

## Responses of Leaf and Root Ecological Stoichiometric Characteristics of *Alhagi sparsifolia* to Water and Nitrogen Addition: Postprint

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### Abstract

Nitrogen and water are important factors affecting the growth of desert plants, while nitrogen deposition and drought, as the main driving factors of global change, directly alter the availability of these two resources in soil. Using annual seedlings of the dominant plant *Alhagi sparsifolia* Shap. at the southern margin of the Taklamakan Desert as the research object, a pot experiment was established. By adding different levels of nitrogen fertilizer and water to simulate different levels of nitrogen deposition rates (0, 3.0, 6.0, 9.0 g · m<sup>-2</sup> · a<sup>-1</sup>) and water conditions (drought and sufficient water), the effects of these two factors on the stoichiometric characteristics of leaves and fine roots of *A. sparsifolia* were investigated. The results showed that: (1) Except for leaf P content, nitrogen and water addition independently or interactively affected the nutrient status of leaves and fine roots of *A. sparsifolia*. Under drought conditions, nitrogen addition significantly decreased the contents of leaf N, Mn, Zn, Cu and other elements ( $P < 0.01$ ), while to some extent increased the uptake of these elements by fine roots; (2) Fine roots of *A. sparsifolia* were enriched with trace elements such as Mn, Zn, Cu, Fe, while macroelements such as N, P, K were preferentially allocated to leaves; (3) Application of 3.0 g · m<sup>-2</sup> · a<sup>-1</sup> under drought stress conditions, and addition of 6.0 g · m<sup>-2</sup> · a<sup>-1</sup> or 9.0 g · m<sup>-2</sup> · a<sup>-1</sup> under sufficient water conditions could significantly alleviate nitrogen limitation in fine roots of *A. sparsifolia* (N:P < 14); (4) Nutrient elements in leaves and fine roots of *A. sparsifolia* exhibited complex interactions both within and between organs, with the proportion of inter-organ relationships being the highest, followed by intra-organ relationships in fine roots, and lowest in leaves. These results indicate that *A. sparsifolia* can coordinate aboveground and belowground nutrient relationships against a background of fluctuating environmental resources; exogenous nitrogen input can improve the nutrient status of fine roots of *A.*

*sparsifolia*, providing a scientific reference for desert vegetation restoration and efficient nutrient management.

## Full Text

### Stoichiometric characteristics of leaves and fine roots in *Alhagi sparsifolia* in response to the addition of nitrogen and water

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## Abstract

Nitrogen and water are important factors affecting the growth of desert plants; nitrogen deposition and drought, the main driving factors of global climate change, will directly change the availability of these resources in soil. Using one-year-old seedlings of *Alhagi sparsifolia*, a dominant plant on the southern edge of the Taklamakan Desert, a pot experiment was conducted. Different amounts of nitrogen fertilizer and water were added to simulate different levels of nitrogen deposition rates (0, 3.0, 6.0, and 9.0 g · m<sup>-2</sup> · a<sup>-1</sup>) and water conditions (drought or well-watered) to explore the effects of these two factors on the stoichiometric characteristics of the leaves and fine roots of *A. sparsifolia*. The results showed: (1) Nitrogen and water addition independently or interactively affected the nutrient status of leaves and fine roots of *A. sparsifolia*, except for P content in leaves. Under drought conditions, nitrogen addition significantly reduced the contents of N, Mn, Zn, and Cu in leaves (P<0.01), while enriching these microelements in fine roots and enhancing their absorption to some extent; (2) Microelements such as Mn, Zn, Cu, and Fe were enriched in the fine roots of *A. sparsifolia*, but macroelements such as N, P, and K were more distributed to the leaves; (3) Applying 3.0 g · m<sup>-2</sup> · a<sup>-1</sup> nitrogen under drought stress, or 6.0 or 9.0 g · m<sup>-2</sup> · a<sup>-1</sup> nitrogen under well-watered conditions, can significantly alleviate nitrogen limitation in fine roots of *A. sparsifolia* (N:P<14); (4) There were complex interactions among nutrient elements within and between organs

of *A. sparsifolia* leaves and fine roots. The occurrence rate of these relationships was greater between organs than within organs, followed by fine roots, and lowest in leaves. These results indicate that *A. sparsifolia* can coordinate aboveground and belowground nutrient relationships under fluctuating environmental resources. Exogenous nitrogen input can improve the nutrient status of fine roots of *A. sparsifolia*, providing scientific reference for desert vegetation restoration and efficient nutrient management.

