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Soil Chemical Properties Along an Elevational Gradient in the Alpine Shrublands of the Northeastern Tibetan Plateau

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Abstract

The high-elevation ecosystems of the Tibetan Plateau provide crucial ecosystem services including watershed protection and water provision for downstream human and wildlife communities. Thus, understanding the relationship between soil properties and vegetation under different management regimes is important as a warming climate alters these systems. This study assessed vegetation cover, quantified the distribution of soil nutrients, and examined the relationships among soil chemical properties and plant cover in the high-elevation shrublands (3300 to 3700 m) in the Qilian Mountains on the northeastern Tibetan Plateau of China. These vegetation surveys and soil sample collections were conducted on 15 shrubland plots at different soil depths and soil chemical properties were investigated at each elevation. The content of soil organic matter (SOM), total nitrogen (TN), available phosphorus (AP), and available potassium (AK) fluctuated along the elevational gradient, while soil pH was close to neutral (pH 7.4). At our sites, SOM and TN contents generally increased with elevation, and AK was positively correlated with *Salix* plant cover. Using PCA, we determined that PC1 captured 43% of the total variance, and SOM and TN were the top contributing features. As climate in the region warms and precipitation becomes more variable, understanding the current soil–vegetation equilibria and how vegetation may migrate in future years is important to predicting changes in this region, especially at high elevations. From a managerial perspective, our goal was to provide additional information for restoring and managing subalpine and alpine shrubland vegetation in the Qilian Mountains to ensure the future sustainable use of these systems.

Keywords: soil nutrients; soil chemistry; Qilian Mountains; subalpine shrublands; Tibetan Plateau; Pailugou watershed

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1. Introduction

Soil physicochemical properties are key indicators for measuring the function and structure of terrestrial ecological systems and are closely linked to vegetation type with

significant variation in nutrient stocks, nutrient cycling, and energy flux in the soil [1,2]. Accurately assessing the soil nutrient status under different vegetation types is of great significance for ecological restoration, vegetation protection, and the sustainable management of altered ecosystems [3]. For example, in the southern Alps, subalpine shrubs maintained higher concentrations of soil carbon than adjacent grasslands but were more susceptible to surface soil erosion and supported less biodiversity [4]. In the French and Austrian Alps, the succession of montane grassland to shrublands increased soil organic matter contents but decreased pH and phosphorus availability, demonstrating that shrub encroachment altered soil properties [5]. In the Spanish Pyrenees, subalpine shrub expansion into grasslands led to an increase in the C:N ratio and a decrease in soil N, P, and K contents, which may have been caused by (1) lowered nutrient inputs from domestic herbivore dung and (2) the transfer of nutrients from the soil to the shrub biomass [6].

In western China, the climatic and hydrological conditions of the Qilian Mountain region (16,133 km^2) supports four forest types: deciduous broad-leaved shrublands, deciduous broad-leaved forests, evergreen coniferous forests, and mixed coniferous and broad-leaved forests. Among these, deciduous broad-leaved shrublands account for most of the total forested area of the Qilian Mountains, and they have a role in regional ecological environmental protection, particularly for water quality and quantity [7–10]. The Qilian Mountains are in the northeastern region of the Qinghai–Tibetan Plateau, a vast high elevation region that is the headwaters to many of the major rivers in Asia. Thus, this region and the sustainable management of its ecosystems are of major importance.

Global climate models currently predict a warmer and wetter Tibetan Plateau in the future, and recent studies of the effects of climate change on vegetation on the Tibetan Plateau have demonstrated increases in grassland, forest, and shrubland cover while barren land is decreasing [11]. In addition, Wang et al. [11] reported increases in vegetation cover at higher elevations. In the northeastern region of the Plateau (our study region), significant vegetation greening trends were observed from 2000 to 2021 due to continuous increases in temperature and water availability [12]. In addition, from 1990 to 2019, Lu et al. [13] reported that increasing temperatures caused an upward movement of the greenness isoline at middle and high elevations (>4000 m) of the Plateau, indicating that vegetation was migrating due to changes in regional climate.

Currently, there is considerable research on the alpine shrublands of the Qilian Mountains, but it is mainly focused on stoichiometric characteristics [14,15], hydro-ecological functions [10,16], protection and management [17], and the influence of grazing on plant communities [18]. In addition, much research has focused on the invasion of shrubs into grassland communities at higher elevations on the Tibetan Plateau, and the effects of this succession on biodiversity and soil nutrients [19,20]. In the Qilian Mountains, patches of four different subalpine shrub species had soil organic matter (SOM) and macronutrient (N, P, and K) concentrations that varied according to patch species and soil depth [21]. In a watershed close to our research site, Ma et al. [22] indicated that soil fertility under *Salix gilashanica* C. Wang & P.Y. Fu was greater than under five other subalpine shrub types.

