



Response of soil properties to C, N, and P stoichiometry of plants in Qilian Mountains, China

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ABSTRACT

Subsequent findings reveal the combination characteristics and spatial patterns of plant functional traits, and their response and adaptation to environmental changes in the Qinghai-Tibet Plateau. We analyzed the variation in characteristics and the influence of environmental factors on leaf functional traits from 78 quadrats in July 2021, using: one-way ANOVA, Tukey's Honest Significant Difference (HSD) post hoc test, Pearson correlation coefficient (r) analysis, and redundancy analysis (RDA) in the Qilian Mountains. Only the leaf carbon content (LCC) of arbors was a weak variation indicator in leaf function traits of different plant types, whereas other leaf function traits including: the LCC of herbaceous plants (herbs) and shrub plants (shrubs), and the leaf nitrogen content (LNC) and carbon to nitrogen (C/N) ratio of arbors were medium variation indicators. The LNC, leaf phosphorus content (LPC), C/N ratio(C/N), C/P ratio(C/P), and N/P ratio (N/P)of herbs and shrubs, and the LPC, C/P, and N/P of arboreal plants (arbors) were strong variation indicators. Altitude was also one of the main factors affecting functional traits of plants in cold regions. Electrical conductivity (EC) and soil phosphorus content (SPC) were the main factors affecting changes in the leaf functional traits of herbs. Soil bulk density (SBD) and Soil salinity (SAL) were the main factors affecting changes in the leaf functional traits of shrubs. Soil nitrogen content (SNC) and soil temperature (ST) were the main factors affecting changes in the leaf functional traits of arbors.

1. Introduction

In recent years, climate change, characterized by global warming, has had a notable impact on terrestrial ecosystems and biodiversity, largely due to the rapid development of human society. Plants are a key component of both Earth's and terrestrial ecosystems (Yan et al., 2021; Feng et al., 2022). These environmental and climatic changes caused by global change significantly affect the normal growth of vegetation. Vegetation is particularly sensitive and responds to environmental, climatic, and global changes. Moreover, leaves are key organs for the normal growth and development of plants, and are the main organs responsible for assimilation, photosynthesis, and transpiration (Zeng et al., 2021). Compared with other plant organs, such as roots and stems, leaves have a large surface area; therefore, the contact area with the surrounding environment is larger. This point allows the leaf to adapt and respond to environmental and climate change (Hao et al., 2022).

Furthermore, leaves are the plant organs most sensitive to environmental and climate change (Ficken and Rooney, 2020). To a certain extent, plants adapt to various environmental conditions in their growing regions for normal growth and development; thus, some changes have occurred that majorly reflect in leaf functional traits (Song et al., 2020; 2021; 2022b). Therefore, the study of plant leaf functional traits and their relationships is of great significance to further understand the adaptive strategies of plants to the environment, and the impact of environmental changes on their external morphology and internal structure.

The adaptation of plants to their growth environment cannot be achieved by simply changing a single functional character. Instead, plant adaptation is achieved by changes in multiple functional characters along a certain environment or resource gradient (Hernández-Vargas et al., 2019). Adaptation allows continued normal plant growth, development, survival and reproduction. Functional character is

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interactive and interrelated between individual plants, and different flora growing in the same or similar habitat conditions may form the same or similar functional character combinations, which also briefly reflects the law of plant convergence and adaptation (Kervroëdan et al., 2018; Ruiz-Guerra et al., 2021). Plant functional traits can further reflect the nutrient balance and survival and adaptation strategies of plants. Plants with different plant heights have different competitive abilities for light acquisition. Plants with different plant heights often affect the light availability of the surrounding plants with shorter growth. The morphological characteristics of leaves can also indicate the strategies of plants in water use efficiency, growth mode and nutrient utilization. The concentration of carbon and nitrogen in leaves reflects the structure and photosynthetic capacity of leaves, and is related to photosynthetic rate, leaf life and decomposition rate. Plant roots are the main organs for plant individuals to compete with each other for matrix resources (Ruiz-Guerra et al., 2021). Research methods based on plant functional traits are very important for predicting plant growth, survival and reproduction. In recent years, the study of plant response and adaptation strategies to the environment has been a hot issue in ecological research. It is generally believed that using plant functional traits is a method to solve the complex network of plant-plant and plant-environment interactions, rather than relying on their taxonomic characteristics (Reich and Cornelissen, 2014; Freschet et al., 2018). The study of plant functional traits is helpful to understand the survival strategies and performance of plants in different environments. Due to the adaptability and plasticity of plants to the environmental gradient, the functional characteristics of different plants are very different. The species itself can reduce the environmental pressure and increase the acquisition of limited resources by adjusting their morphological and physiological characteristics, enhance their adaptability to the environment, and then improve their fitness (Wright et al., 2004; Freschet et al., 2018).

A systematic study showed that the maximum stomata of eight early succession tropical tree species in Southeast Asia has a significant relationship with the leaf nitrogen content (LNC) of plants. The maximum stomata is also closely related to the leaf area based on the functional characteristics of the tropical tree species. Additionally, the maximum atmospheric porosity of early succession tropical tree species has a significant negative correlation with plant leaf size (Jührbandt et al., 2004). Ryser and Urbas (2000) found that this rule generally exists in various broad-leaved, coniferous arbors, and herbaceous plants; that is, leaf life duration shows a significant negative correlation with LNC per unit weight and specific leaf area. Temperature, precipitation, light, and other climatic factors play major roles in the growth and distribution of plants. These climatic factors, exclusively or in combination, directly affect the morphological, physiological, and ecological characteristics of plant leaves. Schoettle (1990) found that the leaf life duration of plants was significantly shortened by high temperatures. The leaf phosphorus content (LPC) of plants showed a significant downward trend with increasing temperatures. Similarly, leaf nitrogen content (LNC) also showed a significant downward trend with increasing temperatures (Reich et al., 2004). Ackerly et al. (2002) found that the specific leaf area and leaf size decreased with increasing sunshine hours. McIntyre et al. (1999) studied the relationship between plant leaf functional properties and precipitation on a global scale, indicating that the LNC of plants significantly increases with increasing precipitation. Furthermore, altitude, slope, slope position, and aspect are the key topographic factors that affect the functional properties of plant leaves, because of gradient differences in precipitation levels, light intensity, temperature, soil quality, and other environmental factors under different topographic conditions. Li et al. (2006) studied the leaf functional properties of Alpine Sclerophyllous Oak and found that the leaf morphological characteristics showed a trend of increasing and then decreasing with an increase in altitude gradient. Han et al. (2005) analyzed 753 species in China and found that LPC and LNC increased with increasing altitude. In recent years, the application fields of plant characteristics have expanded, and scientific issues have involved many aspects of ecological

research. However, international ecological research mainly focuses on plant functional traits in arid and humid areas, whereas similar research in cold areas is scarce. This lack of research in cold areas is mainly because it remains a weak area of relevant research, and research on the response mechanisms of vegetation environmental factors pertaining to plant functional traits and plant functional diversity is lacking.

