SOIL CARBON POOL CHARACTERISTICS AND DRIVING FACTORS IN MOUNTAINOUS AREAS - A CASE STUDY OF FUPING COUNTY, CHINA

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Abstract. This study examined the changes in soil organic carbon (SOC) component contents and the carbon pool management index across different altitudes and land use patterns. Fuping County, China, was selected as the study area. Soil samples were collected from five altitude gradients under four land use patterns. The variations in SOC, easily oxidizable organic carbon (EOC), dissolved organic carbon (DOC) and inert organic carbon (ROC) were analyzed. The main driving factors that caused the variations in these organic carbon components were analyzed via redundancy analysis. At the same altitude, the overall trends in soil SOC, EOC, DOC and ROC were forestland>orchards>cultivated land>grassland. Under the same land use pattern, soil SOC, EOC, DOC and ROC increased with increasing altitude. At the same altitude, soil carbon pool activity ranked as follows: orchards>cultivated land>grassland>forestland. Under the same land use pattern, carbon pool activity decreased with increasing altitude. Total nitrogen, C/N ratio, and amylase activity were the main driving factors influencing variations in the SOC pool across different land use patterns. At different altitudes, land use type and available nitrogen were the main driving factors.
Keywords: *mountain, altitude, land use, carbon pool stability, enzyme activity*

Introduction

The soil carbon pool accounts for the largest proportion of the total carbon pool in terrestrial ecosystems. Global surface soil carbon storage is estimated to range from 700×10^{15} to 2946×10^{15} g, comprising approximately two-thirds of terrestrial ecosystem carbon storage (Sakschewski et al., 2016) and equaling twice the carbon content of the atmosphere. In particular, mountain ecosystems store large amounts of soil organic carbon (SOC; approximately 29%), which plays an important role in regional and global carbon cycles. However, minor variations in soil carbon pools can significantly affect atmospheric carbon dioxide concentrations, potentially triggering positive feedback loops between global warming and the terrestrial carbon cycle (Post et al., 1982). Enhancing SOC is a key strategy for mitigating the rise in atmospheric CO_2 concentrations and combating global warming (Post and Kwon, 2000). Therefore, it is very important to study the variation characteristics of SOC and its components in mountainous areas to formulate strategies to promote carbon stability in mountainous ecosystems.

At present, the change in SOC is very slow, and its responses to climate change, land management measures and vegetation restoration are characterized by lag; therefore, it is difficult to observe slight changes in the short term (Shi et al., 2023). Although active organic carbon accounts for a small proportion of the total SOC, it can sensitively reflect subtle changes in SOC, which is helpful for revealing dynamic changes in SOC (Xie and van Zyl, 2020). Active organic carbon is commonly characterized by indicators such as easily oxidized organic carbon (EOC), dissolved organic carbon (DOC), and microbial biomass carbon. EOC affects the temporal trends and effectiveness of the SOC pool and is very sensitive to changes in the external environment. It is usually used as an indicator to characterize the initial changes in the SOC pool (Wu et al., 2024). DOC has a simple structure and is easily affected by plants and microorganisms. It can decompose and mineralize quickly and can be used to reflect soil nutrient transformation and cycling (Liu et al., 2022). Recalcitrant organic carbon (ROC) is a relatively difficult-to-degrade and stable component of the soil carbon pool. It is a soil response index to long-term changes in the environment, and its content reflects the long-term accumulation and carbon sequestration capacity of soil (Zhang et al., 2022). Lefroy et al. (1993) proposed the soil carbon pool management index (CPMI) in a study of EOC. The CPMI is the product of the ratio of SOC to a reference SOC value and the SOC activity index; this index is more sensitive than active organic carbon in terms of reflecting the degree of soil quality decline or renewal caused by various land use or management measures (Gao et al., 2023). To date, research on CPMI values has focused on different vegetation restoration models (Shi et al., 2023), responses to simulated acid rain (Chen et al., 2019), different tillage measures (Luo et al., 2015), different fertilization conditions (Wang et al., 2024a), different land use patterns (Xu et al., 2024) and so on.

Altitude and land use patterns are important factors affecting SOC and its components in mountainous areas. The natural elevation gradient provides a natural experimental platform for studying the formation and stability of soil carbon pools on large spatial and temporal scales in response to climate change because dramatic changes in biotic and abiotic properties can be observed within a short geographical distance (Zeng et al., 2022). The distribution pattern of mountain slope vegetation types driven by changes in altitude is similar to the distribution pattern of latitude-controlled climatic zones (Zhang et al., 2013). Changes in environmental factors such as soil temperature, humidity and nutrient levels with increasing altitude significantly affect the complex ecosystem processes associated with plant–soil–microorganism interactions (Zhang et al., 2013; Sundqvist et al., 2013). Therefore, altitudinal gradient studies have been widely used to simulate and explore the long-term responses and feedbacks of the soil carbon cycle to climate change (Fukami and Wardle, 2005). The SOC content shows a variety of distribution patterns along simple altitudinal gradients, such as increasing first and then decreasing (Bojko and Kabala, 2017; Tsozué et al., 2019), increasing with increasing altitude (Wang et al., 2024b) and decreasing first and then increasing (Pichler et al., 2022). As the main defining aspect of human intervention in the soil environment, land use affects the input and mineralization of SOC by regulating soil hydrothermal conditions, gas exchange capacity and fertility (Hu et al., 2018). Studies have shown that the SOC content of forestland is significantly greater than that of cultivated land (Xu et al., 2018a; Zhang et al., 2020). One study noted that the SOC contents of five different land use types, i.e., sand dunes, broad-leaved forestland, pine forestland, arid grassland and improved grassland, are quite different (Xiong et al., 2016). These studies noted that altitude and land use patterns significantly affect the distribution characteristics of SOC. However, the combined effects of hydrothermal conditions, vegetation cover types and tillage methods, as well as habitat heterogeneity within each region, lead to differences in organic carbon and its components. Therefore, it is highly important to accurately evaluate the disturbance-induced changes in the soil carbon pool through in-depth analysis of the distribution characteristics and driving factors of SOC and its components at different altitudes and under different land use patterns.

