

Postprint: Leaf and Soil Ecological Stoichiometric Characteristics of Four Shrub Species in the Upper Tarim River Desert Region

Authors: Luo Yan, Gong Lu, Zhu Meiling, An Shenqun

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Abstract

This study analyzed the carbon (C), nitrogen (N), and phosphorus (P) contents and their stoichiometric characteristics in leaves and soils of shrub plants in the desert area of the upper Tarim River, as well as the correlations between them, aiming to elucidate the nutrient cycling and limitation status of desert vegetation under extreme environmental conditions and provide a theoretical basis for the restoration and protection of desert ecosystems in the upper Tarim River. Taking leaves and soils of four desert shrub species in the upper Tarim River—*Tamarix ramosissima*, *Halostachys caspica*, *Lycium ruthenicum*, and *Halimodendron halodendron*—as the research objects, the ecological stoichiometric characteristics of C, N, and P in plant leaves and soils and their correlations were analyzed. The results showed that among the four different desert shrub species, the C content in *Tamarix* leaves was $(484.77 \pm 59.74) \text{ mg/g}$, significantly higher than that in other shrub plants ($P < 0.05$); the N content in *Halimodendron* was $(14.20 \pm 1.58) \text{ mg/g}$, significantly higher than that in other shrub plants ($P < 0.05$); and the P content in *Tamarix* leaves was $(0.54 \pm 0.16) \text{ mg/g}$, significantly lower than that in other shrub plants ($P < 0.05$). The leaf C/N ratio ranking among the four shrub species was *Lycium ruthenicum* > *Tamarix* > *Halimodendron* > *Halostachys*, with *Lycium ruthenicum* having the significantly highest C/N ratio ($P < 0.05$); the C/P ratio ranking was *Tamarix* > *Halimodendron* > *Halostachys* > *Lycium ruthenicum*, with *Halostachys* and *Lycium ruthenicum* having significantly lower C/P ratios than other shrub plants ($P < 0.05$), at (379.76 ± 158.63) and (383.47 ± 128.95) , respectively; the N/P ratio ranking was *Tamarix* > *Halimodendron* > *Halostachys* > *Lycium ruthenicum*, with *Tamarix* having the significantly highest N/P ratio ($P < 0.05$). The soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) contents and their stoichiometric ratio characteristics among the four different desert shrubs showed no significant differences. Correlation analysis revealed that only the P content in *Tamarix* leaves showed a significant positive correlation with soil TP content ($P < 0.05$); leaf C content in *Halimodendron* showed significant negative correlations with soil TN and leaf P content with soil TN/TP ($P < 0.05$), while leaf C content showed an extremely

significant negative correlation with soil TN/TP ($P < 0.01$); no significant correlations were observed between leaf stoichiometric characteristics and soil stoichiometric characteristics for *Halostachys* and *Lycium ruthenicum* ($P > 0.05$). This indicates that leaf stoichiometric characteristics are not directly determined by soil nutrient content characteristics, but are more influenced by the plant's own genetic traits, reflecting the adaptation of desert shrub plants to extreme habitats.

Full Text

Preamble

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Stoichiometry Characteristics of Leaves and Soil of Four Desert Shrubs in the Upper Reaches of the Tarim River

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College of Resources and Environmental Science, Xinjiang University, Key Laboratory of Oasis Ecology, Ministry of Education, Urumqi 830046, China

Abstract

This study analyzed the carbon (C), nitrogen (N), and phosphorus (P) contents and their stoichiometric characteristics in leaves and soils of shrub plants in the desert area of the upper Tarim River, as well as the correlations between them. The aim was to elucidate nutrient cycling and limitation status of desert vegetation under extreme environmental conditions, providing a theoretical basis for the restoration and protection of desert ecosystems in the upper reaches of the Tarim River. Four desert shrub species were selected as study materials: *Tamarix ramosissima*, *Halostachys caspica*, *Lycium ruthenicum*, and *Halimodendron halodendron*. Leaf and soil samples were collected in August 2015 using ground acquisition and quadrat methods, respectively. The concentrations of C, N, and P in plant leaves and soils, their stoichiometric ratios, and correlations were determined.