The present study examined the alpine shrublands of the Pailugou watershed in the Qilian Mountains, and the plant species and vegetation cover were documented for experimental plots located on an elevational gradient. A primary research objective was to estimate soil pH, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available phosphorus (AP), and available potassium (AK) at different depths and elevations to explore relationships among soil chemical factors and vegetative cover and compare our findings with prior studies in the region. A second research objective was to establish baseline data for these shrub communities so changes in species composition and soil physicochemical properties could be tracked in future years as the

climate continues to change in this region. Our primary hypothesis was that SOM would increase with elevation and that changes in plant cover with elevation would be positively correlated with soil chemical properties. From a managerial perspective, our goal was to provide additional information for restoring and managing subalpine and alpine shrubland vegetation in the Qilian Mountains to ensure the future sustainable use of these systems.

2. Methods

2.1. Overview of the Study Area

The study area was the Pailugou watershed on the northern section of the Qilian Mountains (38°24′ N, 100°17′ E). This watershed is the site of long-term ecological studies by the Gansu Qilian Mountain Water Conservation Forest Research Institute, headquartered in Zhangye, Gansu Province, China. The total area of the watershed is 2.85 km^2, with a length of 4.25 km and an elevation range from 2600 to 3800 m. The average annual temperature ranges from −0.6 to 2.0 °C, with an average annual sunshine duration of 1893 h. The mean total solar radiation is 110 kW m^{-2}. The area receives an average annual precipitation of 434 mm, with an average annual evaporation rate of 1081 mm, and has an average annual relative humidity of 60%. The climate is classified as montane, cold, and semi-arid [17].

Complex natural conditions and hydrothermal conditions within the watershed have given rise to vegetation and soil types that vary with elevation. Vegetation types are mountain grassland vegetation, mountain forest/grassland vegetation, subalpine shrub meadow vegetation, and alpine snow vegetation (Figure 1). The soils in the watershed are Entisols (Primosols) and Inceptisols (Cambisols) with Holocene loess (silty loam) predominant in the surface horizons. Locally, these soils are classified as mountain brown calcic soil, mountain gray-brown soil, subalpine shrub meadow soil, and alpine cold desert soil (from lower to higher elevation). Among these, mountain gray-brown soils and subalpine shrub meadow soils support forests. The mountain gray-brown soil between 2600–3300 m coincides with the distribution of spruce (*Picea crassifolia* Kom.) forests; the subalpine shrub meadow soil between 3300 to 3800 m coincides with moist hardwood shrub forests (Figure 1). Dominant shrub species include golden dewberry (*Potentilla fruticosa* L.), ghost arrow mallow (*Caragana jubata* (Pall.) Poir), *Spiraea alpina* Pall., and gila willow (*Salix gilashanica* C. Wang & P.Y. Fu).

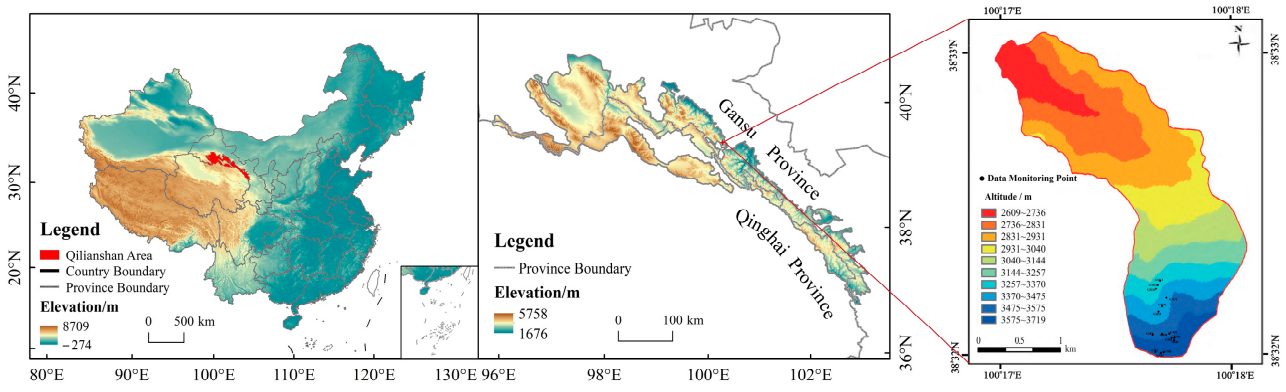


Figure 1. Location and elevational gradients of the Pailugou watershed in the Qilian Mountains [23].