The Taihang Mountain area is located between the Loess Plateau and the North China Plain. It is an important geographical boundary in East China and an important ecological barrier in the North China Plain. Fuping County, Hebei Province, is located in the northern part of the Taihang Mountains. Its topographic and geomorphological characteristics are basically consistent with those in the Taihang Mountains, making it representative of the region. The terrain of Fuping slopes from northwest to southeast. The northwest is characterized by middle- and high-elevation mountains, with the highest elevation reaching 2273 m, whereas the southeastern part has lower elevations, characterized primarily by low mountains and hills. This area is rich in different vegetation belts and ecosystem types, and its SOC pool has great potential. The current study aimed to investigate the variations in SOC components, carbon pool stability, and their driving factors under the combined influence of elevation and land use type. The findings of this study provide data for elucidating the carbon cycle of mountain ecosystems and sustainable land use. The response of the SOC pool to different altitudes in this study might also provide a scientific basis for understanding the soil carbon cycle in the Taihang Mountain ecosystem (Zhang et al., 2019a).

Materials and methods

Overview of the study area

The Taihang Mountains are located in the eastern margin of the second step of China's topography. The mountains are steep in the east and shallow in the west. The altitude is high in the north and low in the south. This mountain range is the geographical boundary of East China and an important ecological barrier for Beijing, Tianjin and Hebei. Fuping County, Hebei Province, is located in the middle of the Taihang Mountains (113°45’-114°31’E, 38°09’-39°07’ N) (*Figure 1*), with a total area of approximately 2496 square kilometers. The topography of the county is basically the same as that of the Taihang Mountains, and the terrain gradually rises from southeast (altitude 192 m) to northwest (altitude 2273 m). Fuping County has a continental monsoon climate, with a mean annual temperature (MAT) of 12.6°, a mean annual precipitation (MAP) of 550–790 mm, and a frost-free period of 140–190 days. The local microclimate characteristics are consistent (https://www.resdc.cn). In 2023, the land use types in Fuping County included cultivated land (10901.74 hectares, accounting for 4.37%); orchards (12157.45 hectares, accounting for 4.87%); forestland (175670.99 hectares, accounting for 70.44%); grassland (31202.29 hectares, accounting for 12.51%); and other land use types (19465.87 hectares, accounting for 7.81%) (https://www.bdfuping.gov.cn). Cultivated land and residential land are concentrated in the valley basin area, and forestland, garden and unused land are mainly distributed in the mountainous area.

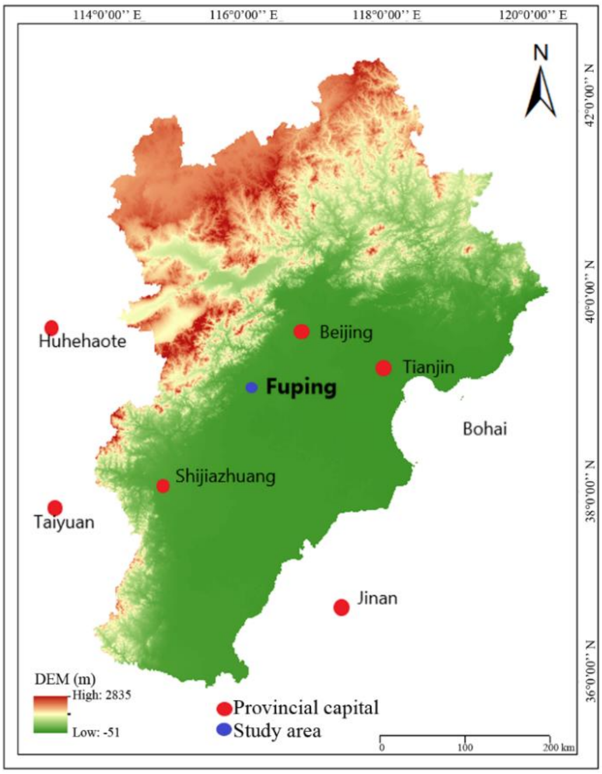

Figure 1. *The geographical location of Fuping County*

Sample selection and sampling

On the basis of a full field investigation and comprehensive consideration of factors such as vegetation type, soil type and climatic characteristics, five altitude levels were set, i.e., 300 m, 700 m, 1000 m, 1400 m, and 1800 m (Li et al., 2022). Sampling was performed in September 2023. Specifically, at each altitude level, different land use types were selected based on the current land use map of Fuping County. Three sampling points were set for each land use type at each altitude, and the location of each sampling point was recorded using a global positioning system (GPS). Three standard plots were selected near each sampling point. The details of the sample plots are summarized in *Table 1*, and the distribution of the sampling points is shown in *Figure 2*. In each plot, surface soil samples (0–20 cm) were collected using the 5-point method (Li et al., 2022), and the five collected soil samples were then mixed to create a composite sample. The soil samples were divided into two parts. A 2-mm-long portion of each fresh soil sample (with plant roots and litter removed) was stored at 4°C for the determination of soluble organic carbon. The other part was naturally air-dried in a cool place for the determination of other soil indicators.

Sample analysis and methods

SOC was determined using the potassium dichromate oxidation-external heating method (with concentrated sulfuric acid). DOC was determined using 0.5 mol/L potassium sulfate (K_2SO_4) extraction (Xu et al., 2010). Briefly, approximately 10 g of air-dried soil was placed in a 50-mL centrifuge tube, followed by the addition of 20 mL of extraction solution.

Table 1. *Basic characteristics of the sample plots*

Altitude	Land use pattern	Altitude (m)	Soil depth (cm)	Latitude and longitude	Dominant vegetation
300 m	Forestland	254	21.2	38°50′13.62″N,114°27′44.14″E	Poplar, wild mugwort
	Grassland	306.8	18.8	38°47′28.78″N,114°15′13.58″E	Dogtail grass
	Cultivated land	285.3	20.6	38°47′8.27″N,114°15′6.71″E	Maize (summer)
	Orchards	266.3	20.2	38°59′57″N,113°50′18″E	Apple tree
700 m	Forestland	707.1	22.1	38°51′19″N,113°56′47″E	Poplar, shrub artemisia
	Grassland	719	17.6	38°44′39″N,113°57′50″E	Herbal artemisia
	Cultivated land	706.8	23.1	38°54′52″N,113°52′52″E	Maize (summer)
	Orchards	699.1	20.5	38°47′40.3″N,114°14′1.53″E	Apple tree
1000 m	Forestland	1027.4	22.6	38°51′16.53″N,113°52′35.97″E	Poplar, shrub artemisia
	Grassland	1016	16.4	38°46′47″N,113°51′44″E	Herbal artemisia
	Cultivated land	1020.1	20.7	38°46′23″N,113°52′11″E	Maize (summer)
	Orchards	998.1	21.1	39°0′36″N,113°58′48″E	Apple tree
1400 m	Forestland	1418.6	20.4	38°55′39″N,113°46′41″E	Pine, shrub artemisia
	Grassland	1393.1	16.4	38°57′7″N,113°49′56″E	Herbal artemisia
	Cultivated land	1354	23.2	38°59′24″N,113°52′48″E	Maize (summer)
1800 m	Forestland	1777.7	22.1	38°58′21″N,113°49′42″E	Pine, mugwort
1800 m	Grassland	1782.9	17.2	38°58′22″N,113°49′40″E	Herbal artemisia

