

Article

Evaluation of Soil Fertility in Alpine Shrub Communities of the Qilian Mountains, Northwest China

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Abstract: Understanding soil fertility is significant for the restoration and scientific management of shrub vegetation in the Qilian Mountains. This study focused on the soils associated with five common alpine shrub species—*Salix gilashanica*, *Potentilla fruticosa*, *Caragana jubata*, *Caragana tangutica*, and *Berberis diaphana*. We examined soil fertility characteristics, analyzed the relationships among soil fertility indicators, and evaluated the comprehensive fertility status of soil within shrub communities using principal component analysis. The results indicated that (1) the mean values of soil organic matter, total nitrogen, and total phosphorus were 77.94, 3.85, and 0.74 g kg^{−1}, respectively; (2) the soil organic matter and total nitrogen content were significantly higher than the national averages, while the total phosphorus content was slightly lower; and (3) the soil pH and total potassium showed weak variability, the total phosphorus content exhibited moderate variability, and other nutrient indicators (including soil organic matter, total nitrogen, alkali-hydrolyzable nitrogen, available phosphorus, available potassium, soil bulk density, and soil water content) exhibited strong variability. Soil organic matter exhibited a significant positive correlation with total nitrogen, alkali-hydrolyzable nitrogen, and soil water content but negatively correlated with soil pH and bulk density. Total nitrogen was positively correlated with alkali-hydrolyzable nitrogen, available phosphorus, and soil water content but negatively correlated with soil pH and soil bulk density. Total phosphorus demonstrated a positive correlation with total potassium and soil bulk density, whereas total potassium was negatively correlated with available phosphorus. The order of soil fertility of the five communities was *Salix gilashanica* > *Potentilla fruticosa* > *Berberis diaphana* > *Caragana jubata* > *Caragana tangutica*. The soil fertility index, based on PCA, indicated that *Salix gilashanica* exhibited the highest fertility status. The findings of this study provide a theoretical reference for the restoration and reconstruction of shrub vegetation, the enhancement of soil fertility, and the improvement of fragile ecosystems in the Qilian Mountains. It also provides essential insights for soil restoration and sustainable ecosystem management in alpine environments.

Keywords: alpine; shrubs; soil fertility; principal component analysis; Qilian Mountains



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1. Introduction

Soil nutrients provide essential support for vegetation growth, while the decomposition of vegetation residues replenishes these nutrients, with microorganisms playing a key

role in the process [1]. A comprehensive evaluation of soil nutrient status is critical for the sustainable management of shrub ecosystems. Soil fertility, a fundamental attribute and essential feature of soil, is mainly reflected in soil organic matter, nitrogen, phosphorus, potassium, and other nutrient indicators [2]. It significantly affects vegetation growth, distribution, community composition, and productivity. Conversely, the growth and distribution of vegetation affect the cycling and availability of soil nutrients [3–5]. Therefore, understanding soil properties and fertility status is essential for optimizing soil resource use, and it has become a key focus of research both domestically and internationally [6,7].

Soil fertility quality refers to the soil's capacity to sustain plant productivity and preserve or enhance water and air quality, which is assessed through indicators like nutrient content and fertility indices [8]. Soil fertility indices mainly include nitrogen, phosphorus, potassium, and other nutrient contents in soil. During soil development, soil nutrient content varies according to soil type and region, mainly determined by the type of soil parent material, soil erosion, and human factors [9]. Moreover, due to terrain attributes [10] and climate factors [11], there are notable differences in the spatial distribution of soil nutrients at local and regional scales. In alpine mountainous areas, the terrain of shrub forests is complex. Topography influences soil fertility not only at a regional scale but also within different soil depths, affecting nutrient availability. Therefore, this study aimed to explore the soil fertility status of different shrub forests, providing technical support for ensuring the sustainable and healthy development of the soil ecology in shrub forests.

The Qilian Mountains, situated on the northeastern edge of the Qinghai–Tibetan Plateau, play a significant role in the conservation of water resources, regulation of climate, and protection of biodiversity [12]. In these high-elevation regions, evergreen and alpine deciduous shrubs dominate the landscape and are the primary vegetation type [13]. These ecosystems are essential for sustaining the ecological integrity of the Hexi Corridor and preserving biodiversity in China. However, since the 1950s, a combination of environmental factors and anthropogenic activities has substantially reduced the shrubland areas [14]. In response, the Chinese government implemented the Natural Forest Resource Protection Project to protect forest resources and improve ecosystem services [15]. Over the past 20 years, shrub cover has increased and dominated certain meadows in the Qilian Mountains [16]. Recent studies on the shrubs of the Qilian Mountains highlighted that (1) the shrubs resist harsh conditions by increasing leaf carbon content, although their growth is often restricted by nitrogen [17]; (2) the soil nutrient content in shrub patches varies with depth and location, and the content is higher at the center, in the Eastern Qilian Mountains [18]; (3) shrublands with higher biomass have improved soil moisture, carbon, and nitrogen content [19]; and (4) soil available nitrogen is significantly positively correlated with other available nutrients in the subalpine shrub zone throughout the growing season [20]. However, there is still a lack of research on soil fertility quality evaluation of shrub communities in the Qilian Mountains.

To address this concern, the specific objectives of this study were to (1) determine the fertility characteristics of shrub communities in the Qilian Mountains; (2) reveal the relationship between the fertility factors of shrub communities; and (3) evaluate the soil fertility status of different shrub types. This research also aimed to provide theoretical references for vegetation restoration and soil fertility improvement.

2. Materials and Methods

2.1. Experimental Site

Our study area is in the Dayekou watershed of the Qilian Mountains, Gansu province, Northwest China. The central location is 100°15' E, 38°31' N, and the total area is 73.32 km², with an elevation range of 2590 to 4645 m (Figure 1). This region experiences a temperate

continental climate, with cold, dry winters largely influenced by the Mongolian anticyclone, resulting in minimal precipitation. The annual average temperatures range between -0.6°C and 2.0°C , with a mean annual precipitation of 434 mm, an average annual evaporation of 1081.7 mm, and an average annual relative humidity of 60%. Soils are classified according to the FAO classification system as Haplic Kastanozems and Haplic Phaeozems [21]. The dominant vegetation includes tree species such as *Juniperus przewalskii* kom and *Picea crassifolia* kom, along with alpine shrubs, specifically *Berberis diaphana* Maxim, *Caragana tangutica* Maxim. ex Kom, *Caragana jubata* (Pall.) Poir, *Salix gilashanica* C. Wang & P. Y. Fu, and *Potentilla fruticosa* (L.) Rydb [17].