**Keywords:** *Alhagi sparsifolia*; nitrogen and water; desert plants; nitrogen deposition; leaves and fine roots; stoichiometric characteristics; nutrient status

## Introduction

Nitrogen and water limitation are important environmental factors affecting plant growth and influencing ecosystem nutrient supply [?]. The acceleration of atmospheric nitrogen deposition caused by human activities such as fossil fuel combustion and excessive nitrogen fertilizer application has already affected the structure and function of global terrestrial ecosystems [?]. On the other hand, drought stress is an inherent survival pressure in desert ecosystems. The interaction of nitrogen deposition and drought has profound effects on the biogeochemical cycles of elements in desert ecosystems [?]. Elemental stoichiometry is commonly used to characterize plant nutrient use strategies [?] and the magnitude and direction of nutrient limitation in ecosystems [?], providing a research basis for evaluating the impacts of global change on plants and ecosystems.

Compared with other ecosystems, desert ecosystems have lower soil water content, which limits the dissolution and movement of nutrient elements, thereby affecting plant root absorption and vertical transport of nutrients, potentially causing asymmetric changes in nutrients among different tissues of desert plants [?]. In addition, the slowdown of soil organic matter decomposition and clay formation processes caused by drought inhibits soil cation exchange capacity, reducing plant utilization efficiency of these cations [?]. To maintain homeostasis, plants typically exhibit stoichiometric plasticity in response to environmental resource fluctuations [?]. Among these cations, potassium (K) is an important element regulating plant water conduction, transpiration, and maintaining osmotic balance [?]; calcium (Ca) is a major component of plant cell walls and can alleviate heavy metal toxicity in plants [?]; magnesium (Mg) is a key element in chlorophyll synthesis and plays an important role in plant photosynthesis [?]. Considering the distinct chemical characteristics of different elements, the coupling relationships among elements, and the differential elemental demands among plant tissues, it is necessary to conduct comprehensive studies on the stoichiometric characteristics of multiple elements in different tissues of desert plants.

Leaves and fine roots are plant organs for nutrient acquisition [?]. Most stoichiometric studies have focused on plant leaves [?]. Different plant tissues typically show different stoichiometric responses to environmental changes [?].

Some studies have shown that, as the entry point for nutrients into plants, fine root nutrients are more responsive to soil nutrients than leaves [?]. Therefore, combining leaves and fine roots to explore stoichiometric characteristics will facilitate better understanding of the connections between aboveground and belowground plant parts under environmental change [?].

*Alhagi sparsifolia* (hereafter “camel thorn”) is a dominant constructive species in the Cele Oasis-Desert transition zone on the southern edge of the Taklamakan Desert, playing an important role in windbreak and sand fixation and livestock development [?]. The region belongs to a typical extreme arid area and is extremely sensitive to environmental changes [?]. This study used *A. sparsifolia* seedlings as research objects, simulated nitrogen deposition under different water conditions, and explored the effects of nitrogen and water changes on the contents and stoichiometric characteristics of major nutrients (N, P, K, Ca, Mg, Fe, Mn, Zn, Cu) in leaves and fine roots of desert plants, aiming to reveal the coupling relationships of important elements in different plant tissues and their response strategies to environmental resource fluctuations, and to provide a scientific basis for efficient nutrient management and vegetation restoration in extreme arid desert ecosystems.

### 1.1 Study Area

The study area is located at the Cele National Station of Observation and Research for Desert Grassland Ecosystems, Chinese Academy of Sciences (hereinafter referred to as the Cele Station), situated in the Cele Oasis-Desert transition zone on the southern edge of the Taklamakan Desert (80°43 45 E, 37°00 57 N). The region experiences windy springs with severe sandstorm disasters, hot and dry summers, with extreme maximum temperatures reaching 41.9°C and an average annual temperature of 11.9°C. The average annual precipitation is only 35.1 mm, while the average annual evaporation can reach 2595.3 mm. Vegetation is sparse with low coverage, and the main plant communities consist of *Alhagi sparsifolia*, *Tamarix ramosissima*, and *Karelinia caspia*.

