The vertical distribution of soil organic and inorganic carbon in a dry alpine rangeland of northern Qinghai-Tibetan Plateau

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Abstract

The spatial patterns of soil carbon in water-constrained alpine ecosystems have been rarely investigated. It remains unclear how changes in biotic and abiotic factors with elevation would shape the distribution of soil carbon stocks when plant communities are co-limited by water and low temperature. To address this uncertainty, we uniformly selected seven points on the vertical gradient at an elevation of 3,000-4,000 meters in the northern part of the Qinghai-Tibet Plateau to analyze the changing trends of organic carbon (SOC) and inorganic carbon (SIC) in the surface soil. Our results showed that the total soil carbon density (TCD) and the SOC density (SOCD) increased with increases in elevation, but the SIC density (SICD) displayed a pattern of nonlinear change along the altitudinal gradient with a peak at the mid-slope of the range. While SIC dominated the soil carbon pool, accounting for 64 - 90% of TCD, the proportion of SOC increased from 10 to 36% of the TCD with increases in elevation. The increases in SOCD with elevation were associated with changes from scrub-dominated vegetation cover to herbaceous plant communities and decreasing MAT, which together attributed to increased level of plant-derived carbon inputs and reduced SOC mineralization at higher elevations. Whereas variations in SICD were mainly explainable by changes in soil C/N ratio and soil water content (SWC), and

likely resulted from non-linear changes in factors related to inorganic carbon production and leaking losses. Findings from this study help fill the knowledge gap on the underlying controls of SOC and SIC distribution along the altitudinal gradient in water- and low temperature-constrained alpine rangeland.

Keywords Qinghai-Tibet Plateau · arid region · carbon pool · soil organic carbon · soil inorganic carbon

1.Introduction

Because soil contains the largest proportion of C stocks in terrestrial ecosystems (Lal, 2018), the size, persistence and storage capacity of soil C pool have been the focal issues in global change research. However, despite extensive studies on soil carbon pools in the past, there is still great uncertainty regarding the response of soil C pools to global climate change.Part of the problems arises from differential alterations of pool size and functional structure of soil C among the world's terrestrial ecosystems as affected by environmental variability and climate change (Sun et al., 2019, 2023; Zhang et al., 2024). Soil C pool is made up of both organic (SOC) and inorganic chemical compounds (SIC). In general, SOC dominates the soil C pool on vegetated sites (Feyissa et al., 2023); Whereas SIC is a major component of soil carbon pool in arid areas where plants are scarce especially in drylands (Du and Gao, 2020; Dong et al., 2024). Previous research has well demonstrated that SOC are jointly controlled by vegetation, climate and soil physicochemical properties (Eswaran et al., 1993; Torn et al., 1997; Schuur et al., 2001; Callesen et al., 2003; Sun et al., 2004). In contrast, SIC pool is mainly affected by abiotic factors such as soil parent material, climate and elevations gradient (Chang et al., 2012; Ma et al., 2022; Dong et al., 2024). The variation patterns of soil organic carbon and silicon carbide reservoirs under different elevation gradients and vegetation types, as well as their response mechanisms to climate, indicators and soil factors, remain unclear.

The Qinghai-Tibet Plateau rises sharply in the elevation gradient, and the ecosystem types have the characteristics of spatial differentiation. Among different ecological types, there are significant differences in climate, vegetation and soil characteristics. With increases in elevation along the mountain slopes on the Plateau, air temperature markedly decreases, and precipitation and the intensity of solar radiation increases, contributing to altitudinal changes in vegetation and soil nutrient availability (Tiemann and Billings, 2011; García-Palacios et al., 2013; Wang et al., 2024). The unique topographic feature and presence of diverse ecosystems have made the region a hot spot for research geared at better understanding of the impacts by climate change on ecosystem structure and function. However, most studies in this region have mainly focused on the vegetation or soil change patterns of permafrost and meadow ecosystems (Wang et al., 2023; Chen et al., 2017; Cai et al., 2025. The variation patterns of vegetation and soil carbon pools in alpine meadow ecosystems in arid areas have been largely ignored. Alpine meadows in arid areas are also an important part of the alpine meadow ecosystem on the Qinghai-Tibet Plateau and are the foundation of agriculture and animal husbandry in the northern part of the Qinghai-Tibet Plateau (Zhang et al., 2021). On the Qinghai-Tibetan Plateau, the abiotic conditions, vegetation and soil types have undergone great changes at different elevations (Li et al., 2017), which would inevitably impose significant impacts on soil C dynamics due to altitudinal shift in vegetation type and hydrothermal conditions (Rodeghiero and Cescatti, 2005). Previous studies have shown substantial variations in the quality and quantity of SOC along the altitudinal gradients in mountainous landscapes (Pepin et al, 2015). The alpine grassland in the northern part of the Qinghai-Tibet Plateau is located in the arid climate area, with a relatively low vegetation coverage. The surface is severely eroded by wind and water, and the community type is mainly desert grassland. In arid alpine rangelands, such as that in the northern Qinghai-Tibetan Plateau region, SIC plays a more dominant role in the soil C storage (Batjes, 2006; Du and Gao, 2020). The soil carbon pool of alpine grassland in arid areas is more sensitive to changes in the microenvironment. Therefore, previous studies may have neglected the role of SIC in soil carbon inventory in this region. But whether or to what extent the altitudinal changes in micro-environments and vegetation would affect SOC and SIC remains unknown..