The results showed that leaf C concentration was (484.77 ± 59.74) mg/g, which was significantly higher in *T. ramosissima* than in the other three shrubs ($P < 0.05$). Leaf N concentration was (14.20 ± 1.58) mg/g, also significantly higher in *T. ramosissima* than in other shrubs, whereas leaf P concentration in *H. halodendron* was (0.54 ± 0.16) mg/g, significantly lower than that of other shrubs. The C/N ratio in leaves ranked as $L. ruthenicum > H. halodendron > T. ramosissima > H. caspica$, with *L. ruthenicum* showing the significantly highest value of (37.83 ± 7.74) ($P < 0.05$). The C/P ratio was ranked as $H. halodendron > T.$

ramosissima > *L. ruthenicum* > *H. caspica*, with *H. caspica* and *L. ruthenicum* showing significantly lower values of (379.76 ± 158.63) and (383.47 ± 128.95), respectively, compared to the other shrubs ($P < 0.05$). The N/P ratio was (22.34 ± 4.60) in *H. caspica*, significantly higher than that of other shrubs. The concentrations and stoichiometric ratios of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) showed no significant differences among the four shrubs ($P > 0.05$).

Correlation analysis revealed that leaf P concentration was positively correlated with soil TP concentration ($P < 0.05$). Leaf C and N concentrations in *T. ramosissima* and *H. halodendron* were negatively correlated with soil P and the TN/TP ratio ($P < 0.05$). Leaf C concentration was highly negatively correlated with the soil TN/TP ratio ($P < 0.01$). However, the stoichiometric characteristics of leaves and soil showed no significant correlations for *H. caspica* and *L. ruthenicum*, indicating that leaf stoichiometric characteristics are not directly determined by soil nutrient content but are more influenced by plant genetic traits, reflecting the adaptation of desert shrubs to extreme habitats.

Keywords: Upper reaches of the Tarim River; desert shrub; soil; stoichiometry

Introduction

Ecological stoichiometry provides a new approach for studying plant element cycling and its interactions with the environment. Carbon, nitrogen, and phosphorus are essential elements for plant growth and development, and key indicators of soil fertility. Studying C, N, and P in plant leaves and soil can provide deep insights into plant resource utilization and soil nutrient cycling status during growth, revealing the balanced constraints between plants and their environment. Ecological stoichiometry has developed rapidly both domestically and internationally, with relevant reports covering different vegetation types in forest, grassland, and other ecosystems. Research spans various regions and ecosystem types, involving stoichiometric characteristics of different plant organs and soils, as well as relationships between leaf nutrient content characteristics and environmental factors. However, less attention has been paid to plant-soil relationships in desert ecosystems, particularly regarding the stoichiometric characteristics of shrub leaves and soils in arid regions.

Desert ecosystems suffer from scarce soil nutrients and water, with soil physicochemical properties showing strong spatial heterogeneity. Under these conditions, the nutrient demands and environmental adaptations of desert vegetation change. Using ecological stoichiometry to study nutrient absorption, utilization, and environmental response mechanisms of desert plants has become an important aspect of ecology in arid regions. The Tarim River is the lifeline for economic development and people's livelihood in the Tarim Basin, and its upper reaches are among the regions with the most prominent ecological and environmental problems. Shrub plants play important roles in windbreak, sand fixation, and green ecological construction in the upper Tarim River, showing

strong adaptability to arid, saline, and alkaline environments. Under the dual impacts of global change and human activities in recent years, the already fragile ecological environment in the upper reaches, combined with large-scale water and soil resource development, has led to continuously declining groundwater levels, substantial reductions in shrub forest area, and increasingly severe soil degradation and salinization. Different shrub species exhibit heterogeneity in nutrient limitation characteristics and habitat adaptability. This study analyzed the C, N, P stoichiometric characteristics of leaves and soil of four desert shrubs in the upper Tarim River and their correlations, aiming to elucidate the adaptation mechanisms of desert vegetation to extreme environments, the cycling and limitation status of soil nutrient elements, and the effects of soil on plant leaf stoichiometric characteristics, providing a scientific basis for the restoration and protection of desert ecosystems in the upper Tarim River.