The Qilian Mountains are located in the ecologically fragile area of Western China, in the center of the Eurasian continent (Li et al., 2017). It is located at the intersection of the Qinghai-Tibet Plateau, Mengxin Plateau, and Loess Plateau (Wang and Hou, 2021). Moreover, it is an alpine, arid, and semi-arid area in Northwest China (Li et al., 2021) and is of great significance in maintaining the ecological balance of the Qinghai-Tibet Plateau, the stability of the Hexi Corridor Oasis, and the ecological security of Western China. As an important part of the national ecological security strategic pattern, the Qilian Mountains play an important role as an ecological barrier in water conservation and species diversity; therefore, this study selected the Qilian Mountains Region as the study area. This study aimed to (1) analyze the variation in the characteristics of leaf functional traits of different vegetation types, (2) explore the influence of environmental factors on leaf functional traits, and (3) discuss the response mechanisms of leaf functional traits to environmental changes. Subsequent findings revealed the combination characteristics and spatial patterns of plant functional traits, as well as their response and adaptation to environmental changes in the alpine region of the Qinghai-Tibet Plateau.

2. Materials and methods

2.1. Study area

The Qilian Mountains are located at the headstream of three major inland rivers: the Shiyang, Heihe, and Shule (Fig. 1). The Mountains are located at the intersection of the Qinghai-Tibet Plateau, the Loess Plateau and the Neimenggu-Xinjiang Plateau (Song et al., 2022a). The geographical coordinates of the area are between 36° 30' – 39° 30' N and 93° 20' – 103° E, spanning Gansu and Qinghai provinces, with a length > 1000 km. The Mountains have an alpine mountain forest grassland climate with complex natural conditions and wide range of hydrothermal conditions, which host a variety of vegetation and soil types with clear vertical gradients and horizontal differences. The Qilian Mountains have “high, cold and drought” characteristics (Li et al., 2015; 2019). The ecosystem has a simple structure and a single function, and is an ecologically fragile area. It is also the focus of research on soil and water conservation and vegetation restoration in arid alpine areas. Grassland accounts for 58% of the total area of the region and comprises the main ecosystem. Vertical zoning and east–west changes in vegetation are notable in the Qilian Mountains, and floristic components, including: temperate desert vegetation, alpine shrub and shrub meadow vegetation, alpine meadow, cushion vegetation, lichen, alpine sub ice, and snow-sparse vegetation, also change significantly with altitude.

2.2. Data and analysis

The sampling in this study was completed in July 2021 in the Qilian Mountains. A total of 78 quadrats were used in this study, and 34 plant species were investigated (Table 1). The sample line and quadrat surveys were combined for the entire study area, and the survey quadrat area was 20 m × 20 m. For the vegetation survey, five small quadrats (1 m × 1 m) were selected: four at the corners and one in the middle of the survey quadrat area. During the investigation and statistical analysis, we recorded the plant species observed in the entire quadrat and preliminarily determined the plant character value. The number, abundance, coverage, and height of objects in each quadrat were recorded. GPS was used to record the longitude, latitude, and altitude of each sample plot. LCC, LNC, and LPC were measured in all plants. During the survey, the dried leaves of each sample were crushed with a grinder, passed through

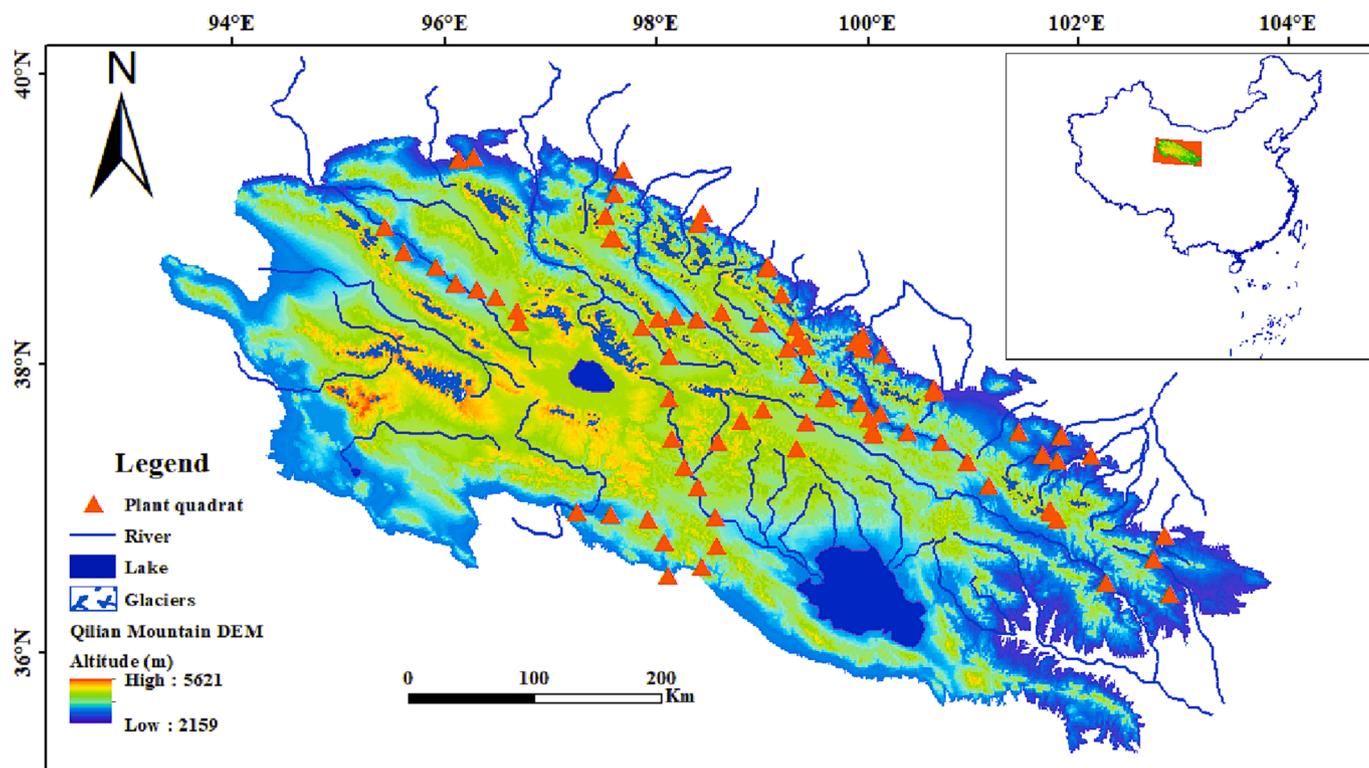


Fig. 1. Study area and the distribution of plant quadrat.