In this study, we investigated the patterns of changes in SOC and SIC in the top 30 cm soil along the southern slope of the Altun Mountain across an altitudinal range of 3000 - 4000 m above sea level (asl), in the northern Qinghai-Tibetan Plateau region, and collected data on plant communities and soil physicochemical properties. The aims of the study were to determine the altitudinal patterns in the density of SOC (SOCD) and SIC (SICD). We hypothesized that (1) With the increase of elevation, the decrease of temperature and the increase of vegetation, the content of soil organic carbon increases; (2) With the increase of elevation, the drought limitation is alleviated and the inorganic carbon content in the soil decreases; (3) With the increase of elevation, the proportion of organic carbon in the soil carbon pool increases, while the proportion of inorganic carbon decreases.

2.Methods and materials

2.1 Study sites and experimental design

Our study sites are located in the Altun Mountain Nature Reserve in the south of Altyn Tagh, situated in the northeastern part of the Qinghai-Tibetan Plateau (87°10'E - 91°18'E, 36°N - 37°49'N). This area is known for harsh environmental conditions characterized by a dry climate, with an average annual temperature of 0 °C and an annual precipitation of around 110 mm. The soils are predominantly yermosols (FAO, http://www.fao.org/soils-portal/so). The Reserve comprises diverse landcover types, including deserts, scrubs, and grasslands. The herbaceous layer typically ranges from 5 to 20 cm in height, with a coverage of 10 - 30%, occasionally reaching 60 - 80%. The main vegetation types being dwarf scrubs in the lower altitudinal range of the slope and grassland at the upper slope. In this study area, the vegetation types are mainly small shrubs and shrubs at the elevation of 3000-3300m, the vegetation types are mixed shrubs and herbs at the elevation of 3300-3500m, and the vegetation types above 3500m are mainly herbs (Fig 1). Dominant plant species are represented by *Stipa purpurea* Griseb. and *Kobresia robusta* Maxim., which are often accompanied by common grassland plants including *Carex kunlumsannsis* N.R.Cui, *Koeleria* *cristata* (L.) Pers., and *Oxytropis falcata* Bunge.

In August 2019, we conducted plant survey and soil sampling at seven elevations (designated as A1-A7) along a vertical transect in an altitudinal range of 3000-4000 m asl in the northern section of the Altun Mountain Nature Reserve. The distance between adjacent survey and sampling elevations ranged from 60 to > 100 m in elevation. All sites are geo-referenced. At each sample point, a 100 m x 100 m area was selected for sampling investigation. A 100 m sample line was set at the middle position, and 10 sample squares were evenly set on the sample line, with each sample square being 1 m x 1 m. Each sample square is spaced 1 meter apart. The altitudinal profile of the sampling sites is illustrated in Fig. 1.