The Pailugou Basin was declared on 14 May of 2019, by the China National Forestry and Grassland Administration, as a protected area, under the name Qilian Mountain National Park, supervised by the Zhangye Branch of Gansu Provincial Administration.

Under this status, human activity, except for livestock grazing, was forbidden. Seasonal grazing of the subalpine shrublands by sheep and yak varies across the watershed.

2.2. Plot Layout

We selected the subalpine shrub community of the Pailugou experimental watershed (3300 to 3700 m) as the research site based on its representativeness for the area and linkage to other research efforts in the Pailugou research watershed. This is also the elevational band which currently supports the alpine shrub communities. Three 10 × 10 m plots were chosen at 100 m elevation intervals (15 plots total). In August 2020, we surveyed the distribution of shrub communities using a Global Positioning System (GPS) and recorded the latitude and longitude, elevation, aspect, and percent slope in the center of each sample plot. Then, each plot was divided into 5 × 5 m subplots using a grid method, and the average height, basal diameter, percent plant coverage (visual estimation of cover classes), and growth condition of the plants within the subplots were determined.

2.3. Sample Collection and Processing

For each plot, triplicate soil samples were collected using a 2 cm diameter soil auger across five depth intervals: 0–10, 10–20, 20–30, and 30–40 cm. After separating plant residues, gravel, and other debris, soil samples were bagged, homogenized, and labeled for transport to the laboratory. Sample aliquots were air-dried, sieved through 1 mm and 0.149 mm mesh sieves, and ground. Soil analysis included the following: pH, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available phosphorus (AP), and available potassium (AK). Sample preparation and analysis were completed using standardized methods [24,25]. Soil pH was determined using potentiometry (Thermo Scientific Orion Star A211, Thermo Fisher Scientific, Waltham, MA, USA), and soil organic matter (SOM) was determined using the potassium dichromate oxidation external heating method and analyzed with a spectrophotometer (Shimadzu UV-1800, Kyoto, Japan). Soil total nitrogen (TN) was determined using the semi-micro Kjeldahl method and analyzed with the FOSS Kjeltec™ 8400 (FOSS Analytical, Hillerod, Denmark). Total phosphorus (TP) and total potassium (TK) were determined using a sodium hydroxide decomposition technique [26]. After fusion, in nickel crucibles, phosphorus reacts with ammonium molybdate to form phosphomolybdenum blue for colorimetric measurement (Spectrophotometer Shimadzu UV-1800, Shimadzu, Japan). For TK, after fusion, K ions were measured by flame photometer (emission at 766.5 nm, Agilent 240FS AA, Agilent Technologies, Santa Clara, CA, USA). Soil available phosphorus was determined using the Olsen method followed by spectrophotometry (700 nm). Soil available potassium was determined using the ammonium acetate extraction–flame photometry method. The potassium concentration in the filtrate was estimated using a flame photometer (766.5 nm emission, Sherwood Model 410, Sherwood Scientific, Cambridge, UK).

2.4. Data Analysis and a Comparison with Prior Studies

Statistical analyses, including the Pearson correlation analysis and one-way ANOVA (and ensuing Tukey's HSD), were performed using SPSS 20.0. Because samples at each elevation were bulked, we performed a one-way ANOVA on each soil variable for elevation and a one-way ANOVA on each soil variable at depth. For the correlations between soil chemical properties and plant cover, we used a logit transformation on percent plant cover. To compare our results with prior studies at similar elevations in the Qilian Mountains, we developed predictive models for soil properties using a second-order polynomial regression. Principal component analysis (PCA) was conducted in R (R Core Team 2023).

3. Results

3.1. Soil Nutrients and pH at Different Elevations in Alpine Shrubland

The vegetation on all plots was composed of the four species: *Potentilla fruticosa*, *Salix gilashanica*, *Caragana jubata*, *and Spiraea alpina*. Shrub cover ranged from 91 to 99% with a mean of 95%. *S. gilashanica* covered the most area on average, followed by *C. jubata*, *P. fruticosa*, and *S. alpina* in declining order (Table 1).

Table 1. Vegetation in the alpine shrubland sample plots of the Qilian Mountains.