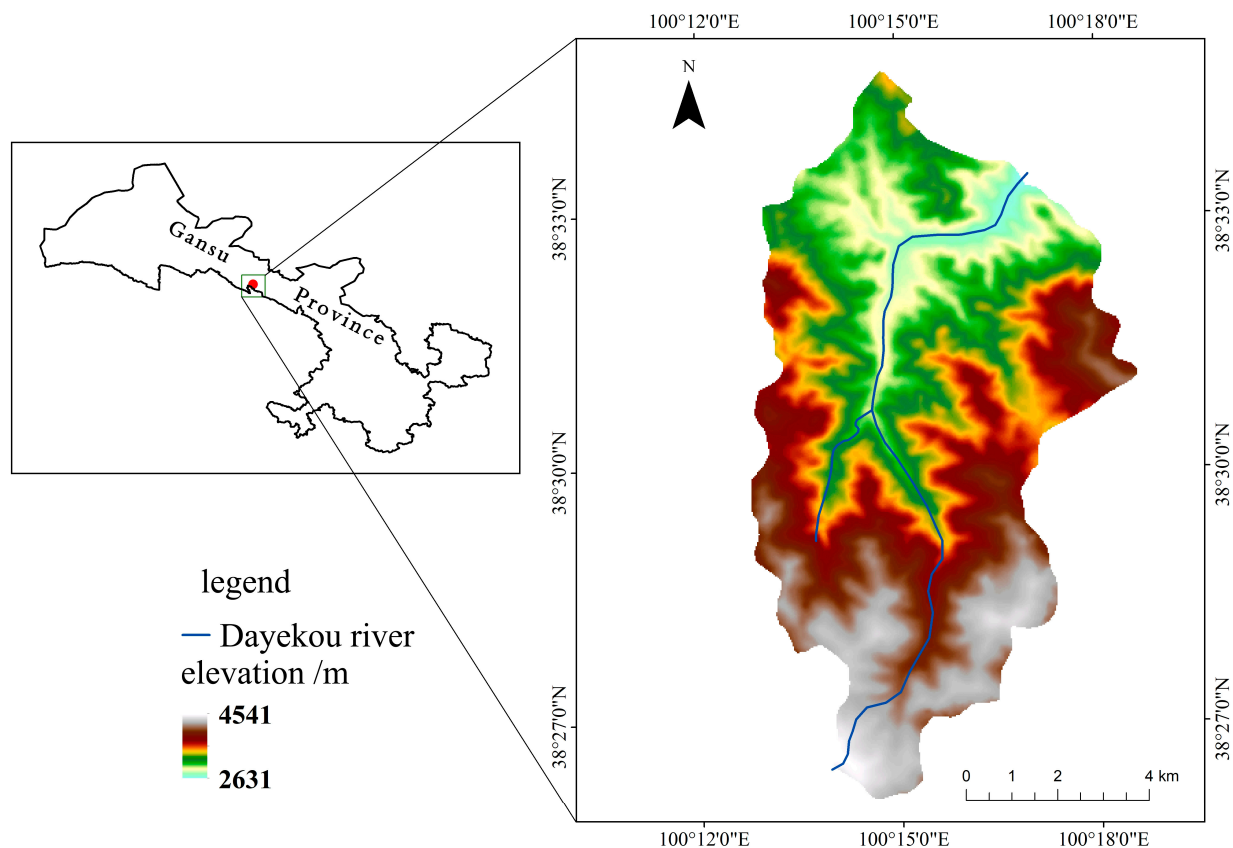


Figure 1. Geographic location of the Dayekou watershed.

2.2. Experimental Design

To ensure typicality and representativeness, we selected five typical shrub communities, *Berberis diaphana*, *Caragana tangutica*, *Caragana jubata*, *Salix gilashanica*, and *Potentilla fruticosa*, as the research subjects. For each community, three survey plots measuring 20×20 m were established, resulting in a total of fifteen plots (Figure 2). Then, each sample plot was divided into $5 \text{ m} \times 5 \text{ m}$ grids by the grid method, resulting in a total of 240 grids. For each grid, we recorded detailed information on geographical location, elevation, slope gradient, slope aspect, and other relevant data. Additionally, we documented shrub-specific characteristics, including species composition, plant height, crown width, basal diameter, and coverage (Table 1).

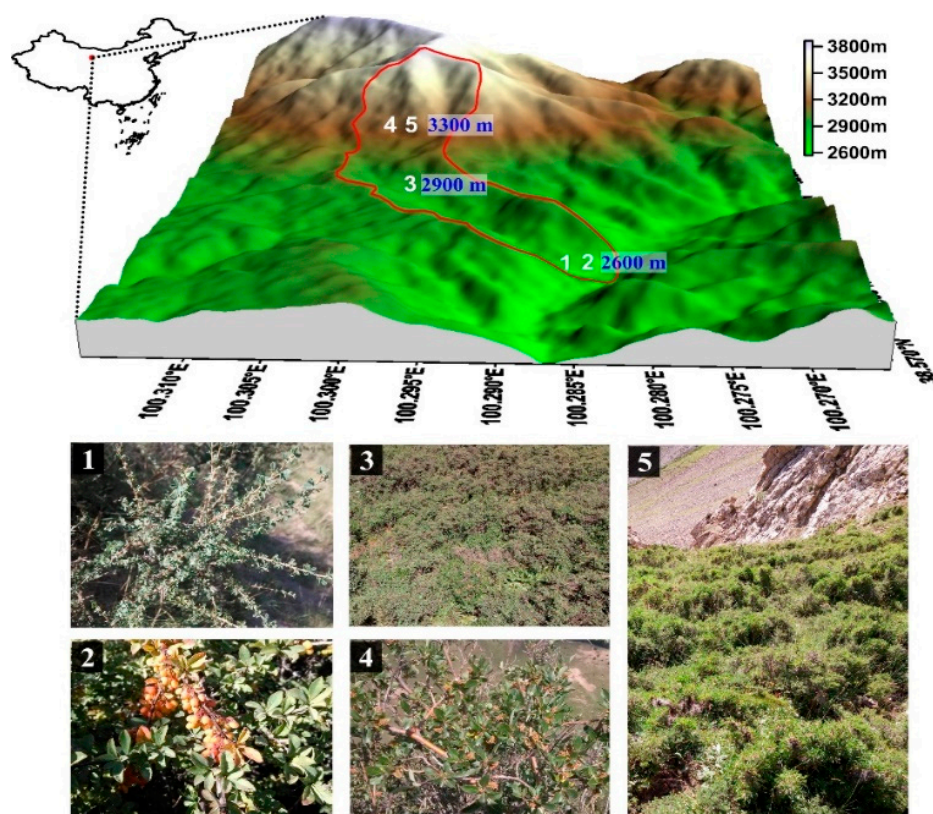


Figure 2. Location of study area and sample plots. Note: No. 1 represents *Caragana tangutica*, no. 2 represents *Berberis diaphana*, no. 3 represents *Potentilla fruticosa*, no. 4 represents *Salix gilashanica*, and no. 5 represents *Caragana jubata*.

Table 1. Basic information on sampling plots.