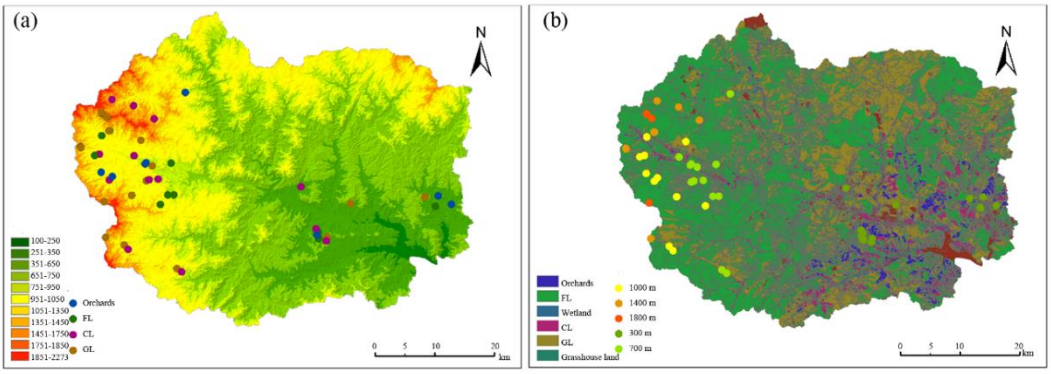

Figure 2. *Distribution of the sampling points used in this study, plotted with ArcGIS. (a) Based on altitude. (b) Based on land use type. Notes: FL, forestland; CL, cultivated land; GL, grassland*

The solution was shaken and filtered, and the obtained filtrate was then analyzed using a total organic carbon/nitrogen analyzer (ThermoFisher Scientific, Shanghai, China) to determine the DOC content. EOC was determined using the potassium permanganate ($KMnO_4$) oxidation method (Blair et al., 1995). Approximately 2 g of fresh soil sample was weighed into a 50-mL centrifuge tube, and 25 mL of potassium permanganate solution at a concentration of 333 mmol/L was added. A blank control was also included. After centrifugation, the supernatant was collected and analyzed using a

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spectrophotometer (MACYLAB Instrument, Shanghai, China) to measure the absorbance. The amount of potassium permanganate consumed was calculated based on the standard curve to determine the EOC content. ROC was determined using HCl hydrolysis followed by the potassium dichromate-concentrated sulfuric acid external heating method (Bao, 2000). Briefly, approximately 2 g of soil was placed in a digestion tube, and 5 mL of 6 mol/L HCl solution was added, followed by digestion at 115°C for 16 h. After cooling, the sample was transferred to a centrifuge tube, washed with deionized water until the pH became neutral, and then dried at 55°C. The organic carbon content, i.e., ROC, was then determined.

The total nitrogen (TN) content was determined via the Kjeldahl method (NKB3100 Kjeldahl nitrogen analyzer; Yihong, Shanghai, China). The total phosphorus (TP) content was determined via the alkali fusion-molybdenum antimony anticolorimetric method (spectrophotometer; MACYLAB Instrument, Shanghai, China). The total potassium (TK) content was determined via the 1-mol L^{-1} NH_4OAC-flame photometric method (flame photometer; Wujiu, Shanghai, China). The alkali-hydrolyzable nitrogen (AN) content was assessed via the alkaline hydrolysis diffusion method. The Olsen method was used to determine the available phosphorus (AP) content (MACYLAB Instrument). The available potassium (AK) content was determined via the 1-mol L^{-1} NH_4OAC-flame photometric method (Shanghai Wujiu). The pH was measured with a benchtop acidity meter (METTLER TOLEDO, Columbus, Ohio, USA). The bulk density (BD) was measured via the ring knife method. The soil moisture content (SWC) was measured via the fresh soil drying method. The above indicators were determined in accordance with 'Soil Agrochemical Analysis', edited by Bao (2000), and 'Soil Agrochemical Analysis Methods', edited by Lu (2000).

The potassium permanganate titration method was used for catalase analysis (Yang et al., 2011); the 3,5-dinitrosalicylic acid colorimetric method was used for amylase activity analysis (Guan and Meng, 1986); the 3,5-dinitrosalicylic acid colorimetric method was used for sucrase analysis; and the nitrobenzene colorimetric method was used for β-glucosidase analysis (Wang and Qin, 2006).

The latest MAP and MAT data (1:1000 km) from the Fuping County meteorological station in 2020 were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn). ArcGIS10.2 was used to extract the MAP and MAT at each sampling point. The DEM was downloaded from the geospatial data cloud (https://www.gscloud.cn), and the aspect slope was extracted via ArcGIS10.2. The slope aspects were divided into shady slopes (including semishady slopes) and sunny slopes (semisunny slopes). The slope was divided into four gradients: 0°-5° indicated a flat slope, 6°-15° indicated a gentle slope, 16°-25° indicated a moderate slope, and 16°-35° indicated a steep slope.