Plot ID	Vegetation	Elevation Above Sea Level (m)	Aspect (°)	Slope Gradient (%)	Stem Count	Mean Height (m)
GM1 GM2 GM3	*Potentilla fruticosa* *Salix gilashanica* *Caragana jubata* *Spiraea alpina*	3700	5	36	62 123 165 42	0.56 0.48 0.36 0.50
GM4 GM5 GM6	*Potentilla fruticosa* *Salix gilashanica* *Caragana jubata* *Spiraea alpina*	3600	330	37	65 120 88 29	0.54 0.46 0.27 0.52
GM7 GM8 GM9	*Potentilla fruticosa* *Salix gilashanica* *Caragana jubata* *Spiraea alpina*	3500	50	35	43 28 60 17	0.64 0.85 0.35 0.44
GM10 GM11 GM12	*Potentilla fruticosa* *Salix gilashanica* *Caragana jubata* *Spiraea alpina*	3400	35	29	58 42 107 28	0.53 1.10 0.56 0.95
GM13 GM14 GM15	*Potentilla fruticosa* *Salix gilashanica* *Caragana jubata* *Spiraea alpina*	3300	350	34	68 48 81 28	0.58 1.05 0.59 0.76

There was significant variation in soil nutrients and pH at different elevations in our study plots (Tables 2 and 3). Many variables were significantly different with elevation as an independent variable, while depth did not have much of an effect (Tables 2 and 4). Soil pH was neutral and ranged from 7.13 to 7.83, with an average of 7.42 (Table 3). Soil pH generally decreased with increasing elevation. TN ranged from 5.60 to 7.21 g kg^{-1}, found at 3300 m and 3500 m, respectively. There were no significant differences for TN at 3500 m, 3600 m, and 3700 m ($p > 0.05$).

Table 2. One-way ANOVA *p*-values for soil variables with elevation and depth as independent variables.

Soil Property	SOM	pH	TN	TP	TK	AP	AK
p-value (elevation)	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01	0.9	0.9
p-value (depth)	0.5	0.5	0.2	0.6	0.9	0.09	≤0.01

Table 3. Soil chemical properties (mean ± s.d.) at different elevations in alpine shrubland (0–40 cm).

Elevation (m)	SOM (g kg^{-1})	pH	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
3700	183 ± 2.55 a	7.3 ± 0.04 ac	7.1 ± 0.19 a	0.7 ± 0.00 a	18.1 ± 0.29 a	12.1 ± 1.31 a	92.0 ± 17.8 a
3600	172 ± 3.00 bc	7.4 ± 0.04 a	6.9 ± 0.06 ab	0.6 ± 0.02 a	19.7 ± 0.25 b	11.7 ± 0.53 a	97.8 ± 4.95 a
3500	185 ± 2.63 a	7.1 ± 0.04 bc	7.2 ± 0.33 a	0.6 ± 0.01 b	18.2 ± 0.15 a	12.7 ± 1.96 a	98.6 ± 2.95 a
3400	179 ± 0.36 ab	7.4 ± 0.11 a	6.1 ± 0.13 bc	0.5 ± 0.00 c	18.1 ± 0.25 a	11.9 ± 1.09 a	95.9 ± 4.18 a
3300	165 ± 2.94 c	7.8 ± 0.07 d	5.6 ± 0.61 c	0.6 ± 0.02 b	18.4 ± 0.44 a	11.1 ± 0.81 a	94.8 ± 5.55 a

Note: Different lowercase letters in the same column indicate significant differences ($p < 0.05$).

Table 4. Mean soil chemical properties (±SE) at depth intervals in alpine shrublands.

Soil Depth/cm	SOM (g kg^{-1})	pH	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
0–10	182 ± 3.81 a	7.3 ± 0.11 a	7.1 ± 0.34 a	0.6 ± 0.02 a	18.5 ± 0.53 a	13.6 ± 1.23 a	115 ± 6.48 a
10–20	176 ± 4.12 a	7.4 ± 0.12 a	6.7 ± 0.23 a	0.6 ± 0.02 a	18.5 ± 0.33 a	12.5 ± 0.67 a	96.7 ± 1.00 ab
20–30	175 ± 3.77 a	7.5 ± 0.11 a	6.5 ± 0.22 a	0.6 ± 0.02 a	18.3 ± 0.42 a	10.3 ± 0.79 a	86.2 ± 4.87 b
30–40	175 ± 3.88 a	7.5 ± 0.15 a	6.0 ± 0.59 a	0.6 ± 0.03 a	18.6 ± 0.28 a	11.2 ± 0.86 a	85.1 ± 5.59 b
Mean	177 ± 1.92	7.4 ± 0.06	6.6 ± 0.19	0.60 ± 0.01	18.5 ± 0.19	11.9 ± 0.51	95.8 ± 3.59

Note: Different lowercase letters in the same column indicate significant differences ($p < 0.05$).