Table 1
The major plant species investigated in the Qilian Mountains.

Plant type	Major plant species
Herbs	Artemisia sacrorum, Saussurea amara, Thermopsis przewalskii, Plantago asiatica, Lancea tibetica, Oxytropis myriophylla, Carduus nutans, Saussurea japonica, Aster alpinus, Corethrodedron multijugum, Reaumuria soongarica, Oxytropis ochrocephala, Suaeda glauca, Stellera chamaejasme, Pedicularis sylvatica, Ranunculus japonicus, Saussurea pulchra, Gentiana macrophylla, Zygophyllum xanthoxylon, Potentilla chinensis, Reaumuria kaschgarica, Comarum salesovianum, Polygonum sibiricum, Ligularia sibirica, Oxygraphis glacialis, Kalidium foliatum, Thermopsis fabacean, Salsola passerina
Shrubs	Potentilla fruticosa, Potentilla glabra, Caragana sinica, Nitraria tangutorum
Arbors	Picea crassifolia, Juniperus przewalskii

a 0.5 mm sieve, and stored for measurement. LCC was determined using a MultiC/N3000 carbon–nitrogen analyzer manufactured in Germany. Moreover, during the determination of LNC and LPC, the samples were digested with H₂SO₄-H₂O₂. LNC was determined using an automatic Kjeldahl apparatus and LPC was determined using Molybdenum Antimony Colorimetry. In this study, Microsoft Excel software was used for preliminary data processing, and Origin software was used for mapping. SPSS 19.0 software was used for statistical data analysis, one-way ANOVA and Tukey’s Honest Significant Difference (HSD) post hoc test were used for variance analysis and significance testing ($\alpha = 0.05$) respectively. Pearson’s correlation (r) analysis was used to analyze the correlations between soil physical and chemical properties (including soil temperature (ST), soil moisture (SM), soil bulk density (SBD), Soil salinity (SAL), soil pH(pH), total dissolved solids(TDS), electrical conductivity(EC), Soil carbon content (SCC), Soil nitrogen content (SNC) and soil phosphorus content (SPC)) and plant leaf functional traits. Canoco5 was used for redundancy analysis (RDA). When performing RDA, a division trend correspondence analysis (DCA) was performed to estimate the gradient length of the sorting axis. RDA was used when the

gradient length was < 3 , DCA was used when the shaving length was > 4 , and both methods could be used when the shaving length was $3 > 4$.

3. Results

3.1. Distribution of plant functional traits

As shown in Table 2, the distribution ranges of LNC, LCC, C/N, and N/P in shrub plants (shrubs) was greater than that of herbaceous plants (herbs), whereas the distribution range of LPC and C/P of herbs was greater than that of shrubs, and the distribution range of shrubs was greater than that of arboreal plants (arbors). Moreover, the average

Table 2
The general pattern of plant functional traits of different plants.

Plants	Plant functional trait	Distribution range	Average value \pm SE	CV
Herbs	LCC	62.21–701.87	348.05 \pm 10.55	0.25
	LNC	1.39–39.20	16.26 \pm 1.27	0.64
	LPC	0.0018–4.38	0.34 \pm 0.078	1.85
	C/N	3.34–216.07	47.96 \pm 6.77	1.15
	C/P	78.02–183008.67	13507.78 \pm 3366.33	2.02
Shrubs	N/P	2.25–3039.34	563 \pm 96.63	1.39
	LCC	64.03–784.02	394.76 \pm 15.63	0.25
	LNC	1.27–55.01	14.66 \pm 1.67	0.72
	LPC	0.0029–2.56	0.35 \pm 0.085	1.54
	C/N	7.86–290.63	53.11 \pm 9.66	1.15
Arbors	C/P	138.27–156117.26	15106.22 \pm 4865	2.04
	N/P	4.25–3407.06	465.08 \pm 133.71	1.82
	LCC	381.74–466.91	438.92 \pm 13.59	0.075
	LNC	4.13–12.58	6.87 \pm 1.12	0.4169
	LPC	0.0029–2.33	0.49 \pm 0.34	0.41
Arbors	C/N	30.34–112.47	73.44 \pm 10.44	0.34
	C/P	163.64–156117.3	29459.45 \pm 23186.02	1.93
	N/P	5.39–2248.78	422.36 \pm 334.44	1.94

values of LCC, LPC, and C/P of arbors were higher than those of shrubs, whereas those of shrubs were higher than those of herbs. However, the LNC and N/P of herbs were higher than those of shrubs, whereas the LNC and N/P of shrubs were higher than those of arbors. The average C/N of shrubs was higher than that of herbs, whereas that of herbs was higher than that of arbors. This result indicated that the C assimilated by arbor photosynthesis provides more energy and substrate for plant physiological and biochemical processes than that of shrubs or herbs. Moreover, N and P are the most important nutrients in plant growth and development; therefore, LNC and LPC levels somewhat reflected the utilization and transformation of nutrients by plants. Generally, highly nutrient-rich plants have relatively high LNC and LPC levels. The coefficient of variation (CV) reflects the dispersion of the random variables. Particularly, the coefficient of variation of the LCC of herbs was equal to that of shrubs in the study area, while the CV of the LCC of shrubs was higher than that of arbors. Furthermore, the CV of the LNC of shrubs was greater than that of herbs, whereas the CV of the LNC of herbs was greater than that of arbors. Meanwhile, the CV of the LPC of herbs was greater than that of arbors, whereas the CV of the LPC of arbors was greater than that of shrubs. According to the standard (Song, 2017), only the LCC of arbors was a weak variation indicator in leaf function traits of different plant types, while other leaf function traits such as the LCC of herbs and shrubs, and the LNC and C/N of arbors were medium variation indicators. However, the LNC, LPC, C/N, C/P, and N/P of herbs and shrubs and the LPC, C/P, and N/P of arbors were strong variation indicators. This result showed that the leaf functional traits of different plant types varied greatly in the Qilian Mountains, which also indicated that different species have notable differences in leaf functional traits during long-term adaptation to the environment, and that the leaf function traits of the same species also vary greatly under the influence of different environmental conditions.

