

Effects of Erosion Gully Drainage on Soil Organic Carbon Spatial Differentiation Pattern in Alpine Peatlands

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Abstract

Hydrothermal pattern and vegetation community structure are key factors affecting the soil organic carbon (SOC) formation and accumulation in alpine peatlands. Research on the influence of vegetation and soil factors on SOC spatial differentiation pattern under the thaw slump erosion gullies drainage gradient, can help understand the alpine peatlands carbon sequestration mechanism under the climate change. In this paper, experiments were conducted in drainage alpine peatlands on Zoige Plateau. From undisturbed peatland to the edge of the erosion gully formed by thaw slump, according to the water level changes. Four drainage gradient sample plots were set up successively, namely undrained (Ⅰ), lightly drained (Ⅱ), moderately drained (Ⅲ) and heavily drained (Ⅳ), the effects of community characteristics and soil factors on the SOC content at different drainage gradients were studied. The results show that: Horizontally, the dominant species succession from *Carex muliensis* (I) to *Blysmus sinocompressus* (II, III) and *Kobresia tibetica* (IV), the SOC, soil water content (SWC), C/N, community biomass (TB), litter count (LC), and root/shoot (R/S) decreased, the soil bulk density (BD), pH and temperature (ST) increased. Vertically, the SOC in Sample plot I decreased, in Sample plot II, III, and IV firstly decreased and then increased. The SOC was highly significant positive correlation with TB, LC, and R/S ($p < 0.01$). Path analysis indicated that the order of soil factors affecting SOC was $SWC > C/N > ST > BD$. Drainage affects the peatlands ecohydrological processes, disrupts the balance of material input and decomposition, changes the SOC horizontal and vertical patterns, causing alpine peatlands degradation.

1 Introduction

Alpine peatlands develops in high-altitude areas with cold and wet climate and poor drainage, the long-term water-saturated anaerobic environment retard decomposition of a large number of wet plant organic residues, which gradually accumulates to form peat-rich swamps. The difference between net primary productivity and decomposition of plant litter promotes the net accumulation of organic carbon, making alpine peatlands become an important carbon sink in terrestrial ecosystem (Morris et al., 2018; Chen et al., 2023). With global warming, perennial permafrost warming and thawing, the water-retaining function of permafrost layer in peatlands is weakened, resulting in thaw slump, continued loss of surface water and groundwater from peatlands (Cox et al., 2000; Sim et al., 2021; Fan et al., 2023). The change of eco-hydrological processes have led to vegetation community succession, affecting the quality and quantity of peatlands material inputs. Meanwhile, organic carbon-rich soil are directly exposed to air and participates in oxidative decomposition (Li et al., 2018; Putra et al., 2021), which may alter the peat accumulation processes, adversely affect the carbon pool stability. On the erosion gullies drainage gradient formed by thaw slump in alpine peatlands, research on the SOC partitioning patterns caused by vegetation community structure and soil physicochemical properties change, can help to understand the carbon pool stability maintenance mechanism in alpine peatlands.

Hydrological processes regulate the organic carbon accumulation and carbon pool stability in peatlands by influencing soil physicochemical properties, as well as plant and microbial community structure (Hopple et al., 2020; Harris et al., 2023). Peatland soil carbon pool are extremely susceptible to environmental changes, abiotic factors such as soil water content, temperature and bulk density influence microbial species composition and activity through coupled effects, controlling organic matter oxidation and decomposition processes, affecting soil carbon cycle and soil carbon pool source-sink processes (Bragazza et al., 2012; Hopple et al., 2020; AminiTabrizi et al., 2022). High water level makes peatlands maintain anaerobic environment, the organic acid produced by anaerobic decomposition processes inhibits microorganisms growth, reproduction and activity, which is conducive to organic residues accumulation and preservation. Low water level decreases soil water content and increases soil aeration, which promotes soil organic matter oxidation processes. The rise of soil temperature enhances the aerobic microbial activity, raises organic matter decomposition rate, which may accelerate organic carbon loss from alpine peatlands (Ise et al., 2008; Peacock et al., 2014). The alternation of dry and wet conditions caused by water level fluctuations affecting alpine peatland freeze-thaw processes, dividing the peatlands into differentiated 'grass hummocks' microtopography and dry-wet habitats. This changing the soil carbon cycle and its income and expenditure pattern, influencing organic carbon accumulation and decomposition processes along the horizontal and