Total phosphorus generally increased with elevation, ranging from 0.53 to 0.66 g kg^{-1}, with an average of 0.60 g kg^{-1}. Between 3300 and 3700 m, available P in the soil represents only 1.8% to 2.2% of the TP content. This indicated that over 98% of the TP in the study area is not readily utilized or absorbed by the shrubs and other plants. Total soil potassium content was highest at 3600 m with 19.7 g kg^{-1}, and lowest at 3700 m with 18.1 g kg^{-1}. Soil available K in the soil was highest at 3500 m (98.6 g kg^{-1}) and lowest at 3700 m (92.0 g kg^{-1}). The Tukey HSD test identified significant differences between the 3300 m and 3500 m groups for SOM, pH, and TN (Table 3).

3.2. Variation in Soil Chemical Properties Across Depth Intervals Along an Elevational Gradient

There were few significant differences among soil depth intervals (Table 4). SOM and TN ranged from 175 to 182 g kg^{-1} and 6.03 to 7.10 g kg^{-1}, respectively. In the 0–30 cm layer, SOM content was highest at 3500 m and was lowest at 3300 m. In the 30–40 cm layer, SOM content generally increased with elevation. Soil TN varied with increasing elevation, and soil pH increased with depth (Table 4). TP content ranged from 0.61 to 0.58 g kg^{-1}, with an average of 0.60 g kg^{-1}. In contrast, available P in the surface layer was 13.6 mg kg^{-1}, which was significantly higher than the AP content in the 20–30 cm layer ($p < 0.05$). The Tukey HSD test for AK at different soil depths revealed significant differences between the 0–10 cm and 20–30 cm depths ($p = 0.003$) and the 0–10 cm and 30–40 cm depths ($p = 0.002$).

3.3. Correlation Among Soil Chemical Properties

Soil organic matter had a significant and positive correlation (r = Pearson correlation coefficient) with TN ($p < 0.01$) and a significant and positive correlation with AP ($p < 0.05$). Additionally, there was a significant negative correlation between SOM and pH ($p < 0.01$). Soil pH was negatively correlated with TN ($p < 0.01$), TP, AP, and AK ($p < 0.05$). Additionally, TN and AP were positively correlated ($p < 0.05$), but TP and AP were not (Table 5).

Table 5. Correlation (*r*) among soil chemical properties in the subalpine shrub.

	SOM	pH	TN	TP	TK	AP	AK
SOM	1.000						
pH	−0.774 **	1.000					
TN	0.732 **	−0.762 **	1.000				
TP	0.142	−0.269	0.406	1.000			
TK	−0.395	0.123	−0.159	0.282	1.000		
AP	0.465 *	−0.268	0.511 *	−0.057	−0.163	1.000	
AK	0.334	−0.250	0.332	−0.189	0.124	0.539 *	1.000

** Represents a significant correlation at the 0.01 level, and * represents a significant correlation at the 0.05 level.

3.4. Principal Component Analysis

PC1 captured the largest amount of variance (43%) and the top contributing features for PC1 were TN, SOM, pH, and elevation. PC2 captured the second largest amount of variation (25%) and the top contributing features for PC2 were TP, elevation, AK, and AP (Figure 2).