3.2. Correlation between leaf functional traits of different plant type

As shown in Table 3, there is a significant positive correlation between LCC-H and C/N-H ($P < 0.05$), LCC-A ($P < 0.01$), and C/N-A ($P < 0.05$), whereas there is a significant negative correlation between LCC-H and LNC-A ($P < 0.05$) and LPC-A ($P < 0.05$) (Table 2). There is a significant positive correlation between LNC-H and N/P-H ($P < 0.01$), LNC-A ($P < 0.01$), and LPC-A ($P < 0.05$), whereas significant negative correlations exist between C/N-H ($P < 0.01$), LCC-A ($P < 0.05$), and C/N-A ($P < 0.01$). However, there is a significant negative correlation between LPC-H and C/P-H ($P < 0.05$) and N/P-H ($P < 0.01$) (Table 2). There is a significant positive correlation between C/N-H and LCC-A ($P < 0.01$) and C/N-A ($P < 0.05$), and significant negative correlations exist between C/N-H and N/P-H ($P < 0.05$) and LNC-A ($P < 0.05$). However, there are significant positive correlations between C/P-H and N/P-H ($P < 0.01$), C/N-S ($P < 0.05$), and C/N-A ($P < 0.05$). Significant correlations exist between the N/P-H and LPC-A ($P < 0.05$). There is a significant positive correlation between LNC-S and LCC-A ($P < 0.05$) and C/P-A ($P < 0.05$), and significant negative correlations exist between LNC-S and LPC-A ($P < 0.05$). There is a significant negative correlation between LNC-S and LNC-A ($P < 0.05$) and LPC-A ($P < 0.01$). Particularly, there is a significant negative correlation between LPC-S and N/P-S ($P < 0.05$) and N/P-S and LCC-A ($P < 0.05$), and a significant positive correlation between C/P-S and N/P-S ($P < 0.01$). However, a significant positive correlation is observed between C/N-S and C/P-A ($P < 0.05$), whereas a significant negative correlation is observed between C/N-S and LPC-A ($P < 0.05$). There is also a significant negative correlation between LCC-A and LNC-A ($P < 0.05$) and LPC-A ($P < 0.05$), but there is a significant positive correlation between LCC-A and C/N-A ($P < 0.05$). There is a significant positive correlation between LNC-A and LPC-A ($P < 0.01$), whereas a significant negative correlation is observed between LNC-A and C/N-A ($P < 0.01$). However, there is a significant positive correlation between the C/P-A and N/P-A

Table 3

The Correlation among leaf functional traits of different plant type (H represents herbs, S represents shrubs, A represents arbors).

	LCC-H	LNC-H	LPC-H	C/N-H	C/P-H	N/P-H	LCC-S	LNC-S	LPC-S	C/N-S	C/P-S	N/P-S	LCC-A	LNC-A	LPC-A	C/N-A	C/P-A	N/P-A	
LCC-H	1																		
LNC-H	-0.090	1																	
LPC-H	0.090	-0.137	1																
C/N-H	0.259*	-0.760**	-0.056	1															
C/P-H	-0.023	-0.101	-0.246*	0.238	1														
N/P-H	-0.069	0.541**	-0.354**	-0.313*	-0.226	-0.209	1												
LCC-S	0.202	0.068	-0.010	0.048	-0.062	-0.068	0.023	1											
LNC-S	0.150	0.010	0.053	0.134	-0.132	-0.121	0.006	-0.022	1										
LPC-S	0.223	-0.142	-0.016	0.292	0.062	-0.068	0.006	-0.597**	-0.141	1									
C/N-S	-0.093	-0.020	-0.126	-0.135	0.329*	0.304	0.185	-0.597**	-0.287	0.085	1								
C/P-S	0.061	0.271	-0.101	-0.237	0.046	0.125	0.144	-0.108	-0.316*	-0.186	0.804**	1							
N/P-S	0.004	0.297	-0.041	-0.197	-0.061	0.001	0.033	0.166	-0.316*	0.337	-0.858*	-0.337	1						
LCC-A	0.994**	-0.737*	0.357	0.941**	0.447	-0.434	0.635*	-0.770*	0.378	0.637	-0.330	0.342	-0.721*	1					
LNC-A	-0.691*	0.837**	0.018	-0.737*	-0.554	0.511	-0.437	0.805*	0.034	-0.396	-0.327	0.512	-0.725*	0.906**	1				
LPC-A	-0.684*	0.676*	-0.168	-0.612	-0.249	0.741*	-0.741*	0.972**	-0.141	-0.706*	0.173	-0.272	0.717*	-0.930**	-0.703	1			
C/N-A	0.709*	-0.856**	-0.130	0.818*	0.752*	-0.240	0.192	-0.582	-0.127	0.160	0.108	-0.368	0.307	-0.056	-0.303	-0.068	1		
C/P-A	0.362	0.347	-0.217	-0.001	-0.016	-0.128	0.688*	-0.422	-0.208	0.765*	0.109	-0.366	0.302	-0.051	-0.301	-0.074	1.000**	1	
N/P-A	0.357	0.352	-0.214	-0.007	-0.024	-0.130	0.689*	-0.420	-0.206	0.765*	0.109	-0.366	0.302	-0.051	-0.301	-0.074	1.000**	1	1

**There was significant correlation at the 0.01 level (bilateral). * There was significant correlation at the 0.05 level (bilateral).

($P < 0.01$). Therefore, a significant correlation exists between the plant functional traits of herbs, shrubs, and arbors, which may be due to the necessary relationship between different plants in adapting to cold environments. Additionally, the plant functional traits of herbs and arbors are closely related, which is largely due to the close relationship between different plant functional traits within a plant species.