Index calculation

The carbon pool management index (CPMI) is calculated as follows (Zhang et al., 2018; Yang et al., 2023):

$$\text{Carbon pool index (CPI)} = \frac{\text{TSOC}}{\text{CSOC}} \tag{Eq.1}$$

where TSOC is the total carbon content of the sample and, CSOC is the reference organic carbon content.

$$\text{Carbon activity (A)} = \frac{\text{ROC}}{\text{SOC}-\text{ROC}} \tag{Eq.2}$$

$$\text{Carbon activity index (AI)} = \frac{\text{A}}{\text{CA}} \tag{Eq.3}$$

where CA is the reference soil pool carbon activity.

$$\text{Carbon pool management index (CPMI)} = CAI \times CPI \times 100 \tag{Eq.4}$$

In this study, grassland soil was used as the reference soil for calculating CPMI under different land use patterns. When CPMI at different altitudes was calculated, soil at an altitude of 300 m was used as the reference soil.

Statistical methods

The data were organized with Excel 2016. One-way analysis of variance (ANOVA) was carried out using SPSS 23.0. The significance of differences between samples was tested using Duncan’s multiple range test ($P < 0.05$). Correlations were analyzed using the Pearson method, with the significance level set at $P < 0.05$. Redundancy analysis was performed using Canoco 5.0. Data visualization was conducted with Origin 2022, and the sampling site distribution map was plotted with ArcGIS 10.2.

Results and analysis

Variations in the contents of SOC and its components

Under the same land use pattern, the contents of SOC and its components increased with increasing altitude (*Figure 3*). For example, in grassland, the SOC content at different elevation levels followed the order 300 m (1.76 g/kg) < 700 m (5.97 g/kg) < 1000 m (12.04 g/kg) < 1400 m (22.1 g/kg) < 1800 m (29.85 g/kg). In forestland, the SOC content generally increased with altitude, as follows: 300 m (9.31 g/kg) < 700 m (25.13 g/kg) < 1400 m (28.59 g/kg) < 1800 m (36.94 g/kg); however, the SOC content was the highest at 1000 m altitude (40.82 g/kg).

At most altitudes, the contents of SOC and its components decreased in the following order of land use types: forestland > orchards > cultivated land > grassland; moreover, the differences between different land use patterns were significant (*Figure 3*). For example, at 700 m altitude, the ranking of the SOC content according to land use type was as follows: forestland (25.13 g/kg) > orchards (15.69 g/kg) > cultivated land (11.04 g/kg) > grassland (5.97 g/kg). At the 300 m level, however, the SOC content in orchards was the highest, which was slightly higher than that in forestland, followed by cultivated land and then grassland.

Variations in the soil carbon pool management index

Under the same land use pattern, except that the CA of forestland was the lowest at an altitude of 1000 m, the CAs of the other land use patterns decreased with increasing altitude, which indicates that the higher the altitude is, the more stable the carbon pool is (*Figure 4*). In forestland, the CA values were between 1.57 and 2.48, with the lowest value occurring at an elevation of 1000 m, which was significantly different from the values at other elevations. In grassland, the CA values were between 0.07 and 2.2, with the highest value occurring at an elevation of 300 m. In cultivated land and garden land, the ranges of CA were 0.05–0.12 and 0.06–0.07, respectively. No significant differences were observed among different elevations.

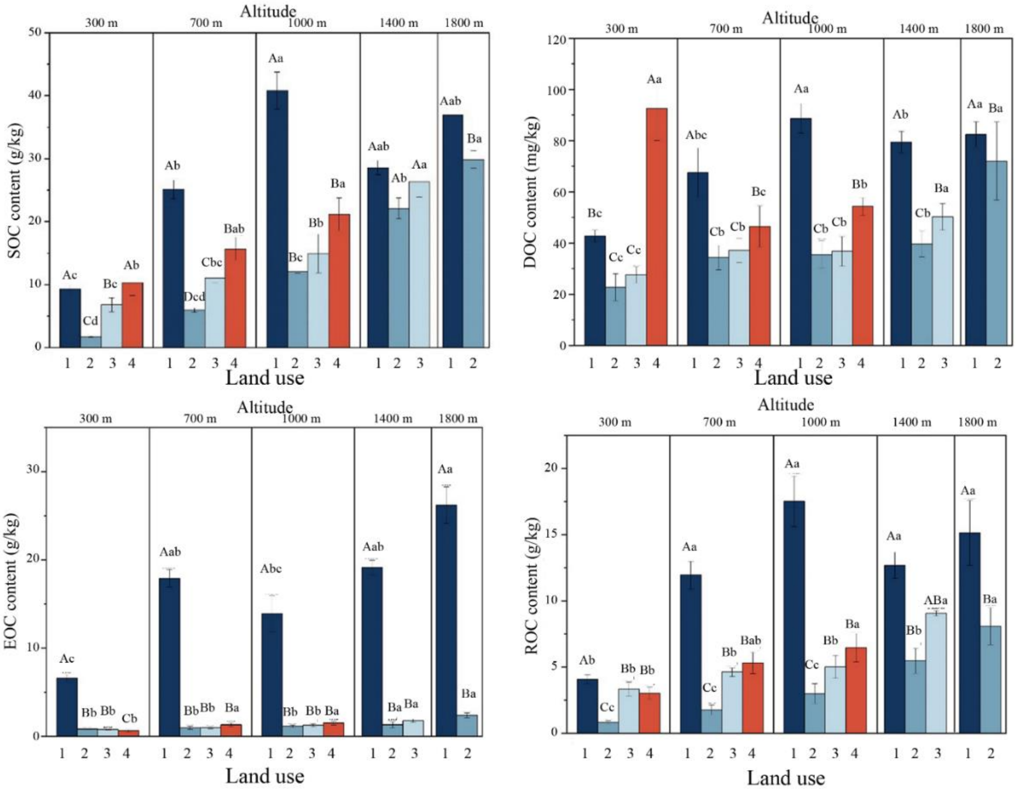

Figure 3. *Changes in soil organic carbon and its components. Notes: Land use types: 1, forestland; 2, grassland; 3, cultivated land; 4, orchards. Uppercase letters indicate significant differences between different land use types at the same altitude, and lowercase letters indicate significant differences between different elevations for the same land use type (P < 0.05)*