vertical gradients in peatlands(Zhong et al., 2020), which is a key issue for studying SOC decomposition and cycling processes.

The quantity and quality of plant inputs are the material basis for forming SOC spatial differentiation pattern in peatlands(Niu et al., 2019; Wan et al., 2019; Huang et al., 2021). Peat geoscience studies have shown that alpine peatland plant residues are mainly the roots and underground stems of perennial Cyperaceae plants, which have well-developed fiber section and high lignin content, not easy to decompose. Annual or perennial forb herbaceous roots, stems and leaves have thinner cytoderm and soft texture, which are decomposed within the current year or relatively shorter period, belong to low-quality litter(Wang et al., 1997; Wang et al., 2012). Peat-forming plants litter debris provides abundant material basis for SOC accumulation, and its material input processes proceeds from the surface downwards, subject to energy loss, the plant residues content gradually reduced, resulting in the SOC content of different soil layers varies(Lützow et al., 2006; Ruiz Sinoga et al., 2012). The alpine peatlands as an intrazonal landscape type with zonal character, has reached the succession climax consistent with alpine wet-cold climate(Galka et al., 2017), and formed typical alpine peatland vegetation flora such as *Carex muliensis*, *Carex atrofusca* and other plants adapted to flooding and barren habitats. With drainage degradation drives the succession of peatland vegetation towards low water-demanding alpine meadow and grassland ecosystems, the dominance of peat-forming plants is replaced by forb herbaceous. This directly alters peatland ecosystems primary production, potentially altering the quality and quantity of peat-forming material inputs (Goud et al., 2018), affecting the SOC accumulation, transformation and migration processes in peatlands.

The Zoige Plateau, located in the edge of the monsoon zone in Tibetan Plateau eastern part, where the cold and humid climate creates unique water-heat pattern, giving rise to alpine peatlands with the highest elevation and richest peat reserves in the world(Jiang et al., 2017). Where is typical climate-sensitive and ecologically fragile zone, and have great significance for analyzing the global carbon cycle mechanism and researching climate change(Yao et al., 2011; Pu et al., 2020). With the climate warming and humidification on the Tibetan Plateau, the drainage of erosion gullies caused by thaw slump in the Zoige alpine peatland have profoundly affected the wetland hydrological cycle. The accumulation and loss of soil moisture, as well as the freeze-thaw cycles have reshaped the peatland microtopography, changed the site conditions that peatland dominant plants for survival. Under the combined action of habitat screening and competitive exclusion ecological processes, the wetland plant functional group has succeeded from high-quality peat-forming plants to easily decomposable forb herbaceous. Changes in aboveground/underground biomass allocation pattern of vegetation community, may alter the quantity and quality of material input and affect the material accumulation of the peatlands(Qi et al., 2019; Stuart et al., 2022). At the same time, the increased decomposition capacity of soil environment promotes the SOC transformation and migration (Huo et al., 2013), resulting in the alpine peatland carbon sink function degradation, which has become a hotspot issue affecting the Tibetan Plateau ecological security.