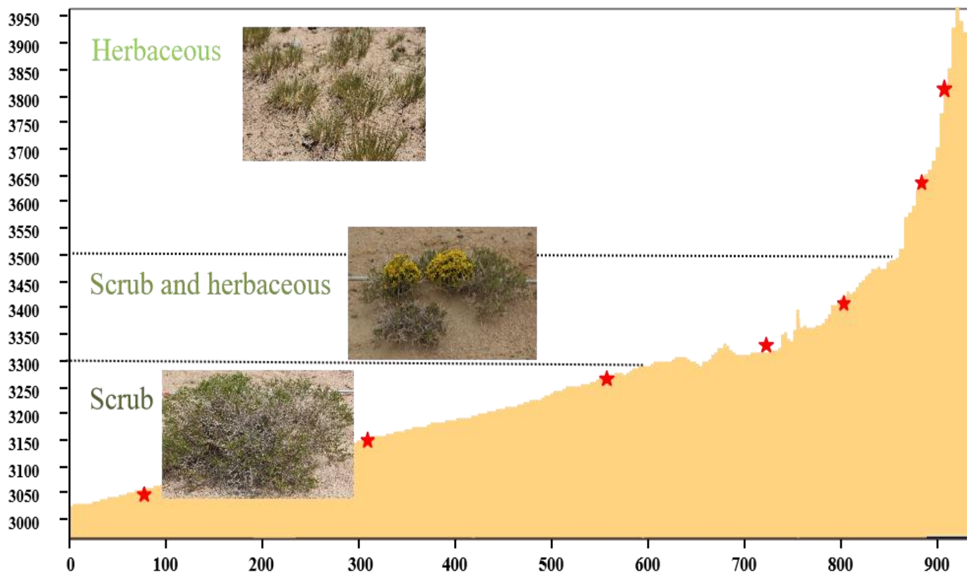


Fig. 1 The vertical profile of sample sites in the northern section of the Altun Mountain Nature Reserve, Qinghai-Tibetan Plateau

2.2 Measurements of plant and soil variables

We determined the relative coverage of each species and the entire community and identified the dominant species. The coverage of the plant community was calculated as the sum of the coverage values for individual species as there are little overlap among plant species at our study sites. All plants within each quadrat were harvested and measured for both fresh and dry mass. Soil samples were collected to 30 cm depth using a 7-cm (inner diameter) augur at locations where the above-ground tissues were harvested for biomass measurements. Roots were picked out of soil samples and measured for dry mass weight. Upon completing the field survey, plant samples were transported to laboratory and oven-dried at 75 °C for 48 h for determination of biomass. Soil water content (SWC) was determined gravimetrically by determining the fresh soil weight and then dry mass after subjecting to oven-drying at 105 °C for 48 h. Soil pH was determined using a conductometer (1:1 soil-water suspension) and acidimeter (1:5 soil-water suspension). Soil bulk density (BD) was determined using cutting ring method. The SOC and plant C contents (above-ground tissues and roots) were quantified using the $K_2Cr_2O_7$ oxidation, and soil TC using an elemental analyzer (TOCV wp; Shimadzu Corp., Tokyo, Japan). The content of SIC was directly determined by neutralization titration. The measurements for plant C were made with samples oven-dried at 75 °C for 48 h.

2.3 Data processing and statistical analysis

The climate data (MAT, NDVI) used in this study were extracted from the website of Global climate data (http://worldclim.org). For plant community structure, we quantified Shannon-Wiener index (*H'*) and species richness (Whittaker and Niering, 1965).

One-way ANOVA was used to determine the effects of elevations on SWC and BD, and Duncan's multiple comparison test to determine the statistical significance of the differences of the variables among elevations. Linear regression was applied to examine the relationships of SOC and SIC with the indices of climate, plant community and soil. Redundancy analysis (RDA) was performed for identification of significant influencing factors on SOC and SIC, and Structural Equation Modelling (SEM) for analysis of direct and indirect influences of climate, plant and soil variables on SOC and SIC. We have developed models for SOCD and SICD that simultaneously consider vegetation, environmental factors, and soil properties. Based on the results of linear regression and RDA, the measurement variables associated with the three potential predictors for SOCD are the NDVI, species diversity, richness, MAT, bulk density BD, and soil N. In contrast, the measurement variables corresponding to the three potential predictors for SICD include root biomass, SWC, BD, and soil C/N. In the model, the significant paths ($p<0.05$) are represented by solid lines and the insignificant paths by dashed lines. The sample size of each measurement index is 35, and the initial model is presented in the supplementary materials (Fig. S1). We acknowledge that the influence of certain excluded variables on SOCD and SICD may have been overlooked. Nonetheless, we have minimized the model's complexity, thereby enhancing our understanding of the primary direct and indirect effects of vegetation, environmental factors, and soil properties on the soil carbon pool. This approach allows us to address our research questions more comprehensively and accurately. All observed variables were initially categorized into composite variables before being incorporated into the SEM. To assess the robustness of the relationships between key ecosystem factors and SOCD and SICD, we employed piecewise SEM to analyze the random effects at the sampling sites, detailing the "marginal" and "conditional" contributions of the predictive factors (Tian et al., 2021). All statistical analyses were implemented within Origin 9.3 and R 4.2.1 (R Core Team, 2020), and composite SEM model analysis in the R packages “piecewise SEM”, “nlme” and “lme4”.

3.Results

3.1. Changes of soil C pools, plant community, climate and edaphic factors with elevations

The total soil C (TC) pool was predominantly made up of inorganic component along the altitudinal gradient, accounting for 64 - 90% of TC (Fig. 2). With increases in elevation, the organic component of soil C (SOC) significantly and linearly increased (Fig. 2a), leading to its increased proportion from 10 to 36% of TC (Fig. 2b).