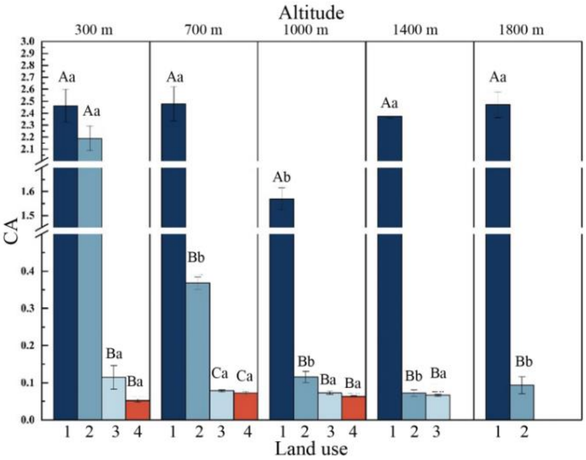

Figure 4. *Variations in soil carbon pool activity. Notes: Land use type: 1, forestland; 2, grassland; 3, cultivated land; 4, orchards. Uppercase letters indicate significant differences between different land use types at the same altitude, and lowercase letters indicate significant differences between different elevations for the same land use type (P < 0.05)*

At the same altitude, CA decreased in the following order: forestland > grassland > cultivated land > orchards. This finding indicated that the carbon pool of orchards was the most stable (*Figure 4*). For example, at an elevation of 300 m, forestland exhibited the highest CA (2.46), followed by grassland (2.19), cultivated land (0.12) and orchards (0.06).

In this analysis, grassland soil at different altitudes was used as the reference soil. The CPMI of forestland was the highest and was significantly higher than that of the other land use types, which indicated that the quality of the forestland carbon pool was the best (*Figure 5a*). At 300 m, the CPMI ranged from 9.97% to 408.28%, and the land use types were ranked from high to low based on their CMPI values as follows: forestland > grassland > cultivated land > orchards. At 700 m and 1000 m, the CPMI ranges were 39.47%-2835% and 78.34%-4601.86%, respectively. At both elevations, the rankings from high to low based on CPMI values were as follows: forestland > grassland > orchards > cultivated land. At 1400 m and 1800 m, the CPMI ranges were 85.15%-4238.41% and 100%-3279.63%, respectively. At both altitudes, the rankings from high to low based on CPMI values were as follows: forestland > grassland > cultivated land.

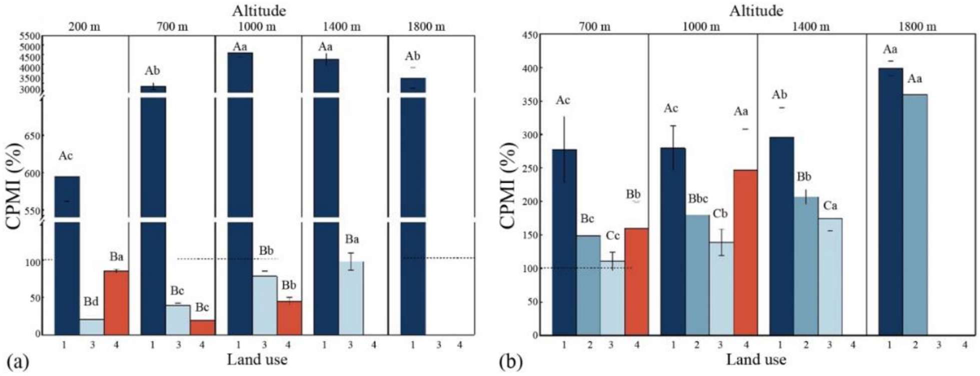

Figure 5. *Variations in the soil carbon pool management index. Notes: Land use type: 1, forestland; 2, grassland; 3, cultivated land; 4, orchards. Uppercase letters indicate significant differences between different land use types at the same altitude, and lowercase letters indicate significant differences between different elevations for the same land use type (P < 0.05). Values calculated (a) with grassland soil as the reference soil and (b) with soil at an altitude of 300 m as the reference soil*

The CPMI (calculated with the value at an altitude of 300 m as a reference) of each land use type increased with increasing altitude, indicating that the soil carbon pool quality was the highest at 1800 m (*Figure 5b*). For forestland, grassland, farmland and orchards, the CPMI ranges were 100%–398.29%, 100%–359.68%, 100%–174.08% and 100%–246.4%, respectively.

Correlations between soil organic carbon, its components, the carbon pool management index and other properties

Soil physical and chemical properties are important environmental characteristics that affect SOC components. To determine the main driving factors that cause the variation in SOC components under different land use patterns, SOC, EOC, DOC, ROC, CA and CMPI were used as response variables, and environmental factors were used as explanatory variables. Redundancy analysis (RDA) and Monte Carlo tests were carried out, and environmental factors with explanatory values and contributions less than 1% were eliminated. The results revealed that the top four variables were TN, AN, C/N and CAT in forestland; TN, MAT, CAT and TK in grassland; TN, C/N, TK and CAT in cultivated land; and TN, C/N, MAP and TK in orchards, accounting for 61.8%, 69.3%, 73.4% and 84.8% of the variation, respectively. Except for C/N and MAT, these variables were significantly positively correlated with SOC, EOC, DOC, ROC and CMPI and significantly negatively correlated with CA (*Figure 6*). In summary, the main driving factors for the variation in organic carbon components and stability under different land use patterns are TN, C/N and CAT.