Vegetation Type	Soil Depth (cm)	Soil Type	Elevation (m)	Slope Gradient (°)	Slope Aspect (°)	Growth Status	Basal Diameter (mm)	Coverage (%)	Average Height (m)
<i>Caragana jubata</i>	60	Alpine meadow soil	3300	40	NE	Average growth	20	60	0.60
<i>Salix gilashanica</i>	60	Alpine meadow soil	3300	32	NE	Good growth	26	55	1.40
<i>Potentilla fruticosa</i>	60	Alpine meadow soil	2900	33	E	Optimal growth	16	90	0.90
<i>Berberis diaphana</i>	60	Chestnut soil	2600	30	W	Average growth	20	70	1.80
<i>Caragana tangutica</i>	60	Chestnut soil	2600	22	SW	Average growth	25	50	1.40

2.3. Soil Sample Collection and Analysis

In August 2022, soil samples were collected from five shrub communities located at elevations ranging from 2600 m to 3300 m, each exhibiting distinct biological characteristics and growth environments (Table 1). For each shrub species, three replicate plots were established. Within each plot, five sampling points were selected using a diagonal sampling method. At each point, a soil profile was excavated, and after removing the litter layer and biological crusts, soil texture and color were recorded. Soil samples were collected at five depth intervals (0–60 cm) based on regional soil classification guidelines and root distribution patterns. For bulk density (BD) and soil water content (SWC) analysis,

three replicates from each depth interval were collected using a 200 cm³ ring knife and transported to the laboratory. Additionally, composite soil samples were collected from the same five depth intervals (0–60 cm). Composite soil samples were also taken from the same depth intervals. These samples were air-dried, ground, sieved, and analyzed for soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), alkali-hydrolyzable nitrogen (AN), available phosphorus (AP), available potassium (AK), and pH. Three replicates from each depth were thoroughly mixed before analysis.

Soil BD and SWC were measured using the oven-drying method. Soil pH was measured at a soil–water ratio of 1:2.5 (weight–weight). SOM was measured using the dichromate oxidation method. Soil TN was measured using the semi-micro Kjeldahl method, whereas soil AN was measured using the alkaline dispersion method. Soil TP and soil available phosphorus (AP) were measured by the phosphorus vanadium molybdate yellow colorimetric method. Furthermore, soil TK and AK were measured using the molybdenum antimony anti-colorimetric and flame photometry methods [22,23].

2.4. Statistical Analyses

We used one-way ANOVA to test the significance of soil fertility indicators among different shrub patches, with multiple comparisons performed using the Duncan method at a significance level of 0.05. The comprehensive soil fertility index was calculated based on principal component analysis (PCA). In this study, SOM, TN, TP, TK, AN, AP, AK, pH, BD, and SWC were used as indicators for the calculation of a comprehensive soil fertility index. Through PCA, we obtained the common factor variances, loading matrix, and contribution rates of the principal components. The principal component eigenvector was calculated by dividing the loading matrix values by the square root of the eigenvalue of the corresponding component. The principal component factor score for each shrub community was derived by multiplying the principal component eigenvector with the standardized data. The comprehensive soil fertility index was then calculated using a weighted method, expressed as follows:

$$\text{IFI} = \sum W_i \times F_i$$

where W_i represents the contribution rate of each principal component, and F_i denotes the principal component factor score of each shrub community.

Figures were prepared using R (version 4.0.1), and statistical analyses were conducted using R (version 4.0.1) and SPSS Statistics (version 25.0).

3. Results

3.1. Statistical Analysis of Soil Physicochemical Properties

The soil physicochemical properties of the 0–60 cm layer for five typical shrub patches are presented in Table 2. The SWC ranged from 16.79% to 116.49%, with an average of 55.09% and a coefficient of variation (CV) of 75%, indicating strong variability. Notably, the SWC for the *Potentilla fruticosa*, *Caragana jubata*, and *Salix gilashanica* patches exceeded 50%, while the SWC for the *Caragana tangutica* and *Berberis diaphana* patches had lower values of 16.79% and 23.27%, respectively. Notably, the *Salix gilashanica* patches demonstrated a significantly higher SWC compared to the other shrub patches ($p < 0.05$). The BD ranged from 0.39 to 0.90 g cm^{−3}, with an average of 0.58 g cm^{−3} and a CV of 39%, indicating strong variability. The soil in the *Caragana tangutica* patches exhibited a significantly higher BD than the other shrub patches ($p < 0.05$), while the *Caragana jubata* and *Salix gilashanica* patches had lower BD values, with no significant difference between them ($p > 0.05$). The soil pH values ranged from 6.64 to 8.54, with an average of 7.95 and a CV of 9%, indicating

weak variability. Except for *Salix gilashanica*, the soils associated with the other four shrubs were alkaline. The SOM content ranged from 23.69 to 129.18 g kg⁻¹, with an average of 77.94 g kg⁻¹ and a CV of 51%, indicating strong spatial heterogeneity. The *Salix gilashanica* patches had a significantly higher SOM content than the other shrub patches ($p < 0.05$). The TN ranged from 1.88 to 6.10 g kg⁻¹, with an average of 3.85 g kg⁻¹ and a CV of 44%, indicating strong variability. The *Salix gilashanica* patches also showed a significantly higher TN than the other shrub patches ($p < 0.05$). The TP content ranged from 0.48 to 0.91 g kg⁻¹, with an average of 0.70 g kg⁻¹ and a CV of 22%, demonstrating moderate variability, with considerable differences among the shrub patches. The TK content ranged from 11.40 to 14.78 g kg⁻¹, with an average of 13.67 g kg⁻¹ and a CV of 10%, indicating weak variability, with minimal differences between the shrub patches. The AN content ranged from 135.00 to 602.60 mg kg⁻¹, with an average of 359.84 mg kg⁻¹ and a CV of 52%, showing strong variability. Notably, there was no significant difference between the soils associated with *Salix gilashanica* and *Potentilla fruticosa* ($p > 0.05$), but significant differences were observed with the other shrub patches ($p < 0.05$). The AP content ranged from 3.22 to 8.13 mg kg⁻¹, with an average of 5.93 mg kg⁻¹ and a CV of 45%, implying strong variability. In a similar manner to AN, no significant difference was found between the soils associated with *Salix gilashanica* and *Potentilla fruticosa* ($p > 0.05$), but significant differences were observed with the other shrub patches ($p < 0.05$). No significant differences were found among the *Caragana jubata*, *Potentilla fruticosa*, and *Berberis diaphana* patches ($p > 0.05$). Finally, the AK content ranged from 52.74 to 192.96 mg kg⁻¹, with an average of 115.84 mg kg⁻¹ and a CV of 57%, indicating strong variability. The *Potentilla fruticosa* patch exhibited a significantly higher AK than the other shrub patches.

Table 2. Characteristics of soil physiochemical properties in shrub patches (0–60 cm). Different lowercase letters indicate significant differences between soils associated with different vegetation types ($p < 0.05$).