4. Discussions

4.1. Effects of altitude on plant functional traits

Altitude gradient is often considered the most important environmental factor affecting plant leaf function traits. Variation in plant leaf function traits along an altitude gradient can demonstrate the impact of environmental changes on such traits (Richards et al., 2011; Song et al.,

2022b). Changes in the elevation gradient affect many environmental factors, such as water, air, heat, and soil quality in the region. As the elevation gradient in a region increases, so does the light intensity, whereas the temperature, air pressure, and carbon dioxide concentration decrease (Richards et al., 2011). Water and temperature conditions in the environment are redistributed, affecting plant growth. Variations in environmental conditions also cause variations in the leaf functional traits of plants. In addition, studies have shown that varying temperature and precipitation characteristics at different altitude gradients play an important role in the soil formation process within forest ecosystems (Song, 2017). As shown in Fig. 2, the LCC of herbs increased with increasing altitude, whereas the LCC of shrubs and arbors ($P < 0.05$) decreased with increasing altitude. Moreover, the LNC of herbs ($P < 0.05$) and arbors ($P < 0.05$) increased significantly with increasing altitude, whereas that of shrubs ($P < 0.05$) decreased significantly with

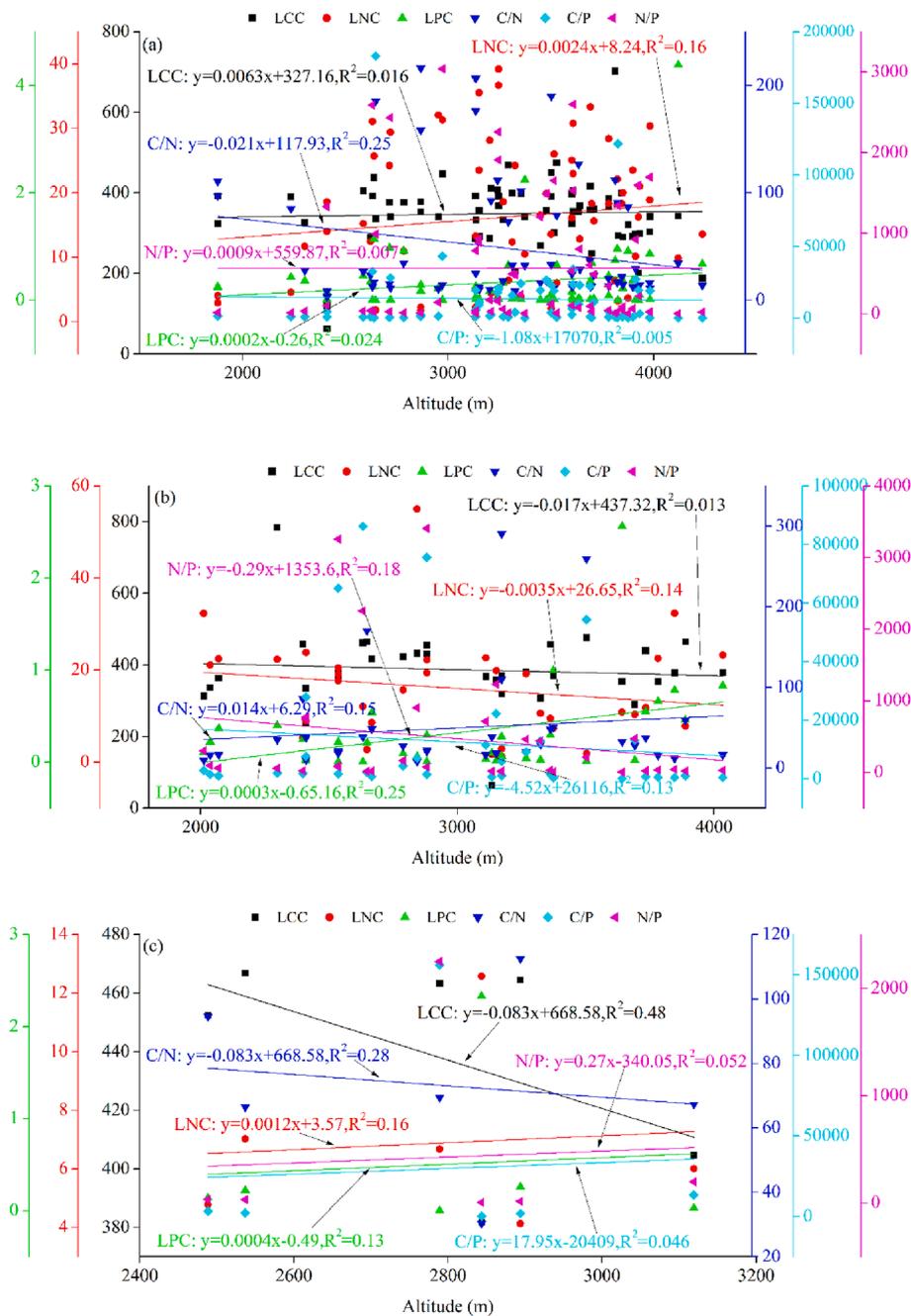


Fig. 2. Effects of altitude on functional characters of different types of plants.

increasing altitude. [Luo et al. \(2005\)](#) studied the response of leaf functional traits of plants to altitude gradient at a national-regional scale and found that the LNC of plants also decreased significantly with the increasing altitude. LPC increased significantly in herbs and shrubs ($P < 0.05$) and arbors ($P < 0.05$) with increasing altitude. [Craine and Lee \(2003\)](#) researched leaf functional traits of herbs in New Zealand and found that the LNC of herbs decreased significantly with the increasing altitude. [Han et al. \(2005\)](#) analyzed 753 plant species in China and found that both LPC and LNC increased with increasing altitude, whereas the leaf N/P remained unchanged. Particularly, the C/N of herbs ($P < 0.05$) and arbors ($P < 0.05$) decreased significantly with increasing altitude, while the C/N of shrubs ($P < 0.05$) increased significantly with increasing altitude. The C/N reflects the ability of plants to absorb nutrients and assimilate C, which can show the nutrient utilization efficiency of plants, to a certain extent. With increasing altitude, the C/N of herbs and arbors decreased significantly, which indicates that the nitrogen use efficiency of herbs and arbors decreases with increasing altitude. However, the C/P of herbs and shrubs ($P < 0.05$) decreased with increasing altitude, while the C/P of arbors increased with increasing altitude. The N/P of herbs and arbors increased with increasing altitude, whereas the N/P of shrubs decreased significantly with increasing altitude.

