and both were significantly negatively correlated with LN and LP contents ($P < 0.01$). Air dryness was significantly positively correlated with C:N and C:P ratios ($P < 0.05$), indicating close relationships between atmospheric dryness and leaf nutrient elements. Therefore, desert plants may adapt to drought not only by altering leaf structure but also by adjusting nutrient content. The N:P ratio ranked among the top three indicator factors in both habitats, making it a key trait for assessing plant nutritional status and community structure in desert ecosystems.

3.3 Responses of Leaf Functional Traits to Environmental Factors

Plants and soil form an interconnected organic system. Soil provides chemical elements for plant internal cycling, while plants return nutrients to the soil through decomposition of litter. Soil is a dominant factor influencing leaf functional traits, supplying essential energy and material resources for plant growth. In this study, leaf functional traits were significantly positively correlated with soil water content (SWC) and soil organic carbon (SOC) ($P < 0.05$), and significantly negatively correlated with air dryness (AD) ($P < 0.05$). Redundancy analysis indicated that leaf functional traits were relatively more affected by soil factors.

In arid regions, desert plant growth is limited not only by water shortage but also by soil nutrient constraints. Soil moisture affects not only plant growth and succession but also soil nutrient distribution. Due to intense evaporation and low rainfall in arid desert study areas, soil water easily evaporates, and declining soil moisture and nutrient content further inhibit nutrient absorption and plant growth. Although evaporation significantly exceeded precipitation in both Minqin and Gaotai, Gaotai’ s soil water content was well supplemented by forestry irrigation water, providing a slightly better habitat than Minqin. According to the dryness index, Minqin has an extremely arid climate, while Gaotai has an arid climate.

In natural environments, leaf functional traits vary with soil water content and other environmental factors such as air dryness, reflecting comprehensive adaptation to environmental factors. The RDA ordination axis showed that as air dryness increased and soil water content decreased, habitats deteriorated and plant nutrient contents declined. Plants in Gaotai had significantly higher nutrient contents than in Minqin, and the decline was more pronounced closer to the desert and farther from the oasis, likely due to soil water and nutrient limitations under extremely arid conditions.

Conclusion

This study investigated typical desert plants *H. ammodendron* and *N. tangutorum* under two habitat conditions to analyze the relationship between leaf functional trait characteristics and environmental factors. The results showed that individuals in Minqin had higher leaf dry matter content (LDMC), leaf nitrogen (LN), and leaf phosphorus (LP) contents, while individuals in Gaotai had higher specific leaf area (SLA) and leaf organic carbon (LOC) content. In desert regions, soil water content (SWC), soil organic carbon (SOC), and air dryness (AD) provided good explanatory power for variations in desert plant leaf functional traits.

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