Vegetation Type	SWC (%)	BD (g·cm ⁻³)	pH	SOM (g·kg ⁻¹)	TN (g·kg ⁻¹)	TP (g·kg ⁻¹)	TK (g·kg ⁻¹)	AN (mg·kg ⁻¹)	AP (mg·kg ⁻¹)	AK (mg·kg ⁻¹)
<i>Caragana tangutica</i>	16.79 c	0.90 a	8.45 a	23.69 c	1.88 d	0.78 b	14.15 ab	135.00 c	3.41 b	52.74 c
<i>Berberis diaphana</i>	23.27 c	0.49 c	8.54 a	59.85 b	3.38 bc	0.66 c	14.78 a	336.40 b	6.88 a	59.72 c
<i>Potentilla fruticosa</i>	61.00 b	0.72 b	8.38 a	106.97 a	4.79 ab	0.91 a	13.56 b	496.60 a	8.01 a	192.96 a
<i>Caragana jubata</i>	57.92 b	0.39 c	7.72 b	70.01 b	3.09 cd	0.48 d	11.40 c	228.60 bc	8.13 a	151.60 ab
<i>Salix gilashanica</i>	116.49 a	0.40 c	6.64 c	129.18 a	6.10 a	0.68 c	14.48 ab	602.60 a	3.22 b	122.20 b
Mean value	55.09	0.58	7.95	77.94	3.85	0.70	13.67	359.84	5.93	115.84
Standard deviation	41.27	0.23	0.75	40.13	1.71	0.15	1.42	187.89	2.68	65.48
Variable coefficient %	0.75	0.39	0.09	0.51	0.44	0.22	0.10	0.52	0.45	0.57

Note: The different lowercase letters in the table indicate that there are significant differences in the soil physiochemical index among different shrubs ($p < 0.05$).

3.2. Spatial Variability in Soil Physicochemical Properties

3.2.1. Spatial Variability in BD and SWC

As the soil depth increased, the BD of *Caragana tangutica* increased first and then decreased, with the maximum value measured in the 10–20 cm soil layer (1.02 ± 0.14 g·cm⁻³) and the minimum in the 40–60 cm soil layer (0.71 ± 0.10 g·cm⁻³). The BD of *Berberis diaphana*, *Potentilla fruticosa*, *Caragana jubata*, and *Salix gilashanica* showed an increasing trend, with the minimum value recorded in the 0–10 cm soil layer (Figure 3a). As the soil depth increased, the SWC of *Caragana tangutica* decreased first and then increased, with the highest value in the 0–10 cm soil layer and the lowest in the 30–40 cm soil layer. The SWC of *Berberis diaphana* showed a fluctuating trend, with the maximum value in the 0–10 cm soil layer and the minimum in the 20–30 cm soil layer. The change in SWC in each soil layer of *Caragana jubata* was small (53.98–65.55%). The SWC of *Caragana jubata* and *Salix gilashanica* showed a decreasing trend (Figure 3b).

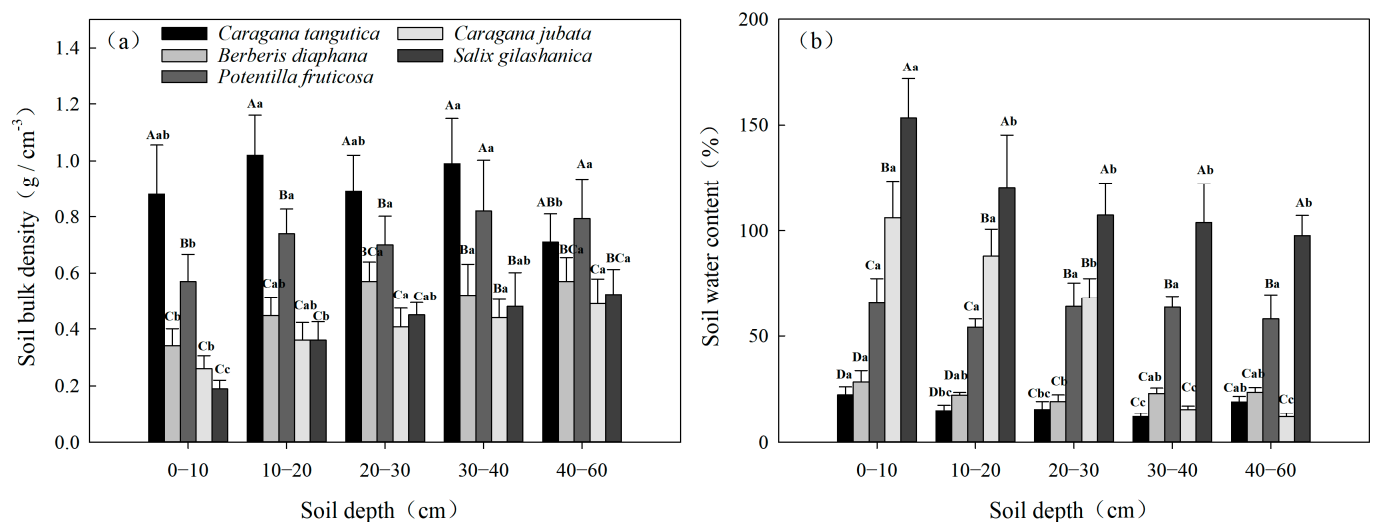


Figure 3. Vertical distribution of soil bulk density (a) and soil water content (b) of different shrub types. Different lowercase letters indicate significant difference among different soil layers of the same shrub, while different uppercase letters indicate significant difference among different shrubs of the same soil layer ($p < 0.05$).

3.2.2. Spatial Variability in SOM and pH

As the soil depth increased, the SOM of the five shrubs showed a decreasing trend, demonstrating a distinct “surface accumulation phenomenon” (Figure 4a). The soil pH value of the five shrubs showed little change, being alkaline with the exception of *Salix gilashanica* (Figure 4b).