1 Materials and Methods

1.1 Study Area

The study area is located in the desert region of the upper Tarim River basin, on the northern edge of the Taklamakan Desert and the southern foothills of the central Tianshan Mountains (80°10' -84°36' E, 40°25' -41°10' N). This region has a typical warm temperate continental arid desert climate, with hot summers, drought, little rainfall, and strong winds. The annual average temperature is 10.4°C, annual precipitation is 50.4 mm, annual evaporation is 1880.0 mm, and average sunshine duration is 2729.0 hours. Surface evaporation is intense. Soil composition is dominated by sand particles, with low organic matter and nutrient contents that mostly accumulate in the surface layer. Vegetation composition is simple with obvious vertical stratification. Representative plants include *Populus euphratica*, *Phragmites australis*, *Tamarix ramosissima*, *Halimodendron halodendron*, *Hexinia polydichotoma*, *Lycium ruthenicum*, *Glycyrrhiza uralensis*, and *Halostachys caspica*.

1.2 Field Sampling

Based on principles of representativeness and typicality, four typical shrub community types distributed in the desert area were selected: *Tamarix ramosissima*, *Halostachys caspica*, *Lycium ruthenicum*, and *Halimodendron halodendron*. In August 2015, leaf and soil samples of these four shrub species were collected along a transect perpendicular to the upper Tarim River channel from west to east. Sampling sites were selected under consistent topographic factors such as slope position and aspect. In each plot, a 20 m × 20 m quadrat was established with intervals of no less than 1 km between plots. The sampling area for each quadrat was 15 m × 15 m. Dominant species and soil samples were collected from each community, with five replicates for each plant and soil sample.

According to plant growth status, healthy mature leaves from the upper and middle parts of plants were collected within each quadrat. Each plant sample

weighed 50 g and was placed in envelopes with appropriate desiccant and labeled. Simultaneously, based on the distribution layers of plant roots, surface soil samples (0–20 cm) under plant canopies were collected using the quartering method within each quadrat. After removing litter and stones, 100 g of soil was placed in sealed bags and labeled for soil nutrient content determination.

Table 1 List of four shrub species in the upper Tarim River desert area

Species	Family	Genus	Plant Height	Frequency	Coverage
<i>Tamarix ramosissima</i>					
<i>Halostachys caspica</i>					
<i>Lycium ruthenicum</i>					
<i>Halimodendron halodendron</i>					

1.3 Laboratory Methods

Plant leaf samples were oven-dried at 65°C to constant weight, then ground with a pulverizer and passed through a sieve. Leaf total carbon (C) content was determined using the potassium dichromate volumetric method with external heating. Total nitrogen (N) content was measured by the Kjeldahl method. Total phosphorus (P) content was determined by the molybdenum-antimony anti-colorimetric method. Results were expressed as nutrient content per unit mass, and stoichiometric ratios were expressed as molar ratios.

Soil samples were air-dried, and plant roots and stones were removed. Soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) were measured using conventional methods. Soil organic carbon was determined by potassium dichromate titration, total nitrogen by the Kjeldahl method, and total phosphorus by sodium bicarbonate extraction-molybdenum antimony anti-colorimetric method.

1.4 Data Processing

SPSS 17.0 software was used for statistical analysis. One-way ANOVA was performed on leaf C, N, P contents and their stoichiometric ratios (C/N, C/P, N/P) among the four shrub species. Levene's test was used to check for homogeneity of variance. Duncan's T2 test was used for multiple comparisons when variances were homogeneous, while Tamhane's test was used when variances were not homogeneous. Relationships between element contents and soil factors were fitted using power function models ($\alpha = 0.05$). Pearson correlation analysis was used to examine relationships between leaf and soil stoichiometric characteristics. Data in figures and tables are presented as means \pm standard deviation.