Under the background of carbon peaking and carbon neutrality, academics have carried out a lot of studies around the control effect of environmental factors on the peat reserves(Swails et al., 2024), and the accumulation and loss of organic carbon in tropical and northern peatlands(Dhandapani et al., 2021; Harris et al., 2023). The relationship between the development of alpine peatlands and community succession(Sun et al., 2017; Zhang et al., 2023), the impact of wetland degradation on SOC loss in Zoige alpine have also received attention(Wang et al., 2019; Zhou et al., 2020). However, research on the effects of erosion gullies persistent drainage caused by thaw slump on the carbon pool differentiation in alpine peatlands and its influencing factors are still weak. Especially, the coupling relationship between material input and output on SOC accumulation and decomposition is not well studied. Consequently, this paper in the degraded alpine peatlands affected by thaw slump in Gahai International Importance Wetland on the Zoige Plateau, investigated the characteristics of vegetation community and SOC content on the erosion gully drainage gradients. The main objectives of the study were as follows: (1) How does drainage affect the alpine peatland plant communities structure? (2) How do the SOC horizontal and vertical differentiation patterns at different drainage gradients in alpine peatlands? (3) What are the main reasons for these patterns? In order to provide scientific basis for alpine peatland ecosystem restoration and wetland carbon pool management.

2 Materials and Methods

2.1 Study Area

The study area is located in the Gahai International Important Wetland within Gannan Tibetan Autonomous Prefecture in the northeastern part of the Zoige Plateau, geographical coordinates are 33°58'12"-34°42'16"N, 102°05'00"-102°47'39"E, with elevation of 3,200-4,000 m, it belongs to the Tibetan Plateau climate zone and the high-cold humid climate area, annual average temperature of 1.2°C, annual average precipitation of 650–800 mm, concentrated from July to September, annual evaporation is about 1,100 mm. The main soil types include meadow soil, swamp soil and peat soil, the vegetation is mainly composed of Cyperaceae and Gramineae. Major plant species include *Carex muliensis*, *Blysmus sinocompressus*, *Kobresia tibetica*, *Deschampsia cespitosa*, *Ranunculus tanguticus*, and *Polygonum viviparum*. The experimental area is less disturbed by human activities, no grazing effect, the plants grew well during the experiment and the experimental data are reliable.

2.2 Experimental Design

Select a flat peatland for the experiment in Gahai International Important Wetland on the Zoige Plateau. This peatland situated in piedmont slope and has been affected by thaw slump, developed a north-south orientated erosion gully with depth of 1.2–1.5 m and width of 2.4–3.5 m, resulting in persistent draining and drying effect on the peatland within the a range of 60-80m around it. The significant changes in surface water levels and groundwater depth, leading to degradation of the peatlands.

Starting from the center of the perennially waterlogged peatlands perpendicularly to the edge of the erosion gully formed by the thaw slump, three parallel sample transects of 20m width and 100m length were arranged sequentially at intervals of 30m to measure groundwater depth and surface water level. A water level observation sample plot was set up at 5m intervals on each sample transects, and a PVC pipe (1m long and 10cm in diameter) is driven into the peatlands at ground level. During the growing season from June to September 2022, the surface waterlogging conditions at each water level observation sample plots are recorded every 5–10 days. The surface water level and groundwater depth are measured using tape measure. Referring to the classification criteria of peatlands drainage gradient by Drollinger(Drollinger et al., 2020), according to the changes in groundwater depth and surface water level. From the center of the peatlands to the edge of the erosion gully, four 25m×120m sample plots (I, II, III, IV) were set up sequentially (Fig. 1): (1) Sample plot I is located in undrained peatlands, the surface water level is 5-15cm, developing spotted grass hummocks. (2) Sample plot II is located in slightly drained peatlands, the groundwater depth of 10–30 cm, and surface water accumulation seasonally from July to August, developing spotted or massed grass hummocks. (3) Sample plot III is located in moderately drained peatlands, the groundwater depth of 40–60 cm, and no surface water accumulation during the experiment, developing massed grass hummocks. (4) Sample plot IV is located in heavily drained peatlands, at the edge of erosion gully, the groundwater depth of 70–90 cm, and no surface water accumulation during the experiment, developing scattered and low massed grass hummocks.