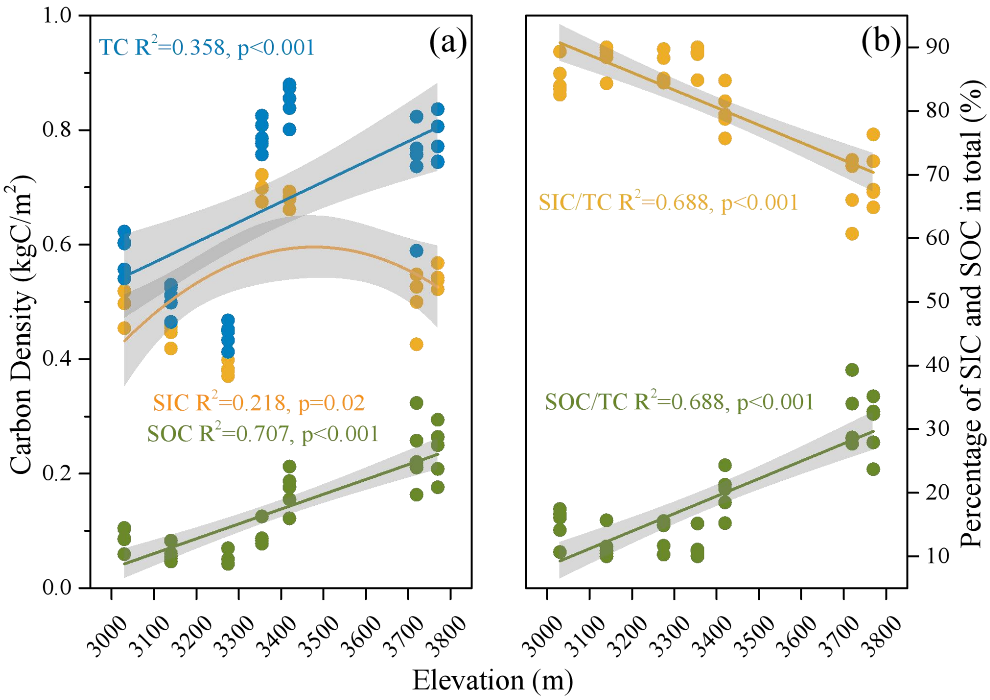


Fig. 2 Altitudinal changes in (a) densities of soil organic (SOC), inorganic (SIC) and total C (TC), and (b) proportions of SOC and SIC in TC in a dry alpine rangeland of Qinghai-Tibetan Plateau

Among the variables characterizing plant communities, NDVI, plant species diversity and richness all increased with rising elevation (p<0.01) (Fig. 3a-c), and above-ground biomass density decreased (p<0.01) (Fig. 3e). However, both fine root biomass density and vegetation cover displayed patterns of curvilinear changes with elevations (Fig. 3d and 3f).