2 Results and Analysis

2.1 Stoichiometric Characteristics of Desert Shrub Leaves

The C, N, and P contents and stoichiometric characteristics varied among the four desert shrub species. Leaf C content averaged (484.77 ± 59.74) mg/g, with *T. ramosissima* showing significantly higher values than other shrubs ($P < 0.05$). Leaf N content averaged (14.20 ± 1.58) mg/g, significantly higher in *T. ramosissima* than in other shrubs ($P < 0.05$). Leaf P content averaged (0.54 ± 0.16) mg/g, significantly lower in *H. halodendron* than in other shrubs ($P < 0.05$).

The C/N ratio of the four desert shrubs ranked as *L. ruthenicum* > *H. halodendron* > *T. ramosissima* > *H. caspica*, with *L. ruthenicum* showing the significantly highest value of (37.83 ± 7.74) ($P < 0.05$). The C/P ratio ranked as *H. halodendron* > *T. ramosissima* > *L. ruthenicum* > *H. caspica*, with *H. caspica* and *L. ruthenicum* showing significantly lower values of (379.76 ± 158.63) and (383.47 ± 128.95) , respectively ($P < 0.05$). The N/P ratio was (22.34 ± 4.60) in *H. caspica*, significantly higher than in other shrubs ($P < 0.05$).

Figure 1 [Figure 1: see original paper] Leaf C, N, P stoichiometric characteristics of four desert shrubs

Correlations among leaf C, N, and P elements showed that C and N contents were significantly positively correlated ($P < 0.05$), while P content was not correlated with C or N. All three elements showed significant positive power function relationships with positive exponents. Leaf C and N contents increased significantly with increasing P content, with N(P) showing the largest exponent (1.2438) and C(N) showing the smallest exponent (0.098).

Figure 2 [Figure 2: see original paper] Relationships between leaf C, N, and P contents of four desert shrubs

2.2 Stoichiometric Characteristics of Desert Shrub Soils

There were few significant differences in SOC, TN, TP contents and their stoichiometric ratios among the four desert shrub soils. SOC content was highest in *H. halodendron* (6.40 ± 5.51) mg/g and lowest in *L. ruthenicum* (4.43 ± 3.34) mg/g, but differences among the four shrubs were not significant ($P > 0.05$). TN and TP contents also showed no significant differences among the four shrubs ($P > 0.05$).

Table 2 Soil C, N, P stoichiometric characteristics of four desert shrubs

Species	C/N	C/P	N/P	C/N	C/P	N/P	C/N	C/P	N/P
All species	-0.15	-0.28	-0.19	-0.02	-0.09	-0.13	-0.18	-	-
								0.65**	0.57**

- Significant at $P < 0.05$ level; ** Significant at $P < 0.01$ level

3 Discussion

3.1 Leaf Element Stoichiometry Characteristics

Carbon, nitrogen, and phosphorus are the most important elements for plant dry matter composition and photosynthesis. N and P are crucial components of various proteins and genetic materials in plants. The overall C, N, and P contents in leaves of the four desert shrubs in the upper Tarim River were relatively low, significantly lower than global and national averages. The harsh ecological environment, low soil nutrient content, and reduced nutrient absorption and utilization rates under water-limited conditions result in lower effective nutrient accumulation in leaves.

The C/N ratio represents a plant's ability to assimilate carbon when absorbing nutrients and its carbon fixation efficiency. The overall C/N ratio of the four desert shrubs was 37.83, about 10 times higher than the global average, indicating high carbon fixation advantages and nutrient use strategies in nutrient-poor habitats. The C/P ratio is an important physiological indicator representing plant nutrient absorption capacity. Higher C/P and C/N ratios indicate advantages in carbon fixation and nutrient use strategies.

The N/P ratio is widely recognized as an indicator of nutrient limitation on plant growth, with thresholds of <14 indicating N limitation, >16 indicating P limitation, and 14–16 indicating co-limitation. In this study, the N/P ratio of *T. ramosissima* was the highest at 22.34, significantly higher than other shrubs, while *L. ruthenicum* had the lowest N/P ratio at 9.60, indicating different nutrient limitations among species.