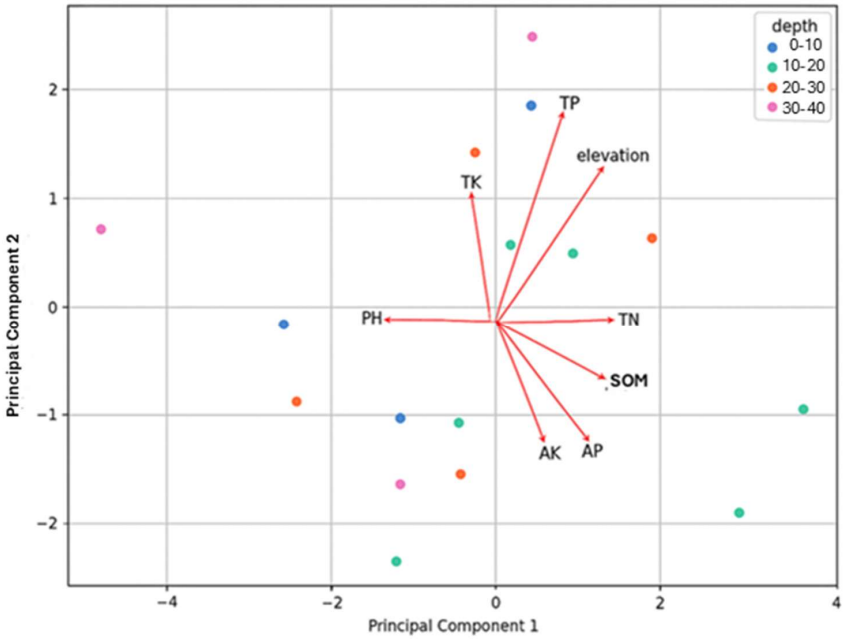


Figure 2. PCA analysis for soils in alpine shrublands.

3.5. The Relationship Between Soil Chemical Properties and Vegetation Cover

We examined the relationships between soil properties (0–40 cm depth) and percent plant cover at all the experimental plots, and *Salix* had a positive correlation with AK ($r = 0.8$, $p = 0.1$). None of the other correlations had a p-value < 0.1. TN and *Potentilla* had a positive correlation ($r = 0.75$, $p = 0.15$), and AP had a positive correlation with *Caragana* ($r = 0.75$, $p = 0.15$). We also examined relationships between percent plant cover and soil properties for the surface horizon (0–10 cm depth) and pH was positively correlated with *Spiraea* ($r = 0.69$, $p = 0.19$), SOM was positively correlated with *Potentilla* ($r = 0.72$, $p = 0.17$), and AP was negatively correlated with *Spiraea* ($r = -0.70$, p-value = 0.18).

3.6. A Comparison with Prior Studies in the Qilian Mountains

Second-order polynomial regression models were developed to predict how soil properties change with elevation. To develop the models, we used our data and data from other sites in the Qilian Mountains [27–29], and these models explained 57%, 47%, 25%,

and 46% of the variation in SOM, TN, TP, and TK, respectively (Figure 3). The regression equations for each model were as follows: SOM = $-0.000144(x^2) + 0.984660(x) - 1488.506$, TN = $0.000005(x^2) - 0.03168(x) + 50.0945$, TP = $-0.001692(x) + 3.4332$, TK = $0.00002(x^2) - 0.12725(x) + 221.4312$.