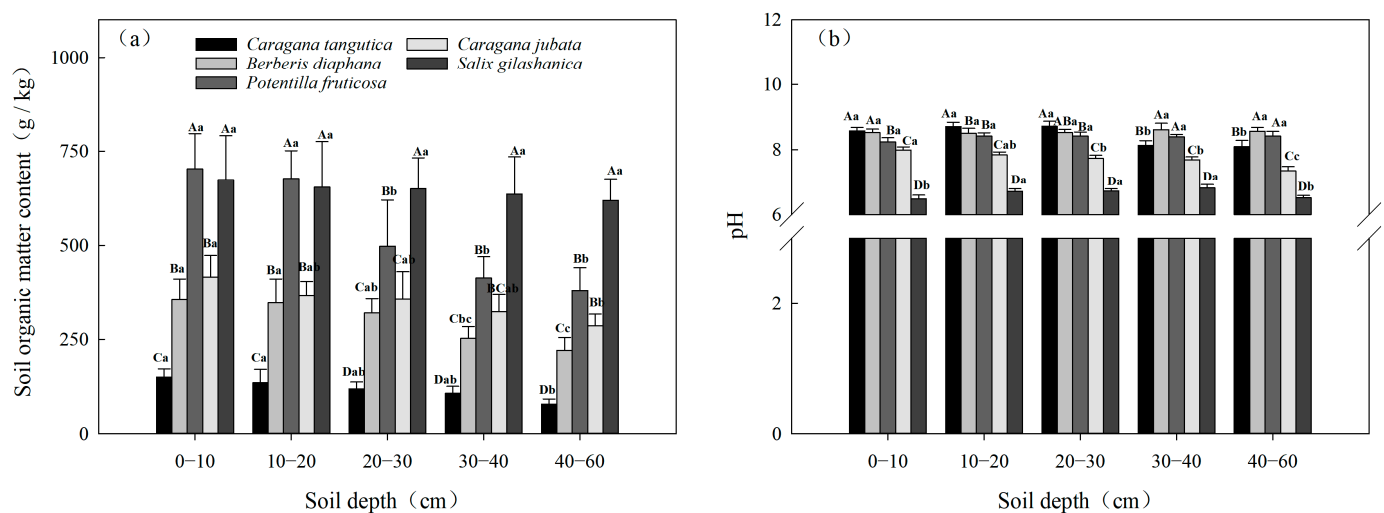


Figure 4. Vertical distribution of soil organic matter (a) and pH (b) of different shrub types. Different lowercase letters indicate significant difference among different soil layers of the same shrub, while different uppercase letters indicate significant difference among different shrubs of the same soil layer ($p < 0.05$).

3.2.3. Spatial Variability in TN and AN

As the soil depth increased, the total nitrogen (TN) content in *Caragana tangutica* exhibited minor variation. In contrast, the TN content of *Berberis diaphana*, *Potentilla fruticosa*, and *Caragana jubata* showed a decreasing trend. For *Salix gilashanica*, the TN content decreased first and then increased, with the highest value recorded in the 0–10 cm soil layer and the lowest in the 30–40 cm soil layer (Figure 5a). As the soil depth increased, the AN content of *Caragana tangutica* in the 0–10 cm soil layer was significantly higher than that recorded in the 30–60 cm soil layer. The AN content of *Berberis diaphana* and *Caragana jubata* in the 0–10 cm soil layer was significantly higher than that in the other soil layers. For *Potentilla fruticosa*, the AN content in the 0–10 cm soil layer was significantly higher than the 20–60 cm soil layers. However, there was no significant difference in the AN content of *Salix gilashanica* among different soil layers (Figure 5b).

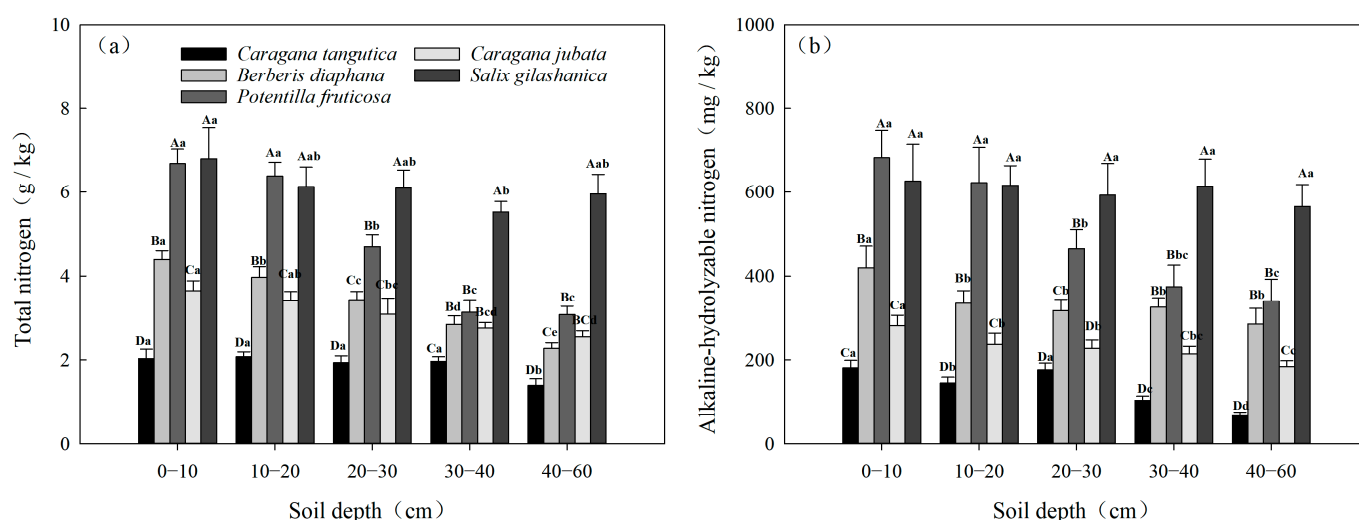


Figure 5. Vertical distribution of soil total nitrogen (a) and alkaline-hydrolyzable nitrogen (b) of different shrub types. Different lowercase letters indicate significant difference among different soil layers of the same shrub, while different uppercase letters indicate significant difference among different shrubs of the same soil layer ($p < 0.05$).

3.2.4. Spatial Variability in TP and AP

As the soil depth increased, the TP content in *Caragana tangutica*, *Potentilla fruticosa*, *Caragana jubata*, and *Salix gilashanica* exhibited relatively minor variations. In contrast, the TP content of *Berberis diaphana* decreased first, then increased, and then decreased, with the highest value recorded in the 30–40 cm soil layer and the lowest in the 10–20 cm soil layer (Figure 6a). As the soil depth increased, the AP content of *Caragana tangutica* increased first and then decreased; the AP content in the 0–10 cm soil layer was significantly lower than in the other soil layers. The AP content of *Berberis diaphana* showed a fluctuating upward trend, while it increased first and then decreased in *Caragana jubata*, showing a decreasing trend. The AP content in *Salix gilashanica* increased first and then decreased, with the highest value recorded in the 10–20 cm soil layer and the lowest in the 30–40 cm soil layer (Figure 6b).