Significant differences in C, N, P stoichiometric characteristics among the four shrubs reflect different resource use efficiencies and adaptation strategies to adverse environments. *Tamarix ramosissima* had the highest element accumulation, likely due to its scale-like leaves forming special photosynthetic stems with high light-use efficiency. *Halimodendron halodendron*, a legume with biological nitrogen fixation, had high N content. *Lycium ruthenicum* had high N content during its fruiting stage and produces protective proteins under extreme stress, requiring substantial nucleic acid replication and transcription.

The significant positive correlation between leaf C and N contents reflects the coordinated change of leaf elements, consistent with general patterns in higher terrestrial plants and indicating that desert plants in the upper Tarim River have stable adaptive characteristics.

3.2 Soil Element Stoichiometry Characteristics

Soil stoichiometric characteristics reflect soil organic matter composition and quality, and are important indicators of internal element cycling. The overall SOC, TN, and TP contents in shrub soils were 5.75, 0.51, and 0.63 mg/g, respectively, far below national levels (11.12, 1.06, and 0.65 mg/g). This indicates extremely poor soil nutrients in the study area, mainly due to reduced litter feedback and low organic matter content. The lack of water and heat conditions limits rock weathering, affecting P availability.

The C/N, C/P, and N/P ratios of the soils were 11.54, 9.60, and 0.85 mg/g, respectively, also below national levels, reflecting poor soil nutrient status. The small differences in soil stoichiometric characteristics among the four shrubs are related to the similar soil nutrient conditions and limited litter feedback. The higher C/N and C/P ratios in *T. ramosissima* soil indicate slower organic matter decomposition, while the higher N/P ratio in *L. ruthenicum* soil suggests higher P availability.

3.3 Correlations Between Plant and Soil Stoichiometry

Plants and soil are different links in biogeochemical cycles with inherent connections. Plant nutrient content reflects environmental adaptation, while soil nutrient conditions reflect plant nutritional status. Studies show that plant habitats are heterogeneous, and soil nutrient differences affect leaf stoichiometric characteristics. However, this study found no significant differences in soil C, N, P stoichiometric characteristics among the four desert shrubs, and no significant correlations between leaf and soil stoichiometry, indicating that soil nutrients have limited direct effects on these shrubs.

Plant leaf stoichiometric characteristics appear to be more related to species-specific traits and plant adaptation to habitats rather than direct soil nutrient limitation. This reflects long-term adaptive characteristics of desert shrubs to extreme environments. However, at the individual species level, some correlations exist. For *T. ramosissima*, leaf P content was positively correlated with soil TP, indicating P limitation on growth. For *H. halodendron*, leaf C and N contents were negatively correlated with soil TN/TP ratio, showing soil nutrient effects on growth. In contrast, *H. caspica* and *L. ruthenicum* showed no correlations, suggesting their stoichiometric characteristics are determined by genetic traits rather than soil nutrients, reflecting unique adaptation mechanisms.

4 Conclusions

This study measured C, N, P contents and stoichiometric ratios in leaves and soils of four desert shrubs in the upper Tarim River and analyzed their correlations. The main conclusions are:

1. Leaf C, N, and P contents of the four desert shrubs were generally low, with significant differences among species, indicating different nutrient resource

use efficiencies. The N/P ratios suggest that plant growth is more limited by P, leading to significant differences in leaf stoichiometric characteristics.

2. There were no significant differences in soil C, N, P stoichiometric characteristics among the four shrubs, indicating similar habitat nutrient conditions. Under the same environmental background, soil stoichiometric characteristics showed no significant differences.
3. Correlations between leaf and soil stoichiometric characteristics were generally weak, indicating that leaf stoichiometric characteristics are not directly determined by soil nutrient content but are more affected by plant genetic traits. This demonstrates that desert shrubs have developed unique physiological and ecological stoichiometric characteristics under relatively scarce nutrient conditions, with relatively stable adaptive characteristics.

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