### 1.2 Experimental Design

This study used one-year-old seedlings of *Alhagi sparsifolia* (hereafter “camel thorn”) as research objects. To reduce the effects of nutrient exchange among plants and to collect intact root systems, a pot experiment was established. Seeds were collected from naturally growing *A. sparsifolia* plants in October 2019. Desert soil from 0-30 cm depth was used as the substrate, with a field water capacity of approximately 21.8% and total nitrogen and phosphorus contents of  $1.19 \text{ g} \cdot \text{kg}^{-1}$  and  $0.23 \text{ g} \cdot \text{kg}^{-1}$ , respectively. The soil was passed through a 2 mm sieve to remove plant residues and large gravel, then filled into pots. Pot dimensions were 50 cm upper diameter, 40 cm lower diameter, and 72 cm height. Plastic trays were placed at the bottom of pots to prevent soil nutrient loss. Sowing was conducted in early March 2020, with approximately 30 seeds

per pot. Watering was performed once daily to ensure normal seed germination. After seedling emergence, thinning was conducted, retaining 3 seedlings per pot for experimental treatments.

The experiment consisted of four nitrogen addition gradients: 0, 3.0, 6.0, and  $9.0 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ , designated as N0, N3, N6, and N9, respectively; and two water treatments: drought ( $0.5 \text{ L} \cdot \text{d}^{-1}$ ) and well-watered ( $1.5 \text{ L} \cdot \text{d}^{-1}$ ), designated as Drought and Watered. The two water treatments corresponded to 35% and 70% of maximum field water capacity, respectively, and obvious stress symptoms were observed in plants under drought treatment. Therefore, the experiment comprised eight treatments in total (4 N treatments  $\times$  2 water treatments), with six replicates per treatment. The experimental period lasted five months, with nitrogen fertilizer applied at the beginning of each month. Solid urea required for each N gradient was dissolved in the water needed for each water treatment and uniformly sprayed near seedling roots, with nitrogen fertilizer applied five times in total.

### 1.3 Sample Collection and Index Measurement

At the end of August 2020, plant samples were collected. Mature leaves were collected from *A. sparsifolia* seedlings with similar growth status. After above-ground sample collection, pots were inverted and soil was washed away with running water to collect plant root systems. Roots were separated into coarse roots ( $>2 \text{ mm}$ ) and fine roots ( $\leq 2 \text{ mm}$ ). The collected leaves and fine roots were placed in an oven, dried at  $65^\circ\text{C}$  to constant weight, ground with a ball mill, sieved, and mixed uniformly for determination of N, P, K, Ca, Mg, Fe, Mn, Zn, Cu, and other element contents.

Samples were divided into two parts: one part was digested with concentrated sulfuric acid and hydrogen peroxide, after which plant N content was determined by the Kjeldahl method and plant P content by the molybdenum-antimony anti-colorimetric method; the other part was digested with nitric acid, and metal element contents were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) [?].

Statistical analysis and plotting were performed using R (<https://www.r-project.org/>). Two-way ANOVA was used to analyze the effects of nitrogen and water treatments on nutrient element concentrations and stoichiometric ratios in leaves and fine roots of *A. sparsifolia*, with the ggplot2 package used for plotting. Least significant difference (LSD) test was used to examine differences in nutrient concentrations and stoichiometric ratios among different treatments.

## 2.1 Response of Nutrient Concentrations in Leaves and Fine Roots of *A. sparsifolia* to Nitrogen and Water Addition

The interactive effects of nitrogen and water significantly affected the contents of N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu in leaves of *A. sparsifolia* ( $P < 0.01$ ). Under different water treatments, their responses to nitrogen addition varied. Under drought stress, leaf N content showed no significant difference among nitrogen treatments, but under well-watered conditions, nitrogen addition significantly promoted leaf N content ( $P < 0.01$ ). In contrast to other elements, leaf P content showed no significant change among different treatments ( $P > 0.05$ ). Under well-watered conditions, nitrogen and water addition separately affected the contents of K, Ca, Mg, Fe, Mn, Zn, and Cu in leaves of *A. sparsifolia*. Nitrogen addition significantly reduced leaf K, Ca, Mg, Fe, Mn, Zn, and Cu contents ( $P < 0.05$ ), but drought significantly reduced leaf K, Ca, Mg, Fe, Mn, Zn, and Cu contents ( $P < 0.05$ ). There was no coupling relationship among these six treatments.