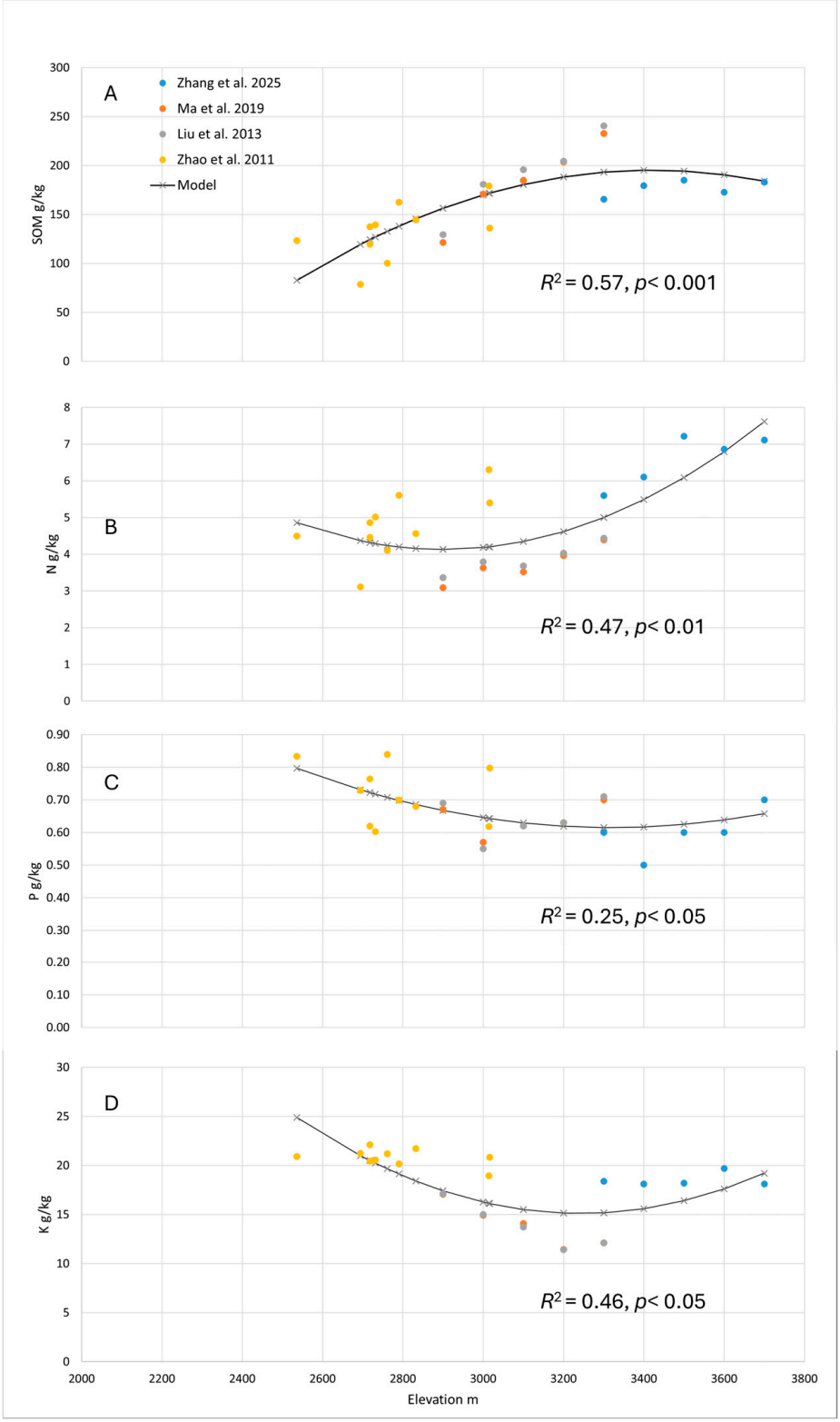


Figure 3. Regression analysis of soil nutrients and SOM at elevational gradients in the Qilian Mountains including soil organic matter (**A**), total nitrogen (**B**), total phosphorus (**C**), and total potassium (**D**) as reported in [27–29] and this study.

4. Discussion

Soil Properties

Soil organic matter is critical in the development of soil structure which in turn influences soil water retention, erosion resistance, fertility, and bulk density [30]. Elevated levels of SOM, TN, and TK within the study area may be related to several factors. Subalpine shrublands are known to raise soil organic carbon and nutrient content by altering the microenvironment and increasing litter inputs to the soil [31]. Alpine shrubs in the Qilian Mountains are also known to alter soil physicochemical properties and microbial biochemical composition and activity [32]. A prior study also indicated that shrub species composition was significantly affected by elevation, slope, soil pH, and soil organic carbon, while species richness of these communities was related to slope and soil bulk density [33]. We note that our sampling took place during the month of August, which is one of the warmest months of the year at this elevation, and thus plant productivity, litterfall rates, and decomposition rates were likely elevated during our sampling period.

In other areas of the world, a changing and warming climate has shifted shrub species distribution in alpine environments and affected soil–vegetation dynamics. For example, in the Austrian Alps, earlier snowmelt in alpine shrub communities was related to shifts in bacterial and fungal community composition as well as ericaceous shrub expansion, and these changes in microbial populations were accompanied by altered soil functioning and decreased soil N availability [34]. In the Swiss Alps, the expansion of *Alnus* dominated shrublands in montane environments was found to convert N-poor grassland into N saturated shrubland which could potentially lead to a long-term reduction in soil C storage because the shrubs limit the re-establishment of natural montane forest [35]. In the Central Italian Alps, a survey of shrubs on a 1000 m elevational transect found that *Salix* shrubs, typically found in riparian forests, were encroaching into subalpine and alpine shrublands and grasslands as a result of climate change, thus changing plant species composition at higher elevations [36].

In the Qilian Mountains, the negative correlation between SOM and pH in our study was consistent with Zhang [37] who found similar trends in alpine grasslands. Low surface soil pH relative to the subsoil can be attributed to greater SOM content in surface horizons, which produces more intermediate products such as tannin and organic acids during decomposition [38]. In our study, average SOM along the elevation gradient was 177 g kg^{-1}, which is lower than the 190 g kg^{-1} reported by prior research in the spruce forests of the Pailugou watershed in the Qilian Mountains [27,29]. Moreover, the "surface accumulation" effect of SOM in the spruce forests (0–10 cm depth) is stronger, with a content of 235 g kg^{-1}, compared to the alpine shrublands, where SOM content was 182 g kg^{-1}. This difference is attributed to the simpler vegetation structure and lower litter deposition in shrublands, which limits the "surface accumulation" effect of SOM compared to spruce forests. Jiang et al. [39] reported SOM content varied significantly under different vegetation types ($p < 0.05$), with SOM increasing progressively from grassland to shrubland to forest and with elevation. Finally, in a similar study of alpine shrubs in a nearby watershed, Ma et al. [22] also found that SOM and TN were the top contributing features to PC1 in their PCA.