2.3 Sample Collection

In each drainage gradient sample plots, six 5m×5m large quadrats were laid out in the 'Z' shape, with a total of 24 quadrats. Five 1m×1m herbaceous community quadrats were laid out in each large quadrats according to the diagonal method. In mid-August 2023, to conduct wetland plant community survey and soil sample collection.

(1) Measure the height, cover, density and aboveground biomass of all plants within the community survey quadrat six times.

(2) Collect all litter within community survey quadrat, remove surface-adhered soil, gravel, etc., seal it into numbered envelopes, and brought back to the laboratory.

(3) According to the root distribution range of wetland plants (0–60 cm), soil column of 20 cm × 20 cm × 30 cm was excavated within community survey quadrat to obtain the community underground biomass, placed in the 0.25mm sieve, washing them in flowing water to separate the roots, seal it into numbered envelopes, and brought back to the laboratory.

(4) Excavate a soil profile within each large quadrats, and collect soil samples from the upper layer (0-30cm), middle layer (30-60cm), and lower layer (60-90cm) in each profiles. Mix six soil samples from each layers of the same large quadrat to form one soil sample, seal it into sample bags, label with quadrat and soil layer number, and brought back to the laboratory for determination of soil physical and chemical properties. Meanwhile, soil samples were collected from each soil layers using ring knife (100 cm³), repeated three times, weighed fresh weight, placed in labeled aluminum boxes, and taken back to the laboratory for determination of soil bulk weight and soil water content. Soil temperature was determined using soil three-parameter meter (Moisture MeterHH2, Delta-T Devices Ltd, Britain).

2.4 Sample Analysis

The aboveground biomass in each community survey quadrats is divided into live plants and litter, together with the root system separated from the soil, fixation in the oven at 105 °C for 30 min, then adjusted to 65 °C for drying until constant weight to determine the community aboveground and underground biomass, and to calculate the root/shoot.

The soil samples taken out by the ring knife were dried (105 °C) and weighed, according to the dry soil weight and the ring knives volume to calculate the soil water content and soil bulk density. Soil pH was determined using PHS-3 acidimeter (ELTA32, Mettler-Toledo, Germany). Soil samples were brought back to the laboratory and dried naturally, removed plant residues and gravel, passed through 2mm sieve. The SOC content was determined using Multi N/C analyzer (Multi N/C 2100/2100S, Analytik Jena, Germany), the total nitrogen content was determined using Semimicro-Kjeldahl Method, and to calculate the C/N.

2.5 Data Analysis

Using Excel 2019 preprocessing the community height, coverage, density, and biomass data within the large quadrat, calculate the important values of each plants to determine the wetland community dominant species of each sample plots. Using SPSS 22.0, variance analysis (ANOVA) was used to show whether there are significant differences in soil physicochemical properties, vegetation community characteristics, SOC content, and the significance level set at 0.05. Pearson correlation analysis was used to analyze the relationship between SOC content and soil physicochemical properties, community characteristics at different drainage gradients. Using path analysis method, based on correlation analysis, the soil physical and chemical factors were decomposed into independent variables, and their simple regression equations for the dependent variable (SOC) were obtained, as well as direct and indirect path coefficients. The contribution rate ranking of independent variables to the dependent variable was obtained by comparing the decision coefficients. The formula for the path analysis is:

$$P_{ijy} = R_{ij} \times P_j$$

$$d_i = P_i^2$$

Where P_{ijy} is indirect path coefficient of X_i to Y through X_j . R_{ij} is correlation coefficient between X_i and X_j . P_j is direct path coefficient of X_i to X_j . d_i is determination coefficient of single independent variable to dependent variable. P_i is path coefficient of independent variable to dependent variable. The data analysis charts in this article were completed in Origin 2023.