Except for P element, nutrient elements in *A. sparsifolia* roots were significantly affected by the independent or interactive effects of nitrogen and water addition (Figure 2). Under drought conditions, nitrogen addition significantly inhibited the accumulation of N, Mn, Zn, and Cu in fine roots ( $P < 0.001$ ), but under well-watered conditions, nitrogen addition had no significant effect on fine root N content ( $P > 0.05$ ). Drought stress significantly inhibited fine root P content ( $P < 0.01$ ), but under well-watered conditions, nitrogen addition had no significant effect on fine root P content ( $P > 0.05$ ). Appropriate nitrogen addition could significantly increase the contents of some elements in fine roots, while excessive nitrogen addition had the opposite effect. Low-level nitrogen addition ( $3.0 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ ) significantly increased the contents of K, Ca, Mg, Fe, and Mn in fine roots, while high-level nitrogen addition ( $9.0 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ ) significantly inhibited the accumulation of these elements in fine roots. Unlike drought stress, under well-watered conditions, nitrogen input significantly promoted the absorption of K, Ca, and Mg by fine roots ( $P < 0.001$ ), while significantly reducing the absorption of Fe, Mn, Zn, and Cu ( $P < 0.001$ ).

[Figure 1: see original paper] Response of nutrient concentration in leaves of *Alhagi sparsifolia* to water and nitrogen addition

*Note: Different lowercase letters above the bars indicate significant differences in nutrient concentrations among different nitrogen treatments under the same water condition (drought or well-watered); different lowercase letters below the bars indicate significant differences in nutrient concentrations among the two water treatments under the same nitrogen treatment; “” and “\*\*” indicate significant differences at  $P < 0.05$  and  $P < 0.01$  levels, respectively. The same applies below.\**

[Figure 2: see original paper] Response of nutrient concentration in fine roots of *A. sparsifolia* to water and nitrogen addition

## 2.2 Stoichiometric Ratios of Nutrient Elements in Leaves and Fine Roots of *A. sparsifolia*

Under two water conditions, the stoichiometric ratios of major nutrient elements in leaves and fine roots among treatments were compared (Table 1). The study found that in terms of the number of stoichiometric ratios showing significant responses to nitrogen addition, leaves and fine roots were equally sensitive to nitrogen addition, but there were differences in specific stoichiometric ratios. The two-way ANOVA showed that the interaction of nitrogen and water significantly affected Ca:Mg and Fe:Mn ratios in leaves, and N:P, Ca:Mg, and Fe:Mn ratios in fine roots (Table 2). Leaf N:P ratio was only significantly affected by water ( $P < 0.05$ ), while fine root N:P ratio was significantly affected by the interaction of nitrogen and water ( $P < 0.05$ ). Leaf Ca:Mg ratio was significantly affected by nitrogen addition ( $P < 0.05$ ), while fine root Ca:Mg ratio was only affected by water ( $P > 0.05$ ). Leaf Fe:Mn ratio was significantly affected by both nitrogen and water addition ( $P < 0.05$ ), while fine root Fe:Mn ratio was only significantly affected by nitrogen addition ( $P < 0.05$ ).

The response of leaf Fe:Mn ratio to nitrogen addition was opposite to that of fine roots. Additionally, leaf N:P ratio showed no significant response to water and nitrogen addition ( $P > 0.05$ ), while fine root N:P ratio was very sensitive to nitrogen addition ( $P < 0.05$ ). The responses of Ca:Mg ratio also differed between leaves and fine roots under different water conditions.

Stoichiometry of nutrient elements in leaves and fine roots of *Alhagi sparsifolia*

Two-way ANOVA of stoichiometry of nutrient elements in leaves and fine roots of *A. sparsifolia*

*Note: Values are means  $\pm$  SE. Different lowercase letters in the same column indicate significant differences among nitrogen treatments under the same water condition ( $P < 0.05$ ). “Drought” indicates drought treatment; “Watered” indicates well-watered treatment. “” and “\*\*” indicate significant differences at  $P < 0.05$  and  $P < 0.01$  levels, respectively.\**

## 2.3 Correlations of Nutrient Element Stoichiometric Ratios in Leaves and Fine Roots of *A. sparsifolia*

The correlation matrix visualized the associations of nutrient elements within and between leaves and fine roots (Figure 3). The results showed that, except for leaf P content, nutrient elements had significant correlations both within and between organs ( $P < 0.05$ ), and most inter-organ correlations occurred between macroelements in leaves (such as N, P, K) and various elements in fine roots. Leaf N, P, and K contents all had significant correlations with elements in fine roots ( $P < 0.05$ ).