At high elevation, soil phosphorus and nitrogen are important factors limiting vegetation growth and affecting the distribution of plant communities. Average TP for this and other studies in other regions of the Qilian Mountains were reported at less than 0.8 g kg^{-1}, suggesting soils in the Qilian range are phosphorus deficient—irrespective of elevation [27–29]. Soils of the *Picea crassifolia* forest in the elevation band below this study (2500 to 3200 m) had an average of 0.761 g kg^{-1} of TP [28], which was similar to our study sites. At our sites, no significant correlation between TP and AP was observed, consistent

with the findings of Song and colleagues [40] and Wang et al. [4]. In our sites, most of the TP was in plant-unavailable forms, which is ecologically significant because P limits plant productivity. Plant mycorrhizal associations may be critical for plant productivity in this environment because they aid plants in P uptake. The significant positive correlation between AP and SOM and TN (r = 0.46, r = 0.51, $p < 0.05$) indicated that higher levels of SOM and TN at our sites were associated with increased availability of phosphorus, perhaps via P mineralization during litter decomposition. The positive correlation between the presence of *Salix* and AK in our sites may be due to increased K release from growing season plant litter, as was reported in a *Salix* leaf decomposition experiment in India [41].

Soil chemical properties and their distribution can influence the direction of vegetation succession above ground. In turn, vegetation can affect soil nutrient properties; for example, *Potentilla fruticosa* can translocate P from lower depths to the soil surface [42]. Shrubs that have deeper rooting depths, wider root distributions, and mycorrhizal associations can move AP from deeper depths to the surface [42]. *Caragana jubata* is a nitrogen-fixing legume and likely has a positive effect on N across the sample area [43], and in general, alpine shrub patches act as aggregation centers for soil nutrients [21].

Although we did not quantify browsing damage in our plots (a limitation in this study), we noted that all the species in our experimental plots were moderately palatable to yak (*Bos grunniens* L.) and sheep (e.g., *P. fruticosa* is less palatable than *S. alpina*), and these shrubs are an indicator of overgrazing [44]. The Qilian Mountains have been grazed by wild and domestic yak for thousands of years [45] and many studies demonstrated that plant communities in the region are highly affected by livestock activity. Baranova et al. [46] indicated that the percentage of unpalatable and toxic plant species in the Qilian mountains is increasing, and Baranova and Schickhoff [18] reported that grazing in the Qilian Mountains by sheep, goats, and yak had a significant impact on the plant community composition. In addition, Li et al. [47] indicated that grazing intensity lowered soil organic carbon and total nitrogen stocks in numerous grasslands across the Tibetan Plateau, and grazing was reported to lower SOM, TN, and soil carbon, particularly on south-facing slopes at lower altitudes [46]. As noted, we did not quantify the extent of grazing and browsing on the vegetation in our plots, but the interaction between grazers and the vegetation that they alter as well as the influence of grazing on soil chemical properties in the alpine shrublands merits further attention.

5. Conclusions

Deciduous broad-leaved shrublands account for a large proportion of the total forested area of the Qilian Mountains in China; thus, it is important to understand soil and vegetation dynamics in these systems that will be highly affected by climate change. At our sites, SOM and TN contents generally increased with elevation, and pH decreased. Available K was positively correlated with *Salix* plant cover, and our sites had similar SOM, TN, TP, and TK contents compared to other sites in the Qilian Mountains. SOM, TN, and TP were also found to be the top contributing features in our PCA. Currently, the reduction in human and animal activities in the region may help minimize the destruction of alpine shrubland vegetation but may also contribute to shrub invasion of high elevation grasslands. Future research efforts should address the effects of a warmer and wetter climate at higher elevations in the Qilian Mountains, including (1) the potential migration of shrub species upwards in the Qilian Mountains and how climate alters vegetation–soil relationships in future years and (2) the effects of a decrease in livestock activity on alpine shrub and grassland communities including the effects on high-elevation biodiversity (including soil microbial communities).

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