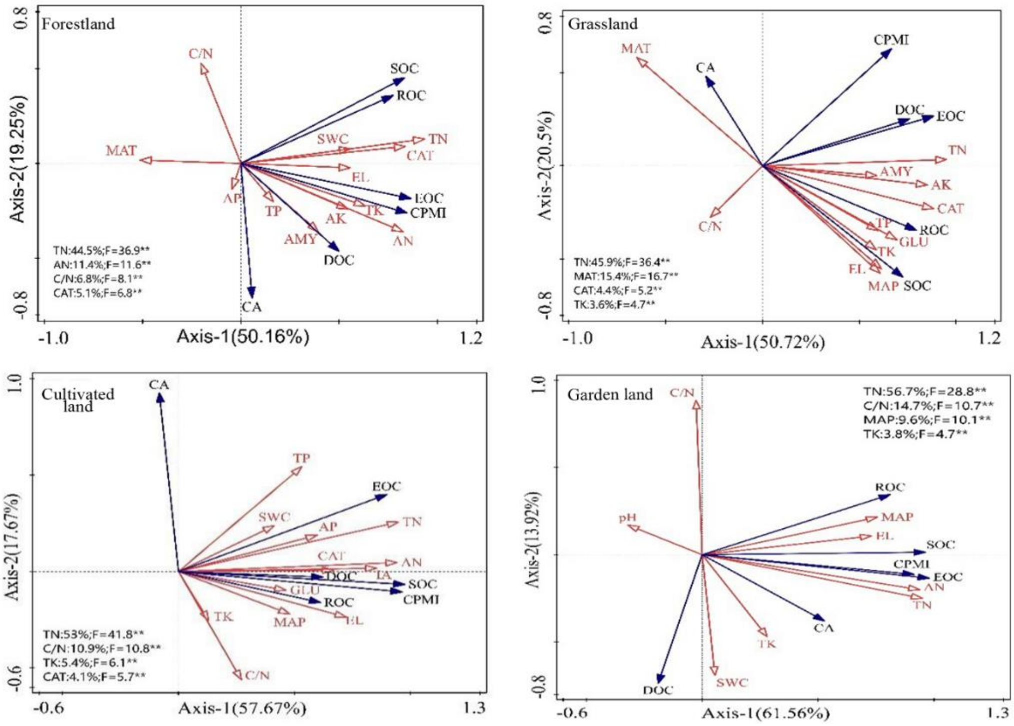

Figure 6. *Redundancy analysis of soil organic carbon components, the carbon pool management index and environmental factors under different land use patterns. Notes: BD: soil bulk density; SWC: soil moisture content; TN: total nitrogen; TP: total phosphorus; TK: total potassium; AN: alkali-hydrolyzable nitrogen; AP: available phosphorus; AK: available potassium; C/N: ratio of carbon to nitrogen; pH: potential of hydrogen; CAT: catalase; IA: sucrase; GLU: β-glucosidase; AMY: amylase activity; MAT: mean annual temperature; MAP: mean annual precipitation; EL: elevation*

RDA and Monte Carlo tests were performed on SOC and soil environmental factors at different altitudes, and environmental factors with explanatory values and contributions lower than 1% were excluded. The results revealed that the top four variables were LU, AN, CAT and C/N at an altitude of 300 m; AN, LU, pH and TK at an altitude of 700 m; TN, AN, CAT and AK at an altitude of 1000 m; LU, TN, CAT and AK at an altitude of 1400 m; and LU, AN, C/N and IA at an altitude of 1800 m. These factors explained 72.6%, 80.6%, 63.8%, 80.6% and 90.5% of the variance, respectively. With the exception of LU and C/N, these variables were significantly positively correlated with SOC, EOC, DOC, ROC, CA and CMPI (*Figure 7*). In summary, LU and AN are the main drivers of variations in SOC and stability at different altitudes.

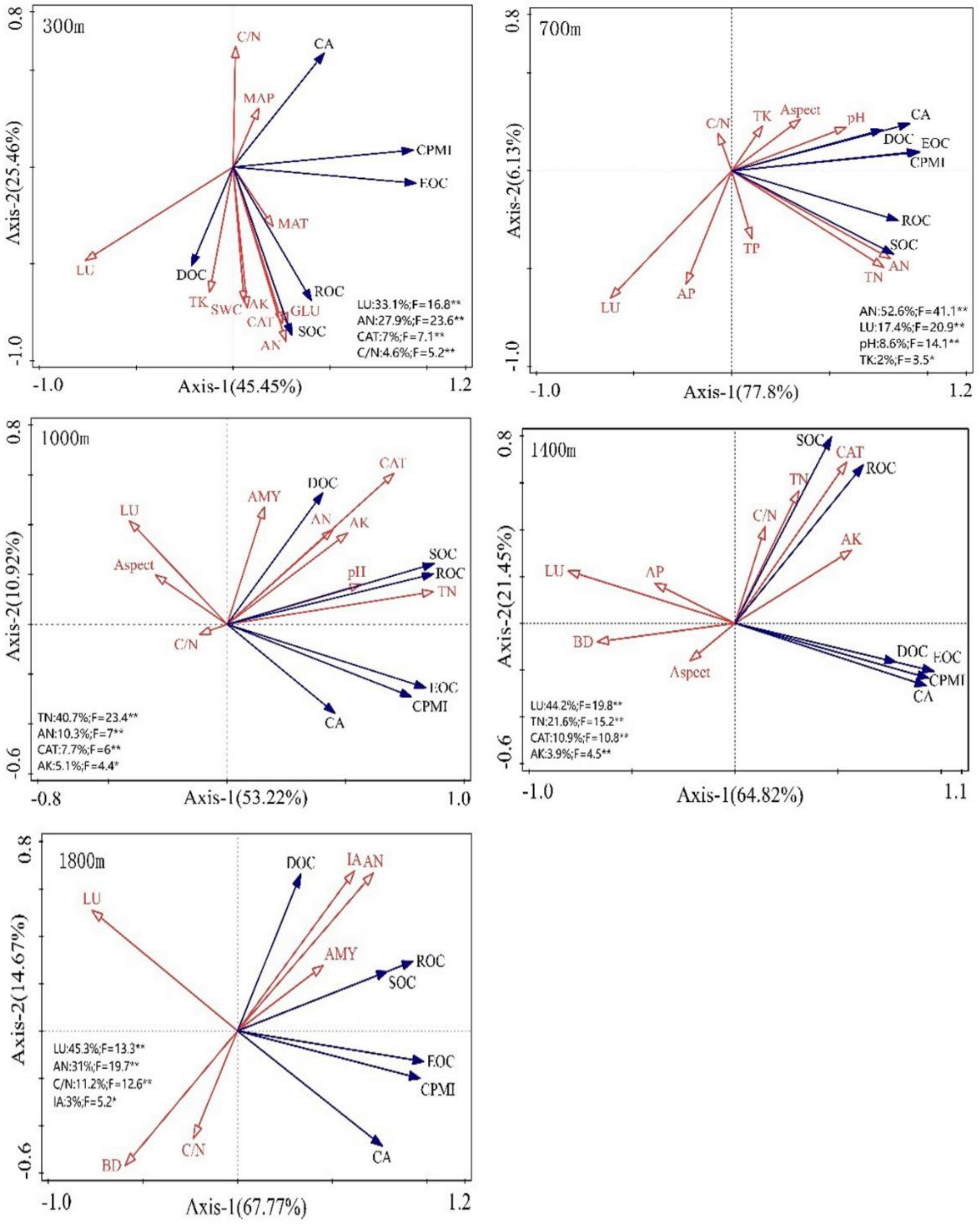

Figure 7. *Redundancy analysis of soil organic carbon components, the carbon pool management index and environmental factors at different altitudes*