Regarding correlations within organs, fine roots had more element pairs with significant correlations than leaves. In fine roots, significant correlations existed

among all elements, while in leaves, elements were mainly concentrated between microelements and macroelements. Except for this, correlations between leaf Ca-Mn and Mg-Fe contents and other elements were weak and did not reach statistical significance ( $P > 0.05$ ). The number of element pairs with significant correlations between organs (12 pairs) was greater than within organs (10 pairs in leaves vs. 10 pairs in fine roots). This indicates that under nitrogen and water fluctuations, the nutrient synergy between leaves and fine roots of *A. sparsifolia* is higher than within organs, and the nutrient network in roots is more complex than in leaves.

[Figure 3: see original paper] Correlation of nutrient elements in leaves and fine roots of *A. sparsifolia*

*Note: Red and blue dots indicate significant ( $P < 0.05$ ) positive and negative correlations between elements, respectively. Dot size indicates the strength of correlation, proportional to the absolute value of the correlation coefficient.*

### 3.1 Effects of Nitrogen and Water Addition on Nutrient Element Concentrations in Leaves and Fine Roots of *A. sparsifolia*

Leaves and fine roots are metabolically active organs in plants and are most sensitive to environmental changes [?]. Except for leaf P content, nutrient elements in leaves and fine roots of *A. sparsifolia* were independently or interactively affected by nitrogen and water addition (Figure 1, Figure 2). Under drought conditions, nitrogen addition promoted the absorption of N, Mn, Zn, and Cu by fine roots to some extent, yet inhibited the accumulation of these elements in leaves. This may be because under soil nitrogen enrichment, the growth of *A. sparsifolia* roots was promoted, and the plant allocated more elements to physiological activities of fine roots to acquire more resources [?]. Under nitrogen and water treatments, fine roots responded to more elements than leaves, indicating that fine roots are more sensitive to environmental changes than leaves. This strong response may be related to the function of fine roots in absorbing soil water and mineral nutrients. Fine roots are spatially closer to soil and can therefore rapidly respond to changes in soil resource availability [?]. On the other hand, the mineral elements examined in this study, especially microelements (such as Fe, Mn, Zn, Cu), had concentrations in fine roots several times higher than in leaves (Figure 1, Figure 2), possibly because these mineral elements were specifically fixed during transport within and between plant organs [?]. Macroelements such as N, P, and K were mainly enriched in leaves, indicating that in desert ecosystems with limited water and nutrients, *A. sparsifolia* allocates macroelements preferentially to aboveground parts. This differential allocation of nutrients between aboveground and belowground parts is related to internal organ structure and tissue functional differentiation [?].

Plant tissue N:P ratio is an important indicator for determining plant nutrient limitation [?]. When  $N:P < 14$ , it indicates nitrogen limitation; when  $N:P > 16$ ,

it indicates phosphorus limitation [?]. The N:P ratio of *A. sparsifolia* leaves basically exceeded 16, indicating that leaves were limited by P and were not significantly affected by nitrogen and water addition (Table 1). In contrast, fine root N:P ratio was mainly affected by the interaction of nitrogen and water, with fine roots under drought stress being co-limited by N and P. These results suggest that *A. sparsifolia* transfers macroelements absorbed by fine roots to leaves for photosynthesis and other processes, causing relative deficiency of P in fine roots. Nitrogen addition and its interaction with water may potentially affect this allocation process.