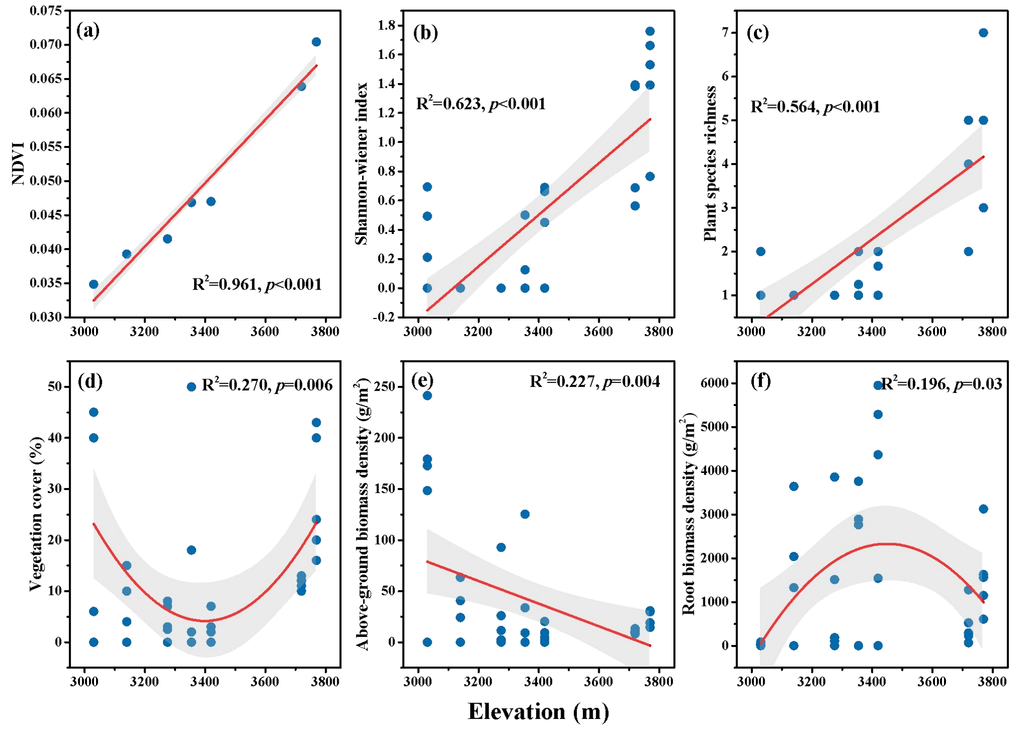


Fig. 3 The elevation variation of selective plant community characteristics in the alpine plateau area of the arid region of the Qinghai-Tibet Plateau. (a) Normalized difference vegetation index (NDVI); (b) Shannon-Wiener index; (c) plant species richness; (d) vegetation cover; (e) aboveground biomass density; and (f) fine root biomass density

Among the climatic and edaphic variables, there were a significant linear decrease in MAT ($p<0.01$; Fig. 4b) and a significant linear increase in soil N content increased with increases in elevation ($p<0.01$; Fig. 4d). Soil pH, BD and C/N all exhibited a hump-shaped pattern of changes along the altitudinal gradient ($p<0.01$; Fig. 4c, e, f).

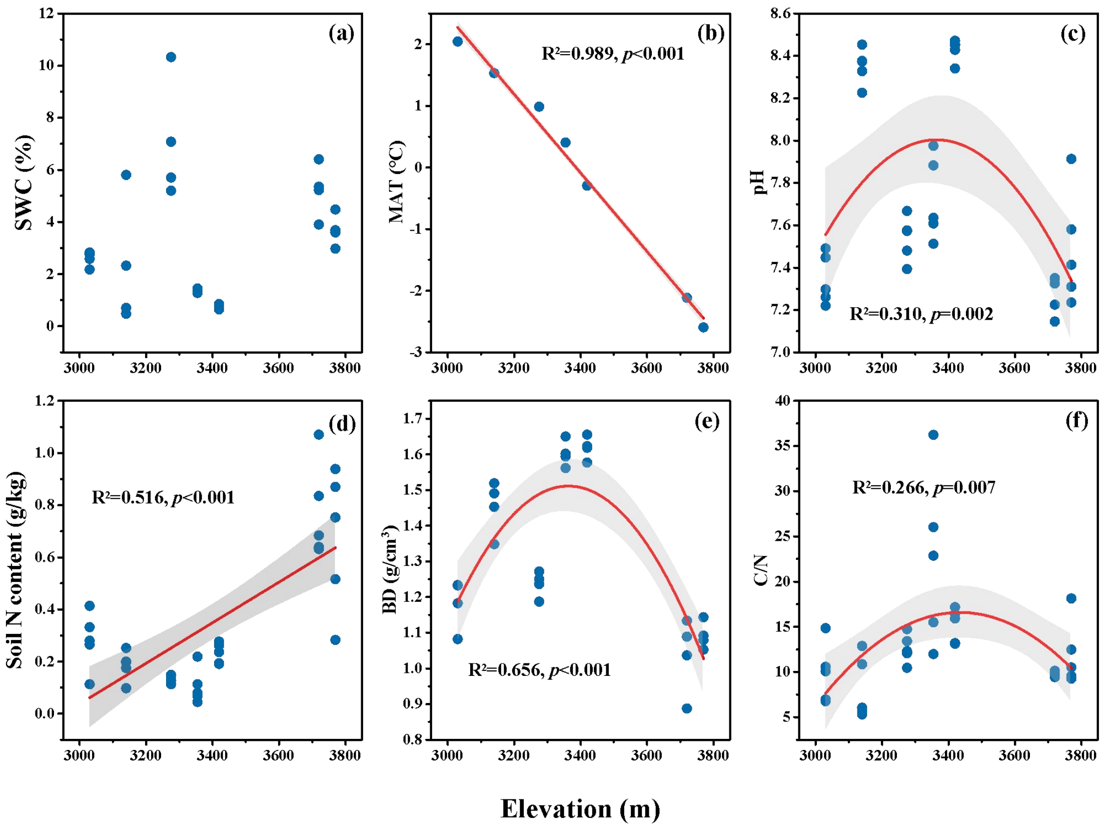


Fig. 4 The elevation variation of selective climatic and soil variables in a dry alpine rangeland of Qinghai-Tibetan Plateau. (a) Soil water content (SWC); (b) mean annual temperature (MAT); (c) soil pH; (d) soil N content; (e) soil bulk density (BD); (f) soil C to N ratio (C/N)