Discussion

In this study area, the number of land use types decreases with increasing altitude. There are four land use types below 1000 m above sea level. At an altitude of 1400 m, there are only three land use types: forestland, grassland and cultivated land. At an altitude of 1800 m, there are only two land use types: forestland and grassland. The results revealed that the distributions of the SOC, EOC, DOC and ROC contents were approximately the same regardless of land use pattern or altitude. At the same altitude, the contents of SOC components followed the order forestland > orchards > cultivated land > grassland, with significant differences among the different land use patterns. This

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pattern indicated that forestland is more conducive than other land use types to the accumulation of SOC. Land use (Bughio et al., 2016), vegetation cover type (Wang et al., 2022) and agricultural management measures (Goydaragh et al., 2021) affect the storage and turnover of the SOC pool. Forestland, the main land use pattern in the study area, is characterized by a large amount of litter return and slow decomposition, which are conducive to carbon accumulation (Luo et al., 2020). Moreover, the EOC content in forestland was significantly higher than that in other land use patterns. This occurred because the soil EOC content is significantly affected by vegetation (Zheng et al., 2021). Forest roots are deep and vigorous and produce more vegetation residues and secretory substances (Jackson et al., 1996), so the EOC content of forestland is greater. The total amount of litter in orchards is less than that in forestland, and crop harvest reduces the amount of soil organic matter returned to the soil; therefore, in this study, the SOC content was significantly lower in orchards than in forestland. At an altitude of 300 m, the SOC content of orchards was slightly greater than that of forestland. In previous research, it was found that compared with orchards at other altitudes, orchards at an altitude of 300 m had higher quality, better human management, and significantly greater annual organic fertilizer inputs. This may explain why the SOC contents of forestland and orchards at an altitude of 300 m were similar. The SOC contents of forestland and orchards were significantly greater than that of cultivated land. The reason is that during the farmland tillage process, the soil structure is destroyed, and the SOC decomposition rate is accelerated; in contrast, litter from forestland and orchards accumulates on the soil surface, and a humus layer is formed after decomposition (Lavallee et al., 2020). The reason for the low SOC content in grasslands is that the main carbon source input pathway is the decomposition of underground roots; this process depends on the developed underground fine root network of grassland vegetation and fixes a large amount of SOC in the rhizosphere (Li et al., 2024). However, in the grasslands of the study area, the distribution of vegetation roots is relatively shallow, and the vegetation coverage is low, resulting in a relatively small amount of exogenous carbon inputs such as litter. This situation limits the accumulation of organic carbon in the soil.

The SOC content increased with increasing altitude in all four land use types considered in this study, which is consistent with previous results (Wu et al., 2023; Feyissa et al., 2023). The reason for this trend is that with increasing altitude, the temperature decreases, soil microbial activity weakens, the decomposition rate of animal and plant residues decreases, and the SOC decomposition rate decreases, so the accumulation of organic carbon components increases (Dai et al., 2021; Ren et al., 2021; Zhang et al., 2023a). The SOC content of forestland reached a maximum at an altitude of 1000 m. The main reason is that the amount of litter in forestland at an altitude of 1400 m is small, and litter is an important source of SOC. The decrease in organic carbon input into the soil caused a decrease in SOC accumulation at altitudes of 1000–1400 m.

At the same altitude, the CPMI and CA of forestland and grassland were greater than those of cultivated land and orchards, which indicated that the carbon pool quality of forestland and grassland was the highest and that these land use types had a more active carbon pool. This finding is similar to the results of Zhang et al. (2016). The main reasons are that cultivated land and orchards are greatly disturbed by human activities, the farming management practices in the area are not scientific, the surface vegetation is seriously damaged, and the carbon pool management approach is not reasonable; these factors collectively led to the low quality of the carbon pool in the garden land and cultivated land in the study area. Among these land use types, gardens have the most stable carbon pool, which is consistent with the results of Zhang et al. (2023b). The main reason is that the long-term application of chemical fertilizers to orchards within the study area increased the content of only inert organic carbon in the soil (Zhang et al., 2009), which reduced the amount of carbon sources available to microorganisms. As a result, the content of active organic carbon components decreased, which increased the stability of the soil carbon pool. Under the same land use pattern, the CPMI increased with increasing altitude, and the results of Wang et al. (2023) confirmed this conclusion. CA decreased with increasing altitude because in high-altitude soils with more precipitation and suitable temperatures, microorganisms can decompose more organic carbon into active or inert organic carbon. Moreover, soil microorganisms further decompose active organic carbon to promote microbial activity and quantity, while inert organic carbon is retained in the soil; thus, the quality and stability of the soil carbon pool are enhanced.

The SOC fraction and CPMI were positively correlated with soil nutrients (TN, AN, TP, AP, TK, and AK), indicating that these indicators can be used to evaluate the dynamic changes in the soil carbon pool and soil nutrient quality, which is similar to the results of previous studies (Van Den Brink et al., 2023; Zeng et al., 2023). This is mainly due to the complementary relationship between soil nutrients and biodiversity. An increase in soil nutrient content can promote the circulation and turnover rate of the soil carbon pool and improve soil quality and productivity. The SOC fraction and CPMI were negatively correlated with BD. The main reason for this association is that soil BD can reflect the degree of ventilation, water permeability and toughness in the soil. When BD is greater, the soil porosity is lower, the soil is relatively compact, the ventilation and water permeability are poor, soil microbial activity is inhibited, and the decomposition rates of litter, animal and plant residues are lower (Zhao et al., 2021). An appropriate SWC promotes the contents of organic carbon components and the CPMI. Under conditions of sufficient soil moisture, soil microbial activity is usually strong, which helps litter decompose and promotes the accumulation of SOC. For example, Fang et al. (2014) reported that a low SWC was not conducive to the decomposition of SOC; therefore, the content of organic carbon was reduced. Antisari et al. (2015) reported that a high SWC was negatively correlated with the content of active organic carbon. The reason for these differences may be the different soil textures in different regions. The pH values of the four land use types decreased with increasing altitude. The decrease in pH slowed the degradation of organic carbon and exogenous organic matter in the soil (Wang et al., 2007), increased the accumulation of organic carbon components and the quality of the carbon pool, and ultimately increased the stability of the soil carbon pool.