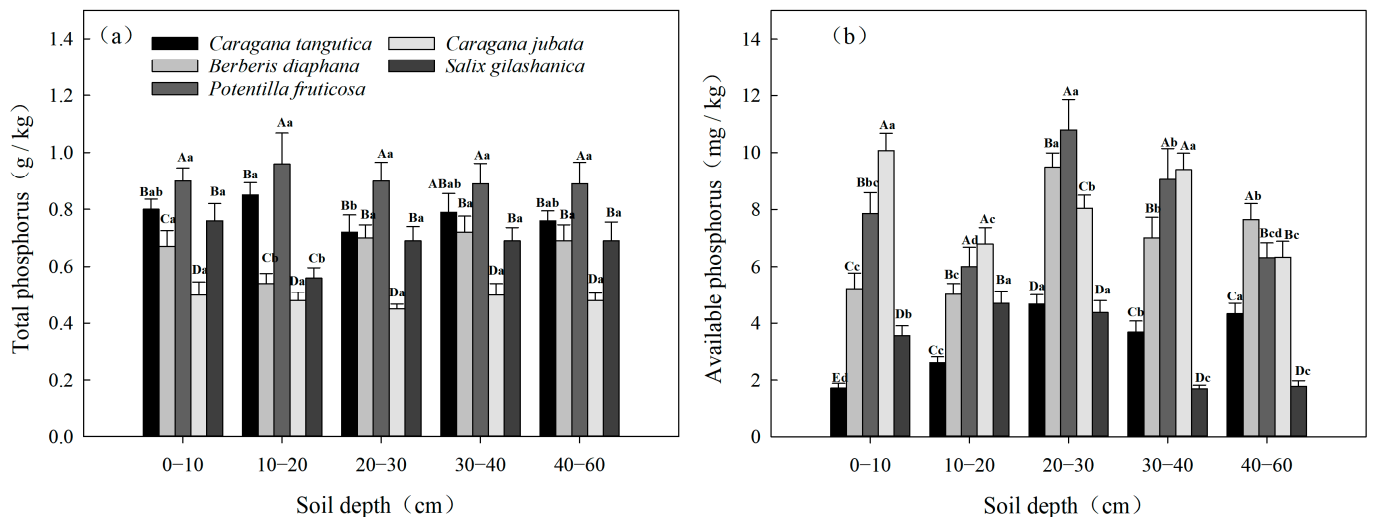


Figure 6. Vertical distribution of soil total phosphorus (a) and available phosphorus (b) of different shrub types. Different lowercase letters indicate significant difference among different soil layers of the same shrub, while different uppercase letters indicate significant difference among different shrubs of the same soil layer ($p < 0.05$).

3.2.5. Spatial Variability in TK and AK

As the soil depth increased, the TK content in *Caragana tangutica*, *Potentilla fruticosa*, *Caragana jubata*, and *Salix gilashanica* showed a fluctuating trend. In contrast, the TK content of *Berberis diaphana* decreased gradually. Notably, the TK content in the 0–10 cm soil layer was significantly higher than that in other soil layers ($p < 0.05$) (Figure 7a). As the soil depth increased, the AK content in *Caragana tangutica*, *Berberis diaphana*, and *Caragana jubata* decreased gradually, and the AK content in the 0–10 cm soil layer was significantly higher than that in other soil layers ($p < 0.05$). For *Potentilla fruticosa* and *Salix gilashanica*, the AK content decreased first and then increased, and the value recorded in the 0–10 cm soil layer was significantly higher than in other soil layers ($p < 0.05$) (Figure 7b).

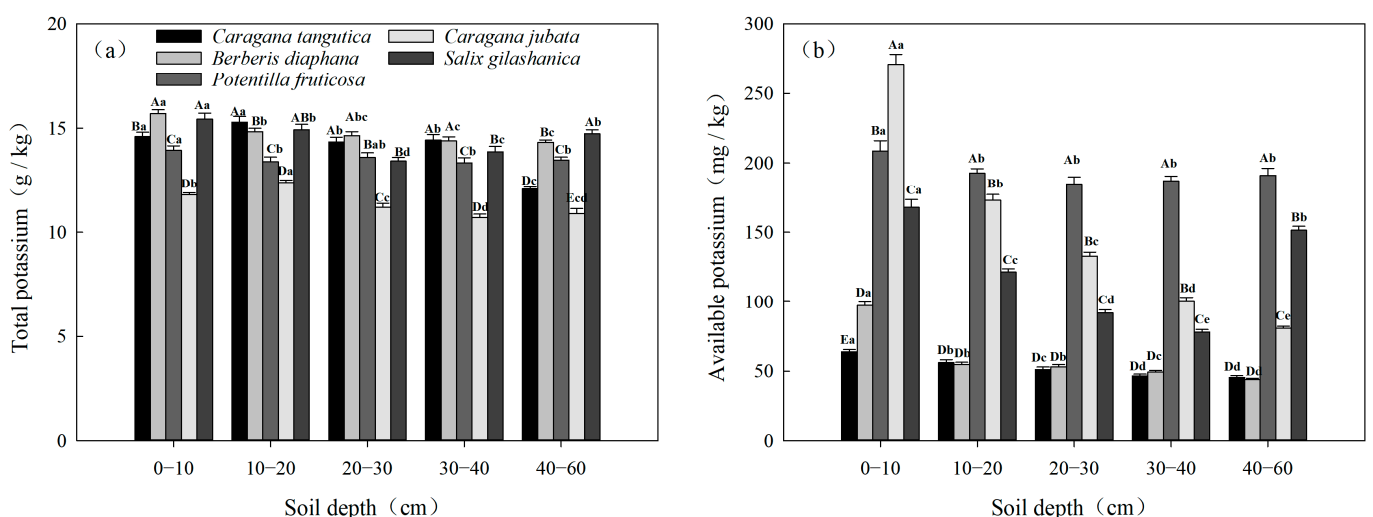


Figure 7. Vertical distribution of soil total potassium (a) and available potassium (b) of different shrub types. Different lowercase letters indicate significant difference among different soil layers of the same shrub, while different uppercase letters indicate significant difference among different shrubs of the same soil layer ($p < 0.05$).

3.3. Correlation Analysis of Soil Physicochemical Properties

Pearson's correlation analysis indicated that SOM exhibited a significant positive correlation with TN, AN, and SWC, while it was negatively correlated with pH and BD. TN was positively correlated with AN and AP, as well as with SWC, but negatively correlated with pH and BD. TP exhibited a positive correlation with TK and BD, whereas, TK was only negatively correlated with AP. AN was positively correlated with AK and SWC, but negatively correlated with pH and BD. Additionally, AP was positively correlated with AK, and AK was positively correlated with SWC. Conversely, SWC was negatively correlated with both BD and pH, and pH was negatively correlated with BD as well (Figure 8).