3.2. Influencing factors on changes in soil organic C density (SOCD) and inorganic C density (SICD)

The results from both correlation analysis and RDA showed that SOCD had a significant negative correlation with MAT, and significant positive correlations with BD, soil N content, NDVI and plant diversity (Table 1; Fig. 5). In contrast, SICD was negatively correlated with SWC, and positively with BD, soil C/N and fine root biomass density (Table 1; Fig. 5). In general, changes in SOCD was mostly explainable by variables related to climate and plant community traits; whereas SICD was predominantly associated with edaphic factors.

Table 1 Summary of the correlation coefficients for relationships of SOCD and SICD with selective variables for climatic, edaphic and plant community characteristics. * $p<0.05$, ** $p<0.01$

	Climatic factors		**Soil factors**				**Plant community factors**					
	SWC (%)	MAT (°C)	pH	BD (g/cm^3)	Soil N content (g/kg^2)	C/N	NDVI	Shannon-wiener index	Plant species richness	Vegetation cover (%)	Above-ground biomass density (g/m^2)	Root biomass density (g/m^2)
SOCD (kg C/m²)	0.039	-0.872**	-0.244	0.394*	0.885**	-0.128	0.843**	0.843**	0.771**	0.279	-0.265	0.12
SICD (kg C/m²)	-0.718**	-0.224	0.311	0.634**	-0.09	0.561**	0.163	0.113	0.055	0.034	-0.093	0.412*

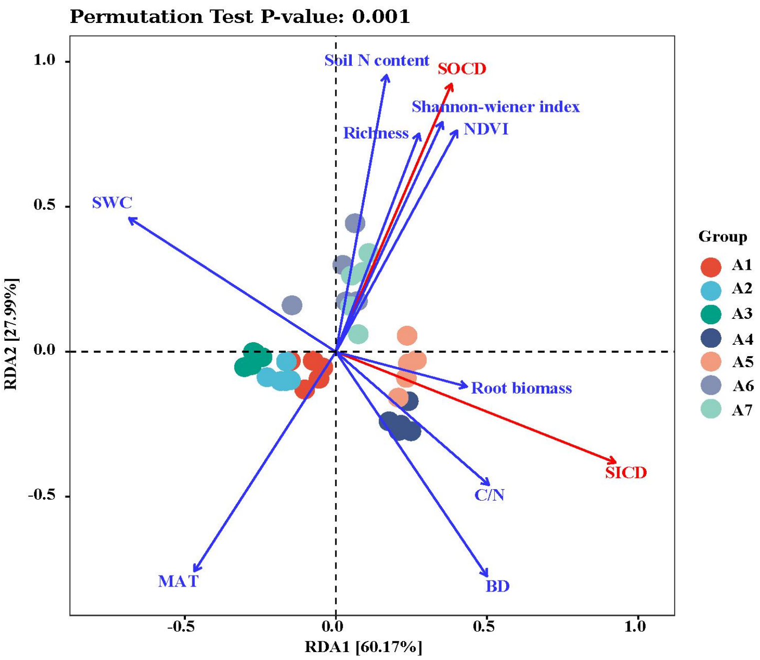
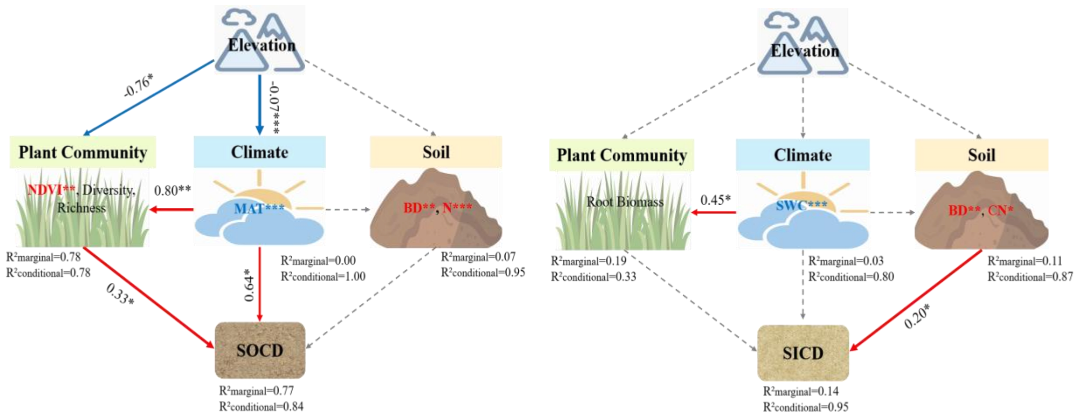