The correlations of SOC fractions with carbon pool stability and soil enzyme activity can indirectly reflect the relationships between SOC and microorganisms (Zhai et al., 2015). The results of this study revealed that the SOC composition and carbon pool stability are positively correlated with enzyme activity, but the results differ significantly. The reason may be that, on the one hand, different enzymes have different functions (Tischer et al., 2014), so microorganisms in different land use patterns tend to exhibit different behaviors. On the other hand, N or P limitation may occur in vegetation–soil systems under different land use patterns (Xu et al., 2018b), which promotes or inhibits the expression of different soil enzyme activities and affects microbial activity. There was a significant negative correlation between CA and soil enzyme activity in grassland, possibly because the soil properties of the grasslands were relatively stable and the content of inert organic carbon in grasslands was greater than that of other SOC components. This shows that inert organic carbon is the main factor affecting the change in grassland organic carbon. Moreover, these results demonstrate that changes in inert organic carbon in the soil matrix are sufficient to offset the influence of soil enzymes on active organic carbon components.

Under different land use patterns, organic carbon components and the CPMI were negatively correlated with MAT and had different degrees of positive correlation with MAP, which was similar to the results of Sanderman et al. (2003). The main reason is that with increasing altitude, the temperature decreases, the amount of rainfall increases, the amount of water in the soil increases, and the species and quantity of microorganism decrease, which lead to the accumulation of organic carbon. In contrast, CA showed the opposite trend; i.e., with decreasing temperature and increasing rainfall, CA decreased, and the stability of the carbon pool increased. This trend further demonstrates that with increasing altitude, the carbon pool becomes more stable. At a given altitude, the changes in MAT and MAP among the four land use types were minor, and their correlation with the organic carbon pool was not significant. The organic carbon fraction and CPMI were positively correlated with altitude, whereas CA was negatively correlated with altitude. These findings indicate that the organic carbon composition and carbon pool quality and stability increase with increasing altitude. The organic carbon components and CPMI were negatively correlated with slope aspect. The main reason is that the soil on shady and sunny slopes is affected by different light intensities for a long period of time, resulting in very different soil water and heat conditions, which further affect the accumulation of SOC. The negative correlation with slope means that the smaller the slope was, the greater the SOC content was. The main reason is that when the slope is steeper, it becomes more difficult to preserve litter, and the degree of water erosion increases. These conditions are not conducive to the preservation and infiltration of soil organic matter and ultimately affected the contents of SOC components.

Under different land use patterns, TN and the C/N ratio were the main driving factors for the variation in organic carbon components and carbon pool stability, which is consistent with the results of Zhang et al. (2019b). This finding can be attributed to two factors (Nottingham et al., 2015). On the one hand, an increase in nitrogen in soil may inhibit soil respiration, thus reducing the amount of CO_2 released by the soil. On the other hand, N plays a vital role in plant growth; this element is easily absorbed and utilized by plants, directly affects the growth of plants, and ultimately affects the input of plant litter. At different altitudes, AN, C/N and land use pattern were the main drivers of changes in organic carbon fractions and carbon pool stability. This may be because AN affects the decomposition and utilization rates of organic carbon by plants and microorganisms, resulting in inconsistent trends in organic carbon fractions and thus variations in carbon pool stability (Ma et al., 2022). In addition, the intensity of human disturbance directly affects the contents of organic carbon components and the stability of the carbon pool. The main reason is that unreasonable human farming strategies destroy surface vegetation and soil structure, which in turn aggravates soil erosion (Wang et al., 2011). Under different altitudes and land use patterns, the C/N ratio played an important role in the variations in organic carbon components and carbon pool stability. High-quality litter usually has a relatively high nitrogen content and low C/N ratio and is relatively easily decomposed by soil microorganisms (Wu et al., 2023). By adjusting the C/N ratio in the soil, the formation of large aggregates in the soil can promoted, and the conversion rate of SOC components is affected, which in turn affects the stability of the soil carbon pool. Under different altitudes and land use patterns, the C/N ratio plays an important role in the variation in organic carbon components and carbon pool stability. High-quality litter usually has a relatively high nitrogen content and low C/N ratio and is relatively easily decomposed by soil microorganisms (Wu et al., 2023). By adjusting the C/N ratio in the soil, the formation of large aggregates in the soil can be promoted, and the conversion rate of SOC components is affected, which ultimately affects the stability of the soil carbon pool.

Conclusion

In this work, the variations in the contents of soil organic carbon components and the carbon pool management index under different altitudes and land use patterns and the corresponding driving factors were explored, and the following conclusions were drawn.

(1) At the same altitude, the overall trend of soil organic carbon content was forestland > orchards > cultivated land > grassland, and the content in forestland was significantly greater than that in other land use patterns. Under the same land use pattern, the soil organic carbon content increased with increasing altitude, with a trend of 1800 m > 1400 m > 1000 m > 700 m > 300 m. Under different altitudes and land use patterns, the variations in easily oxidized organic carbon, soluble organic carbon and inert organic carbon were basically the same as that in the organic carbon content.

(2) At the same altitude, the carbon pool activity and carbon pool management index followed the order forestland > grassland > cultivated land > orchards. Under the same land use pattern, the carbon pool activity of forestland, grassland, cultivated land and orchards decreased with increasing altitude, whereas the carbon pool management index increased with increasing altitude.

(3) Total nitrogen, C/N and amylase activity were the main factors influencing the variation in the soil organic carbon pool under different land use patterns. Land use type and available nitrogen were the main factors influencing the variation in the soil organic carbon pool at different altitudes.

The results of this study clarified the characteristic variations in the soil carbon pool under different altitudes and land use patterns and revealed the driving factors of changes in the soil carbon pool. Furthermore, this research provides experimental and theoretical data for better predicting the formation of and changes in the soil carbon pool under climate change. To better understand the spatial and temporal variations in the soil carbon pool along the vertical soil profile under climate change and the underlying mechanisms, soil sampling at different soil depths should be performed in future studies. Moreover, the temporal dynamics of the driving factors of soil organic carbon under different altitudes and land use patterns should be systematically evaluated and quantified through long-term multistage sampling.

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