4.2. Effects of soil physical and chemical properties on plant functional traits

As shown in [Fig. 3](#), the LCC and SPC of the herbs showed a significant positive correlation, whereas the LCC and SBD showed a significant negative correlation. Moreover, the LNC of herbs were positively correlated with SPC, electrical conductivity (EC), SAL, TDS, and ST, whereas it was negatively correlated with SNC and SCC. However, the LNC of shrubs was positively correlated with SNC and SCC, whereas it was negatively correlated with SBD. Similar to LNC, the C/N of the herbs was positively correlated with SPC, EC, SAL, TDS, and ST, whereas it was negatively correlated with SNC and SCC. However, the C/N of shrubs was positively correlated with SBD, whereas LNC was negatively correlated with SNC and SCC. The N/P of herbaceous plants was negatively correlated with SPC, EC, SAL, and TDS, whereas it was positively correlated with SNC. The LPC and SNC of tree plants showed a significant positive correlation. Soil has the closest relationship with the functional properties of plant leaves ([Song, 2017](#)). Plants improve soil quality by decomposing the nutrient cycle of leaf litter; however, soil quality has an impact on the direction and speed of vegetation growth and community succession. The key soil factors affecting the functional properties of leaves differ. Therefore, studying the response of leaf functional traits of different plant types to varying soil factors is crucial to reveal ecological adaptation strategies at the community level ([Begum et al., 2023](#)).

Leaves are the primary functional organs of plants. Plants adapt to the environment primarily through changes in their leaf characteristics. Nutrient content and plant growth are also reflected by the leaves to a certain extent. By studying the influence of environmental factors on plant chemometric characteristics, the adaptation of plants to the external environmental factors can be explored. The DCA was used to determine the gradient length of the sorting axis. The gradient length of the sorting axis is 0.9 (<3), therefore it is optimal for RDA.

According to the RDA of herbs ([Fig. 4](#)), the correlation coefficients of plant leaf functional traits and influencing factor ordination axes 1 and 2 were 0.7615 and 0.6139, respectively. Ordination axes 1 and 2 explained 75.44% and 10.43% of the total difference in the functional traits of the plant leaves, respectively. The first two ordination axes cumulatively explained 85.87% of the relationship between the plant functional traits and influencing factors, indicating that they contained the majority of the data. The results showed that pH, SPC, SM, SAL, TDS, EC, ST, and SBD were positively correlated with ordination axis 1, of which SM had a high correlation (0.792), and EC had a low correlation

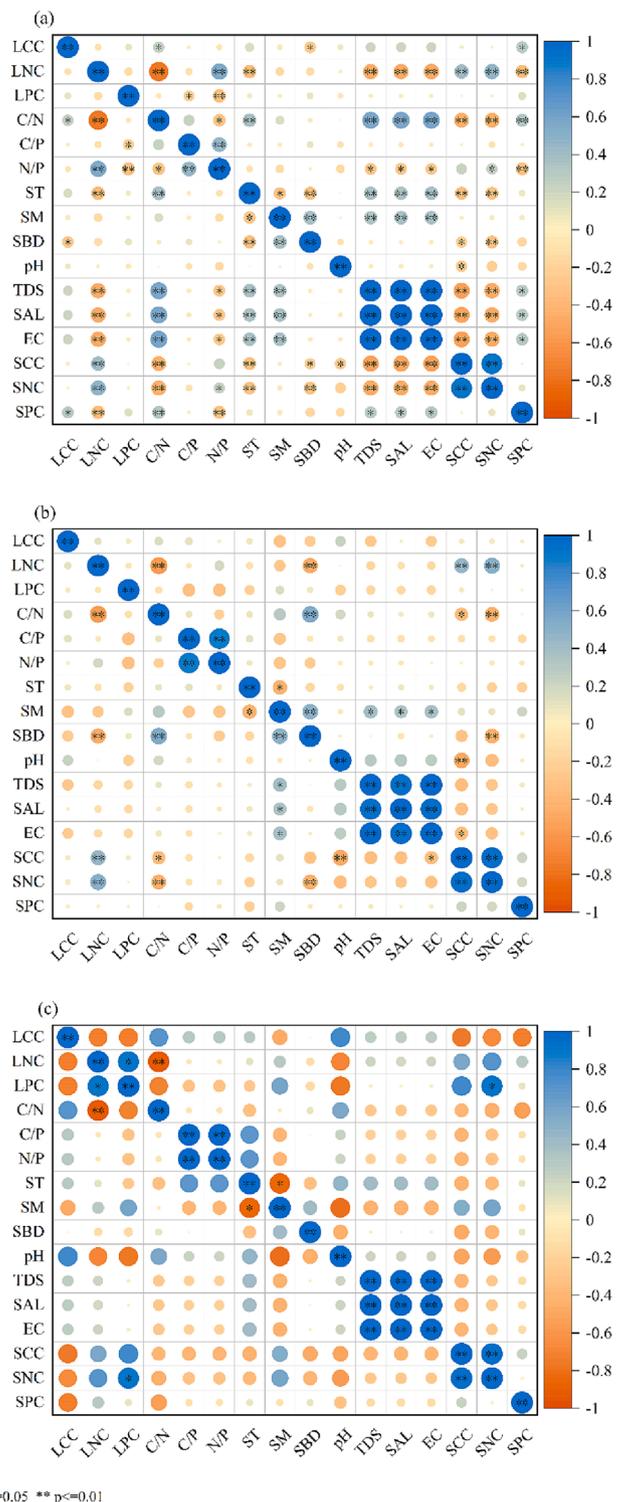


Fig. 3. Effects of soil physical and chemical properties on plant functional traits (a: herbs; b: shrubs; c: arbors).

(0.002). SNC and SCC were negatively correlated with ordination axis 1, whereas SCC had a high correlation (-0.324) and SNC had a low correlation (-0.008). According to the RDA ranking chart of the characteristics of functional traits and influencing factors of herb leaves ([Fig. 4](#)), LCC, LPC, C/N, and C/P of herb plants were located in the positive area of ordination axis 1, whereas LNC and N/P were located in the negative area of ordination axis 1. The explanatory degree of influence factors on the chemometric characteristics of evergreen tree leaves ([Fig. 4](#)) shows