### **3.2 Effects of Nitrogen and Water Addition on Nutrient Element Stoichiometric Ratios in Leaves and Fine Roots of *A. sparsifolia***

Plant stoichiometric characteristics can reflect plant adaptation to environmental changes during long-term evolution [?]. Under soil nitrogen enrichment, desert plants need to increase their demand for phosphorus to maintain elemental homeostasis, therefore fine root N:P ratio is significantly inhibited by nitrogen addition [?]. However, water did not significantly affect the N:P ratio in leaves and fine roots of *A. sparsifolia*. This may be because desert soils have high pH and salinity but low organic matter content [?], and short-term water addition cannot reverse the situation of effective phosphorus deficiency in soil [?]. Notably, unlike other studies, nitrogen addition significantly reduced the Fe:Mn ratio in leaves of *A. sparsifolia* ( $P < 0.05$ ), while fine root Fe:Mn ratio was only affected by water status, but not by nitrogen addition (Figure 1, Figure 2). Leaves are photosynthetic organs, and we speculate that the Fe:Mn ratio in *A. sparsifolia* leaves is related to photosynthetic capacity and is influenced by the interaction of nitrogen and water.

Fe and Mn are essential microelements for plant growth and development, both participating in chloroplast synthesis, photosynthesis, and electron transport chains [?]. Fine roots are the entry point for these heavy metal elements into *A. sparsifolia*. Due to their low mobility, heavy metals accumulate in large quantities in fine roots and are affected by water status but not by nitrogen addition. The response of heavy metals in leaves and fine roots of *A. sparsifolia* to soil resource fluctuations differs, with leaf heavy metal stoichiometric ratios being more sensitive to environmental changes than fine roots (Table 1, Table 2).

### **3.3 Correlations Between Nutrient Element Stoichiometric Characteristics in Leaves and Fine Roots of *A. sparsifolia***

K is a necessary element for plant growth and metabolism, playing important roles in plant water conduction, transpiration, and osmotic regulation. Ca is a major component of cell walls. Although in terms of quantity, the elemental stoichiometric ratios in leaves and fine roots of *A. sparsifolia* responded similarly

to nitrogen addition (Table 1), the demand for macroelements, especially K and Ca, was greater in leaves to maintain aboveground physiological activities under drought background. The results showed that under well-watered conditions, the coupling of nitrogen and water could coordinate the utilization of these important elements by aboveground parts to some extent.

Compared with fine roots, leaf N:P ratio was less sensitive to nitrogen addition and water treatment ( $P > 0.05$ ). Among the 36 element pairs in fine roots and leaves of *A. sparsifolia*, 12 element pairs reached significant levels between organs (vs. 10 pairs within organs), with 7 positive and 5 negative correlations. This indicates that under nitrogen and water fluctuations, the nutrient synergy between leaves and fine roots of *A. sparsifolia* is higher than within organs, and the nutrient network in roots is more complex than in leaves. This is because the nutrient turnover capacity differs between leaves and fine roots of *A. sparsifolia*, with the root system requiring more comprehensive nutrient demand for rapid turnover to occupy more space. The lower sensitivity of leaf N:P ratio is related to strong plant drought tolerance. Inter-organ element correlations were mainly concentrated between leaf macroelements (such as N, P, K) and various elements in fine roots, consistent with previous discussions.

#### 4 Conclusion

This study investigated the ecological stoichiometric characteristics of leaves and fine roots of *A. sparsifolia* and their responses to nitrogen and water addition, drawing the following conclusions: (1) Except for leaf P content, the nutrient status of leaves and fine roots of *A. sparsifolia* was independently or interactively affected by nitrogen and water addition. Under drought conditions, nitrogen addition facilitated the absorption of N, Mn, Zn, and Cu by fine roots rather than leaves; (2) Microelements (such as Mn, Zn, Cu, Fe) were mainly enriched in fine roots, while *A. sparsifolia* allocated macroelements such as N, P, and K preferentially to aboveground parts; (3) Applying  $3.0 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$  nitrogen under drought stress, or  $6.0$  or  $9.0 \text{ g} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$  nitrogen under well-watered conditions, could alleviate nitrogen limitation in fine roots of *A. sparsifolia* ( $\text{N:P} < 14$ ). However, this increased the phosphorus limitation of *A. sparsifolia*; (4) There were complex interactions among nutrient elements within and between organs of *A. sparsifolia* leaves and fine roots. The occurrence rate of these relationships was greater between organs than within organs, followed by fine roots, and lowest in leaves.

These conclusions enrich our understanding of the interactions between desert plants and environmental resources and can provide references for nutrient management of desert vegetation in arid regions. Considering the limitations of pot experiments and single plant age, the general applicability of these conclusions needs to be verified through more relevant studies in desert ecosystems in the future.

## References

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