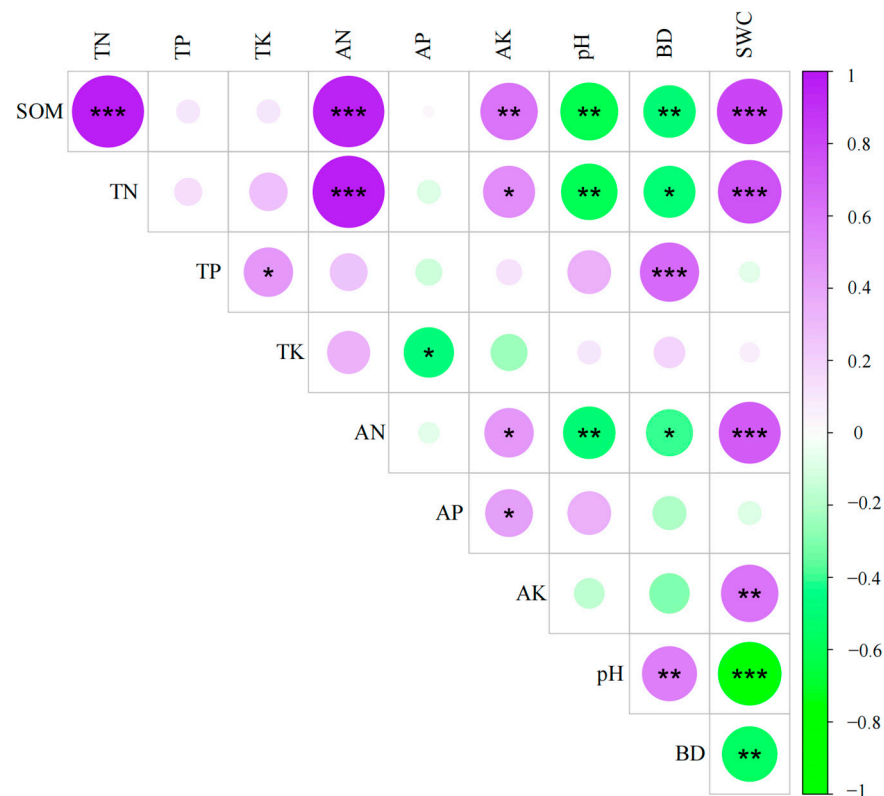


Figure 8. Pearson's correlation heatmap of soil properties. The color intensity represents the strength and direction of the relationships between variables (purple and green colors indicate positive and negative correlations, respectively, whereas light and white colors represent weak and no correlations, respectively). Asterisks indicate statistical significance (* $p < 0.05$; ** $p < 0.01$; and *** $p < 0.001$).

3.4. Principal Component Analysis of Soil Fertility Indicators

Principal component analysis (PCA) was employed to assess the soil fertility indices of shrub ecosystems. According to the criteria of an eigenvalue greater than 1 and a cumulative variance contribution rate exceeding 85%, it was determined that the eigenvalues of the first three principal components were 2.190, 1.480, and 1.260, respectively, with a cumulative contribution rate of 86.00% (Table 3). This result indicates that these three principal components collectively explained 86.00% of the total variability in the original dataset, effectively capturing the variation in soil fertility. Consequently, the first three components were selected for further analysis.

Table 3. Total variance analysis table of principal component analysis.

Principal Components	Initial Eigenvalue			Sum of Square Loadings		
	Eigenvalue	Contribution Rate %	Cumulative Contribution Rate %	Eigenvalue	Contribution Rate %	Cumulative Contribution Rate %
1	2.190	48.000	48.000	2.190	48.000	48.000
2	1.480	22.000	70.000	1.480	22.000	70.000
3	1.260	16.000	86.000	1.260	16.000	86.000
4	0.827	6.800	92.600			
5	0.624	3.900	96.500			
6	0.423	1.800	98.300			
7	0.307	0.940	99.200			
8	0.237	0.560	99.760			
9	0.142	0.200	99.960			
10	0.060	0.035	100.000			

Let F_i represent the i -th evaluation index of soil fertility, while $X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9$, and X_{10} denote SOM, TN, TP, TK, AN, AP, AK, pH, BD, and SWC, respectively. The expressions for the three principal components are as follows:

$$F_1 = 0.441X_1 + 0.431X_2 - 0.019X_3 + 0.045X_4 + 0.412X_5 - 0.017X_6 + 0.277X_7 - 0.334X_8 - 0.296X_9 + 0.413X_{10}$$

$$F_2 = 0.064X_1 + 0.153X_2 + 0.547X_3 + 0.551X_4 + 0.218X_5 - 0.378X_6 - 0.14X_7 + 0.114X_8 + 0.383X_9 - 0.034X_{10}$$

$$F_3 = 0.113X_1 + 0.04X_2 + 0.397X_3 - 0.156X_4 + 0.088X_5 + 0.573X_6 + 0.504X_7 + 0.417X_8 + 0.192X_9 - 0.054X_{10}$$

The first principal component (F_1) captured 48% of the total variance, mainly influenced by soil organic matter (0.441) and nitrogen content (0.431). This finding indicates that these two factors exert a significant impact on soil fertility levels, with higher values generally corresponding to better fertility. For the second principal component (F_2), TP and TK exhibited large positive loadings. This suggests that elevated concentrations of these nutrients contribute to an improvement in soil fertility. Similarly, the third principal component (F_3) was characterized by substantial positive loadings for AK and AP, indicating their critical role in improving soil fertility (Table 4).

Table 4. Score coefficient matrix of the first three principal components.

Indicators	Principal Component		
	F_1	F_2	F_3
SOM (X_1)	0.441	0.064	0.113
TN (X_2)	0.431	0.153	0.040
TP (X_3)	−0.019	0.547	0.397
TK (X_4)	0.045	0.551	−0.156
AN (X_5)	0.412	0.218	0.088
AP (X_6)	−0.017	−0.378	0.573
AK (X_7)	0.277	−0.140	0.504
pH (X_8)	−0.334	0.114	0.417
BD (X_9)	−0.296	0.383	0.192
SWC (X_{10})	0.413	−0.034	−0.054

Based on the principal component expressions, we calculated the comprehensive soil fertility index scores for various shrub patches. The order of soil fertility among the shrub patches was *Salix gilashanica* > *Potentilla fruticosa* > *Berberis diaphana* > *Caragana jubata* > *Caragana tangutica* (Table 5).

Table 5. Comprehensive scores of soil fertility in different shrub communities.

Shrub Community	F_1	F_2	F_3	Comprehensive Scores	Average Scores	Rank
<i>Salix gilashanica</i>	4.480	0.819	−1.096	2.505	1.709	1
	3.376	0.096	−1.401	1.647		
	2.850	0.232	−1.102	1.444		
	2.575	0.863	−1.773	1.328		
	2.899	1.042	−1.424	1.620		
<i>Potentilla fruticosa</i>	2.514	1.113	2.190	2.094	1.082	2
	1.733	1.636	2.100	1.776		
	0.651	0.357	2.630	0.943		
	−0.280	0.387	2.231	0.357		
	−0.441	0.731	1.615	0.241		
<i>Berberis diaphana</i>	−0.019	0.628	−0.440	0.069	−0.597	3
	−0.729	−0.024	−1.033	−0.604		
	−1.236	−0.010	0.460	−0.606		
	−1.467	0.183	−0.074	−0.785		
	−1.839	−0.062	−0.087	−1.057		
<i>Caragana jubata</i>	1.372	−3.116	1.444	0.232	−0.747	4
	0.468	−2.190	−0.196	−0.338		
	−0.094	−2.834	−0.195	−0.817		
	−1.018	−2.932	0.074	−1.307		
	−1.221	−2.473	−1.006	−1.503		
<i>Caragana tangutica</i>	−2.607	1.630	−0.774	−1.178	−1.448	5
	−3.058	2.199	−0.402	−1.214		
	−2.935	0.855	−0.339	−1.480		
	−0.035	1.302	−0.700	−1.488		
	−2.938	−0.432	−0.703	−1.880		

4. Discussion

The content and distribution of soil nutrients reflect the potential of soil to provide nutrients for vegetation and affect the growth and development of vegetation [24,25]. In this study, the mean values of SOM and TN in shrub soils were 77.94 g kg^{−1} and 3.85 g kg^{−1}, respectively. Compared with the national averages for SOM (33.32 g kg^{−1}) and TN (1.61 g kg^{−1}) [26], the shrub soils in the study area exhibited significantly higher levels. This implies that the water and temperature conditions in the Dayekou Basin of the Qilian Mountains are favorable, thereby resulting in relatively abundant SOM and TN contents. Simultaneously, the low temperature and humid environment lead to low microbial activity in the organic layer. As a result, litter decomposition proceeds slowly, and organic matter accumulates continuously. However, it cannot be excluded that livestock excrement, which contains a large amount of nitrogen, contributes to the increase in soil nitrogen content. The mean TP content in shrub soils was 0.74 g kg^{−1}, which is significantly lower than the global average of 2.8 g kg^{−1}. This is consistent with previous research indicating that soil phosphorus levels in China are generally lower than the global average [27]. This can be ascribed to the fact that the total phosphorus density decreases significantly with the increase in annual average precipitation and annual average temperature. Over the past 25 years, the average temperature in China has shown a significant upward trend, and the change in precipitation also exhibits distinct regional characteristics [28].