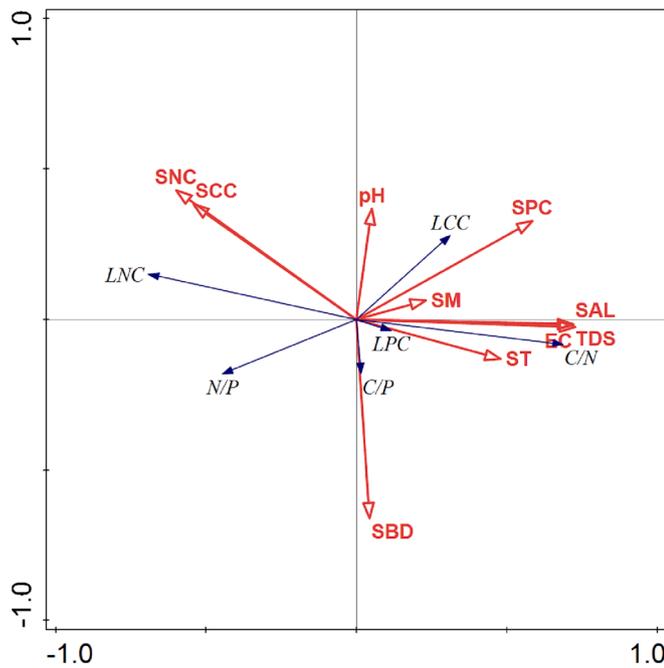


Fig. 4. RDA ordering diagram of soil physical and chemical properties on plant functional traits of herbs.

that the explanatory degree of EC and SPC on the characteristics of leaf plant functional traits were 41.4% and 13.6%, respectively, and the total explanatory degree of both was 55%. From the degree of interpretation, SNC, SCC, SAL, pH, ST, TDS, SBD, and SM were 16%, 5.2%, 4.5%, 4.5%, 3.6%, 5%, 4.1%, and 2.1%, respectively. Overall, the physical and chemical properties of the soil had a significant impact on the functional properties of herb leaves. The gradient length of the sorting axis is 0.8 (<3), therefore it is optimal for RDA.

According to the RDA of shrubs (Fig. 5), the correlation coefficients of the plant leaf function traits and influencing factor ranking axes 1 and 2 were 0.8583 and 0.6482, respectively. Ordination axes 1 and 2

explained 52.59% and 21.77% of the total difference in the functional traits of the plant leaves, respectively. The first two ordination axes cumulatively explained 74.36% of the relationship between the plant functional traits and influencing factors, indicating that they contained most of the data. The results showed that SAL, SBD, SM, SPC, EC, and TDS were positively correlated with ordination axis 1, of which SPC had a high correlation (0.958) and SBD had a low correlation (0.006). SNC, SCC, ST, and pH were negatively correlated with ordination axis 1, where SCC had a high correlation (-0.894) and pH had a low correlation (-0.126). According to the RDA ranking chart of the characteristics of functional traits and influencing factors of shrubs leaves (Fig. 5), LPC and C/N of shrub plants were located in the positive area of ordination axis 1, and LCC, LNC, C/P, and N/P were located in the negative area of ordination axis 1. The explanatory degree of influence factors on the chemometric characteristics of evergreen tree leaves (Fig. 5) shows that the explanatory degree of SBD and SAL on the characteristics of leaf plant functional traits was 28.3% and 16.2%, respectively, and the total explanatory degree of both was 44.5%. From the interpretation degree, SNC, SM, EC, TDS, pH, ST, SCC, and SPC were 8.2%, 8.9%, 8.3%, 10.4%, 11.8%, 4.7%, 1.9%, and 1.3%, respectively. The physical and chemical properties of soil had a significant impact on the functional properties of shrub leaves. The gradient length of the sorting axis was 0.9 (<3); therefore, it was optimal for RDA.

According to the RDA of arbors (Fig. 6), the correlation coefficients of plant leaf function traits and influence factor ranking axes 1 and 2 were 0.5789 and 0.335, respectively. Ordination axes 1 and 2 explained 57.89% and 33.50% of the total difference in the functional traits of the plant leaves, respectively. Ordination axes 1 and 2 cumulatively explained 91.39% of the relationship between the plant functional traits and influencing factors, indicating that they contained the majority of the data. According to the results, SNC, SCC and SM had a positive correlation with ordination axis 1, of which SCC had a strong correlation (0.981) and SNC had a weak correlation (0.14). ST and pH were negatively correlated with ordination axis 1, and both had the same correlation values (-0.298). According to the RDA ranking chart of the characteristics of functional traits and influencing factors of arbor leaves (Fig. 6), the LPC and LNC of arbors were located in the positive area of ordination axis 1, and the LCC, C/N, C/P, and N/P were located in the

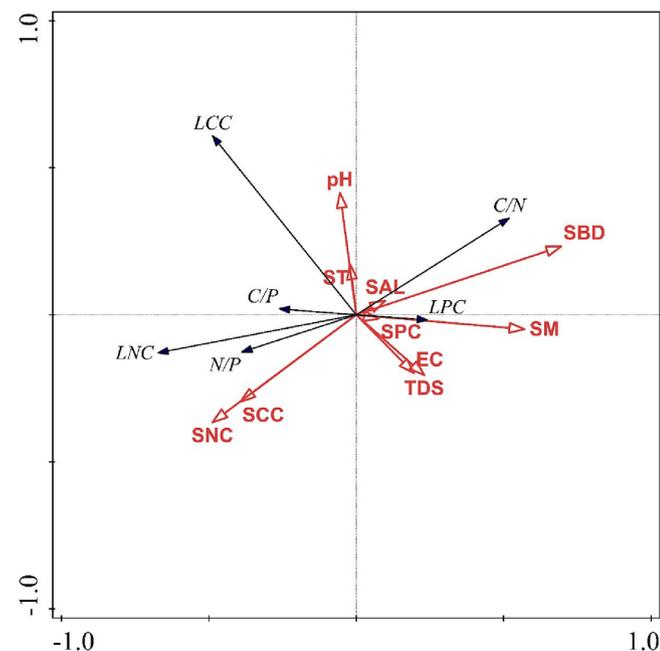


Fig. 5. RDA ordering diagram of soil physical and chemical properties on plant functional traits of shrubs.