Fig. 5 RDA ranking of soil C pool (red line) and environmental variables (blue line) at different elevations. Arrow-lines represent relative values of environmental

variables and soil C pool. Correlations between environmental variables and soil C pool are indicated by the cosine of angles between the corresponding arrow-lines; angles <90° indicate a positive correlation, and >90° a negative correlation. Projecting the arrow-line for a soil C pool into an arrow-line for a corresponding environmental variable, the distance from the origin to the projection point indicates the relative power of the environmental variable in explaining the size of soil C pools.

In the structural equation modelling, the effects of elevation on SOCD were implemented via modifications of climate and plant communities (Fig. 6a); whereas variations in SICD were mainly associated with edaphic factors (Fig. 6b), consistent to the results from the RDA.



(a) (b)

Fig. 6 Structural equation models of the influences on (a) soil organic C density (SOCD) and (b) soil inorganic C density (SICD) by elevation, climate, and plant community, and soil. (a) Fisher's C = 4.714; $p = 0.318$; df = 4; AIC = 44.714; BIC = 75.821; (b) Fisher's C =5.000; p = 0.287; df = 4; AIC = 45.000; BIC = 76.107. Numbers adjacent to arrows are the standardized path coefficients (equivalent to correlation coefficients). Arrow thickness indicate the strength of the relationships. Red solid arrows denote significant positive effects (p<0.05) or marginally significant (0.05<p<0.1) effects. Blue solid arrows denote significant negative effects (p< 0.05) or marginally significant (0.05<p<0.1) effects. R^2 values associated with response variables indicate the variance accounted for by the model. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4. Discussion

Soil carbon pool, as the largest carbon pool in terrestrial ecosystem, has been extensively studied in different scales and regions (Zhang et al., 2024; Chalchissa and Kuris, 2024). However, previous studies have not paid much attention to the composition of different carbon pools in extreme environments. We studied the altitudinal patterns of soil organic and inorganic C pools in an alpine rangeland where ecosystem processes are co-limited by drought and low temperature. Contrary to the previous research results that the soil carbon pool of alpine meadows or moist grasslands was mainly composed of organic carbon (Chen et al., 2017; Chen et al., 2022). Our research results show that inorganic carbon in the soil of arid and alpine plateaus dominates. Our results showed a linear increase in soil organic C pool with rising elevation. Further, soil organic C pool linearly increased, while soil inorganic C pool appears to be nonlinear along the altitudinal gradient.

In this study, the linear changes in soil organic C pool along the altitudinal gradient were positively related to the altitudinal distribution of plant diversity and NDVI, but negatively to aboveground biomass density. It is generally found that increases in plant diversity and species richness promote the formation of soil organic C (Gu et al., 2019; Xu et al., 2021; Spohn et al., 2023). This is because SOC are predominantly derived from plant residues (Schmidt et al., 2011). More diverse plant species optimize the complementary use of resources and increase community productivity in areas with lower species richness (Lehmann et al., 2020). Unexpectedly, this study found the negative correlation between soil organic C pool and aboveground biomass density. This could be explained by the shift in vegetation cover type from slow-turnover scrubs (e.g. *Krascheninnikovia compacta* (Losinsk.) Grubov and *Salsola abrotanoides*) at the lower altitudinal range to fast-turnover grassland plants (e.g. *S. purpurea* and *P. bifurca*) at the higher altitudinal range. Scrubs typically have greater standing biomass but much slower turnover rate the organs and tissues than herbaceous plants. Moreover, with increases in elevation, temperature decreased and precipitation increased, both of which favoring the preservation of soil organic C.

Therefore changes in both vegetation and climatic conditions led to an increased SOC pool content at the higher elevations (De Deyn et al., 2008).