In this study, the SOM and TN contents in the five shrub communities exhibited an “inverted pyramid” distribution pattern as the soil layer deepened. This can be attributed to the fact that SOM and N primarily originate from the return of litter. Upon decomposition,

litter initially accumulates on the soil surface and subsequently diffuses downward through water or other media. Coupled with the influence of soil microorganisms, animals, and the absorption of plant roots, the SOM and TN contents exhibited a vertical distribution pattern, from high to low, with the deepening of the soil layer. The TP content of the five shrub communities demonstrated minimal variation across different soil layers. This is because soil P is a sedimentary substance, mainly derived from rock differentiation, and is not conducive to migration [27]. Additionally, the shrub soil types in the study area are chestnut soil and alpine meadow soil, and their aluminum and iron oxide contents are relatively high, a condition which has a fixed effect on P, reducing its effectiveness and affecting its cycle. Consequently, the difference in the TP content in each soil layer was relatively small. This also indicated that vegetation type was the primary factor contributing to the variation in total P content in the surface soil [29].

The CV reflects the degree of variability in soil physiochemical properties. According to the classification of Wilding (1985) [30], the degree of variation is divided into weak variation ($C_v < 15\%$), moderate variation ($16\% < C_v < 35\%$), and strong variation ($C_v > 36\%$). In this study, the CV of the soil pH value in shrub soils was 9%, indicating weak variability; this finding aligns with previous studies of planted forests in Guangxi [31]. This is because the soil pH value is influenced by the soil biochemical activity and parent material in the study area. The results also showed that soil TK exhibited weak variability, mainly because of the limited mobility of potassium due to dependence on soil characteristics, degree of weathering, and leaching processes [32]. In contrast, SOM and soil nitrogen showed high variability, likely due to their dependence on the decomposition and transformation of litter and plant roots. The large CV for soil phosphorus may be related to the unique environmental conditions of the Qilian Mountains and the growth characteristics of alpine shrub plants, which influence soil nutrient distribution. In contrast, the CV of SOM, TN, and AN were 51%, 44%, and 52%, respectively, indicating strong variability. This was related to the decomposition of litter, the influence of soil microorganisms and animals, and absorption by plant roots.

The relationships between the soil nutrient indicators of the shrubbery were close. This study found that the correlation coefficient between SOM and TN in the shrub community reached 0.87, indicating that the carbon and nitrogen contents in the soil respond in unison to vegetation types and external factors. Then, the significant correlation between total nitrogen and soil organic matter suggests strong microbial-mediated nutrient cycling. The soil fertility index and soil nutrient content in the shrub communities were closely related. Specifically, higher soil nutrient levels were associated with a larger soil fertility index, while lower soil nutrient levels corresponded to a smaller fertility index. Variations in the accumulation of SOM and available nutrients among different communities resulted in different soil fertility [33]. In our study, the soil fertility index of the *Salix gilashanica* patch was the largest. This can be attributed to the fact that *Salix gilashanica* grew at an elevation of 3300 m, where hydrothermal conditions were optimal. Here, the vegetation was lush, with abundant litter and high biomass. These factors contributed to increased nutrient return to the soil. Additionally, the relatively undisturbed nature of this area, with minimal human interference, further aided the maintenance of high-quality soil conditions. As a result, the soil within this community demonstrated elevated levels of SOM, TN, and AN. Moreover, the low temperatures at high elevations reduced soil microbial diversity and richness, which inhibited the mineralization and decomposition of organic matter [34]. Although *Caragana jubata* shrubs also grew at an elevation of 3300 m, the soil layer was thin, with sandstone mainly distributed underneath, making the soil infertile. Moreover, the productivity of the *Caragana jubata* community was relatively low, resulting in a low nutrient content.

Potentilla fruticosa that grew at an elevation of 2900 m was observed to have a notably higher aboveground biomass compared to other elevations. The higher aboveground biomass in *Potentilla fruticosa* contributed to greater litter input and soil nutrient enrichment. As the elevation rises, precipitation increases while temperature decreases, creating an ideal hydrothermal environment for soil microbial activity. The higher microbial biomass and activity at the mid-elevation enhanced the decomposition of vegetation litter [35], which contributed to elevated levels of organic matter and nitrogen in the soil [36]. As a result, the soil fertility index was comparatively higher at these elevations.

Our study also revealed that the soil fertility index of the *Caragana tangutica* patch was the lowest. This is because the *Caragana tangutica* patch was located at a low altitude, with a large slope, low soil moisture content, low vegetation density, and a small amount of litter, as this could not easily accumulate on the woodland ground due to atmospheric precipitation, grazing, and trampling, and the nutrient accumulation was small. Furthermore, the low vegetation density restricted the quantity of organic matter returned to the soil, leading to meager levels of SOM, TN, and AN. The higher temperatures at this elevation further enhanced soil microbial activity, which consumed significant amounts of nutrients, further depleting soil fertility [37]. Meanwhile, there were also human activities such as grazing in this elevation. Past land use changes, particularly grazing intensity, may have influenced soil nutrient levels and heterogeneity.

5. Conclusions

The soil fertility indicators of different shrub communities in the Dayekou watershed of the Qilian Mountains varied significantly, with differing degrees of variability for each indicator. Among these, the soil pH and TK content exhibited weak variability, the TP content exhibited moderate variability, and other soil fertility indicators showed strong variability. The ranking of soil fertility among the five shrub communities was determined as follows: *Salix gilashanica* > *Potentilla fruticosa* > *Berberis diaphana* > *Caragana jubata* > *Caragana tangutica*.

In this study, we investigated the fertility status of five shrub species and analyzed the inter-relationships among soil fertility factors. Nevertheless, future studies should incorporate plant nutrient analysis and long-term monitoring of soil changes, systematically studying the coupling characteristics of plant–soil nutrients in shrub communities and their responses to changes in environmental factors. It is also essential to protect understory shrubs and herbaceous vegetation, minimize human-induced disturbances to low-altitude shrub communities, and promote the progressive succession of vegetation.

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