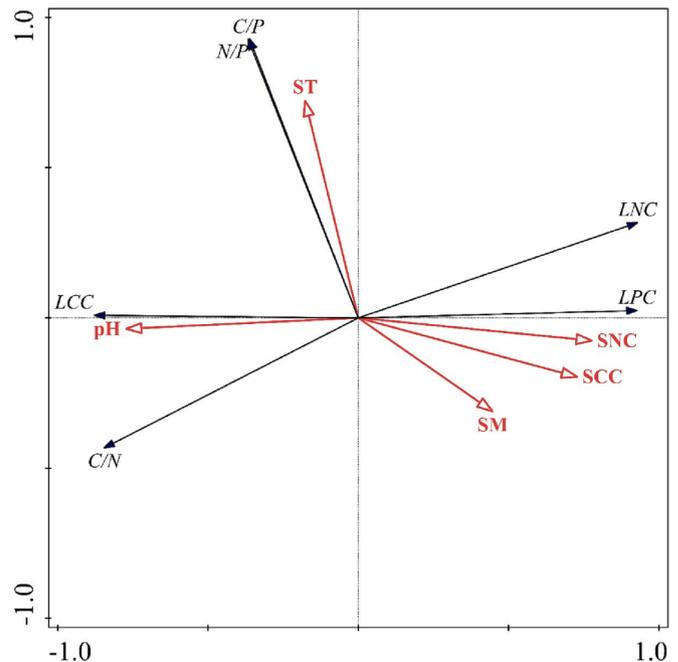


Fig. 6. RDA ordering diagram of soil physical and chemical properties on plant functional traits of arbors.

negative area of ordination axis 1. The explanatory degree of the factors influencing the chemometric characteristics of evergreen tree leaves (Fig. 6) show that the explanatory degrees of SNC and ST on the characteristics of leaf functional traits were 36.1% and 20.5%, respectively. The total explanatory degree is 56.6%. From the degree of interpretation, SM, pH, and SCC were 16.7%, 17.8%, and 9%, respectively. The physical and chemical properties of the soil had a significant impact on the functional properties of arbors.

A strong material transformation relationship exists between plants and soil (Chai et al., 2016). Plant litter is decomposed into nutrients and returned to the soil under the action of microorganisms; simultaneously, the nutrients released by plant roots change the physical and chemical properties of the soil. However, water and nutrients required for plant growth are provided by the soil and have an important impact on changes in plant functional properties (Zhang et al., 2019). This study found that the leaf functional properties of different types of plants correlated with soil factors, indicating that the leaf functional properties of different types of plants responded significantly to variations in soil factors.

As an important part of the grassland ecosystem, soil stores large amounts of C, N, P, potassium (K), and other nutrients that play vital roles in plant growth (Song et al., 2022b). These elements not only maintain fertility but also contribute to protecting the balance of materials and energy in grassland ecosystems. Organic C and N contained in the soil, which are important ecological factors in grassland ecosystems, have received considerable attention from researchers and have become core components of sustainable development research on grassland ecosystems (Song et al., 2022b; Begum et al., 2023). The influence of soil physical and chemical properties on the characteristics of plant leaves and plant functional properties, such as carriers of plant growth, soil nutrient metabolism, and photosynthesis, are inseparable from the supply of soil nutrients. Soil nutrients are affected by ground vegetation, rainfall, land use patterns, and ecosystem types. SCC is an important material basis for soil fertility and belongs to active parts of the soil (Song, 2017; Wang et al., 2020). Its content and dynamic changes play an important role in soil productivity, land use and protection, and the global carbon cycle. C is one of the main elements in the dry matter composition of plants. Plants use C mainly through the carbon assimilation process in plant photosynthesis, and then return it to the soil in the form of litter. In the analysis of the characteristics of leaf plant functional properties in relation to influencing factors, SCC has a negative correlation with LCC; however, the impact is not significant, which may be related to plants' ability to utilize atmospheric CO₂. N and P content in the plant leaves was positively correlated with N and P content in the soil, indicating high SNC and SPC. Plants readily absorb N and P, which indicates that plant demand for these elements is high, therefore plants in the study area are limited by the availability of N and P in the soil (Song, 2017; 2022b; Maza-Villalobos et al., 2022; Wang et al., 2022).

Soil acidity and alkalinity affect both soil fertility and nutrient availability. In general, the higher the pH value is, the lower the soil organic carbon and total nitrogen content is (Duan et al., 2022). Soil factors and leaf functional traits of different plant types responded to each other, among which EC and SPC were the main influencing factors affecting changes in the leaf functional traits of herbs; SBD and SAL were the main influencing factors affecting changes in the leaf functional traits of shrubs; and SNC and ST were the main influencing factors affecting changes in the leaf functional traits of arbors. This study explored the changes in leaf functional traits of plants in the Qilian Mountains, and the adaptation strategies of leaf functional traits to environmental changes. Further research is needed to integrate other environmental factors to explore the relationship between the leaf functional traits of different plant types and other environmental factors in the Qilian Mountains.

5. Conclusions

We analyzed variations in leaf characteristics and the influence of environmental factors on leaf functional traits in the Qilian Mountains. The average LCC, LPC, and C/P values of arbors were higher than those of shrubs, whereas those of shrubs were higher than those of herbs. However, the LNC and N/P of herbs were higher than those of shrubs, whereas the LNC and N/P of shrubs were higher than those of arbors. The average C/N of shrubs was higher than that of herbs, whereas that of herbs was higher than that of arbors. Only the LCC of arbors was a weak variation indicator of leaf functional traits in different plant types, and other leaf functional traits such as the LCC of herbs and shrubs and the LNC and C/N of arbors were medium variation indicators. However, LNC, LPC, C/N, C/P, and N/P of herbs and shrubs and LPC, C/P, and N/P of arbors were strong variation indicators.

The LCC of herbs increased with increasing altitude, whereas the LCC of shrubs and arbors decreased with increasing altitude. The LNC of herbs and arbors increased significantly with increasing altitude, whereas the LNC of shrubs decreased significantly with increasing altitude. LPC increased significantly in herbs, shrubs, and arbors with increasing altitude. Furthermore, the LCC and SPC of the herbs showed a significant positive correlation, whereas LCC and SBD showed a significant negative correlation. The LNC of herbs was positively correlated with SPC, EC, SAL, TDS, and ST, whereas it is negatively correlated with SNC and SCC. However, the LNC of shrubs was positively correlated with SNC and SCC, whereas it was negatively correlated with SBD. Similar to LNC, the C/N of the herbs was positively correlated with SPC, EC, SAL, TDS, and ST, whereas it was negatively correlated with SNC and SCC. The N/P of the herbs was negatively correlated with SPC, EC, SAL, and TDS, whereas it is positively correlated with SNC. Additionally, the LPC and SNC of the arbors show a significant positive correlation.

According to the RDA of herbs, shrubs, and arbors, soil factors and leaf functional traits of different types of plants respond to each other, among which EC and SPC are the main influencing factors affecting the changes in leaf functional traits of herbs, SBD and SAL are the main influencing factors affecting changes in leaf functional traits of shrubs, and SNC and ST are the main influencing factors affecting the changes in leaf functional traits of arbors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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