Climate is an important abiotic factor affecting the size and stability of soil C pool (Possinger et al., 2021; Zhang et al., 2024). Our study showed that decreases of MAT and SWC contributed to increased SOCD. This is contrary to the findings from previous studies in humid environments that SOC increases with rising temperature (Chalchissa and Kuris, 2024; Jiang et al., 2024). The discrepancy is mainly because that our study area is situated in an extremely arid region, such that the transpiration is much greater than that of precipitation. When temperature decreases, the transpiration decreases significantly, which is more conducive to plant growth and soil C accrual (Schmidt et al., 2011). In addition, lower temperature also significantly inhibits the activity of soil microorganisms, reducing the microbial decomposition of soil organic matter (Sun et al., 2019). In the case of small climate differences brought about by changes in elevation gradient, vegetation abundance and diversity increase with the increase of elevation gradient, which leads to the increase of plant carbon input, but the mineralization of microorganisms remains unchanged (Yue et al., 2017). Therefore, with the increase of the elevation gradient and the decrease of temperature, the vegetation type gradually changes from desert to grassland, the soil carbon input increases, the mineralization rate decreases, and the SOC content increases.

Apart from the effects of climatic factors and plant community factors, previous studies also suggested that soil properties had direct and major effects on soil C stock (Hemingway et al., 2019). Overall, however, we found that the effect of soil factors on SOC was weak, and indirectly through biological factors in the form of plant community structure (Fig. 6a). In this study, we found that soil N level was greater at the higher elevations, favoring the accumulation of SOC (Puspok et al., 2023). This is mainly because that an increase in soil N content suggests the greater abundance of nitrogen-fixing plants and/or microorganisms, and the acceleration of underground N cycling. Under this condition,, plants may grow faster and turn over more rapidly, thereby enhancing the inputs of soil organic matter (Reay et al., 2008; Sonam et al., 2016).

In contrast to the clear altitudinal pattern of SOCD, SICD did not display a consistent pattern of altitudinal changes. Previous studies have proved that soil inorganic carbon is more influenced by abiotic factors such as topography, soil and climate (Mi et al., 2008; Li et al., 2024). It initially decline with elevation up to about 3300 m asl (Fig. 2), but peaked at about 3400 m asl, at a position where the gentle slope at the lower elevation gave way to a much steeper mountain slope (Fig. 1). According to the sampling positions at each point, the abnormally high SICD value at the foot of the steep slope could be attributed to alluvial deposit and carbonate rock accumulations formed on the uphill slope, reflecting geological and hydrological effects. The correlation analyses revealed that SICD was mostly related to non-biotic factors such as soil bulk density and soil water. The main constituents of the SIC reservoir are carbonate salts (Zhao et al., 2019). When soil water content is high, CO_2 is readily transformed into carbonic acid (H_2CO_3), carbonate (CO_3^{2-}), and bicarbonate (HCO^{3-}), which promotes the dissolution of calcium carbonate and reduces the SIC content (Huber et al., 2019). The greater precipitation at the higher elevations may facilitate the leaching of SIC to the deep layer, resulting in a decrease in the surface soil inorganic C pool (Du and Gao, 2020). As a result, soil SIC content is higher and more stable in the arid soils of low elevation area (Ren et al., 2024). Previous studies have shown that SIC is not only affected by abiotic factors, but also by biological factors (Ma et al., 2024). Increased plant growth and biological activity enhance root respiratory secretion, resulting in dissolution and loss of SIC (Kuzyakov and Razavi, 2019). In this study, however, SICD was weakly correlated with root biomass, likely due to the low level of soil development in the study area. In the composite SEM model analysis, the increases in BD and soil C/N led increased level of soil inorganic C (Fig. 6b). There are two main reasons for this phenomenon, on the one hand, the distribution law of SIC comes from the distribution law of soil parent material itself, which has nothing to do with external factors. On the other hand, the turnover rate of SIC is low, the time stability is high, and the response to influencing factors is weak.

The change of SIC in arid area is mainly influenced by long-term geological cycle.

5.Conclusion

Our research results show that in the dry, high and cold plateau area of the Qinghai-Tibet Plateau, organic carbon increases linearly with the increase of elevation, while silicon carbide first increases and then decreases with the increase of elevation. SOC increased its relative contribution to total C pool at the higher elevations because of changes in plant communities and climatic conditions promoting soil organic C production and preservation. Overall, inorganic C played a predominant role in determining the soil C pool size in dry alpine rangeland, the difference of SIC distribution at different elevations is not affected by vegetation and climate change caused by elevation gradient. The results show that the soil carbon pool in the alpine desert region is mainly composed of SIC compared with that in the humid region, but the influence of climate, vegetation and other environmental conditions on the soil carbon pool is mainly achieved by changing SOC. Therefore, maintaining ecological stability in cold and dry region has an important impact on the carbon cycle of terrestrial ecosystems.

Data availability. The links to data are provided in the paper.

Authorship contribution. ALZ conceived and designed the experiments; QLL wrote the manuscript; JFY and YXZ analysed the data and contributed to the discussion; XYL, OJS, and YJ revised the article.

Competing interests. 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.

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