3 Results

3.1 Peatland Vegetation Communities Characteristics at Different Drainage Gradients

With the drainage intensity increased, from the undrained peatlands (Sample plot Ⅰ) to the heavily drained peatlands (Sample plot Ⅳ), the peatland vegetation communities underwent succession. The dominant species in Sample plot Ⅰ community is *Carex muliensis*, in Sample plot Ⅱ and Ⅲ is *Blysmus sinocompressus*, in Sample plot Ⅳ is *Kobresia tibetica* (Table 1). The ANOVA results showed that there were significant differences ($p < 0.05$) in the peatland vegetation community characteristics in different drainage gradients (Table 1). From Sample Plot Ⅰ to Ⅳ, the community height (H), coverage (C) and density (D) increased first and then decreased, the community total biomass (TB) and litter count (LC) decreased significantly, the community root/shoot (R/S) showed a downward trend.

Table 1
Vegetation community characteristics at different drainage gradients

Sample plot	H(cm)	C(%)	D(branch/m ²)	TB(g/m ²)	R/S	LC(g/m ²)	Dominant species
Ⅰ	24.61 ± 1.02B	92 ± 2.53B	1341 ± 78.07B	2685.49 ± 174.78A	8.53 ± 0.96A	63.03 ± 4.27A	<i>Carex muliensis</i>
Ⅱ	26.69 ± 0.67A	99.1 ± 0.49A	1675.6 ± 74.8A	2463.23 ± 171.4B	6.05 ± 0.49C	56.45 ± 3.25B	<i>Blysmus sinocompressus</i>
Ⅲ	25.29 ± 1.75AB	99.1 ± 0.8A	1448.2 ± 53.51B	2119.48 ± 171.04C	6.17 ± 0.46C	50.83 ± 4.71C	<i>Blysmus sinocompressus</i>
Ⅳ	21.25 ± 1.47C	90.6 ± 4.12B	851.2 ± 191.15C	1703.96 ± 95.75B	6.86 ± 0.43B	33.19 ± 5.80D	<i>Kobresia tibetica</i>

H: Height; C: Coverage; D: Density; TB: Total biomass; R/S: Root/shoot; LC: Litter count. Capital letters indicate the differences among sample plots ($p < 0.05$).

3.2 Soil Physicochemical Properties Differentiation Patterns at Different Drainage Gradients

The results of ANOVA showed that there were differences ($p < 0.05$) in soil physicochemical properties at different drainage gradients and different depths (Table 2). Soil water content (SWC) ranged from 8.27–208.21%, with decreasing trend from Sample plot Ⅰ to Ⅳ, reduction of 87.42%. Soil bulk density (BD) ranged from 0.24 to 0.73 g/cm³, with increasing trend from Sample plot Ⅰ to Ⅳ, increment of 77.14%, drainage causes soil drying and compaction. Soil pH ranged from 5.25 to 7.88, with increasing trend from Sample plot Ⅰ to Ⅳ, increment of 16.53%, drainage caused the soil environment changed from weakly acidic environment to neutral. Soil temperature (ST) ranged from 8.63 to 20.27°C, with increasing trend from Sample plot Ⅰ to Ⅳ, increment of 25.62%. Soil C/N ranged from 5.43 to 44.84, with decreasing trend from Sample plot Ⅰ to Ⅳ, reduction of 71.18%.

On the vertical gradient, in Sample plot Ⅰ, each layers was in the state of water supersaturation, in Sample plot Ⅱ, Ⅲ and Ⅳ, SWC firstly decreased and then increased, the lowest SWC in the 30-60cm soil layer. BD showed an increased trend with increasing depth. pH showed a decrease trend with increasing depth. Lower layer soil being less affected by near-surface temperature conduction and close to the permafrost layer, ST showed a decrease trend with increasing depth. C/N increases gradually with increasing depth.

Table 2
Soil physicochemical properties changes at different drainage gradients

Sample plot	Soil layer	SWC(%)	BD(g/cm ³)	pH	ST(°C)	C/N
Ⅰ	0–30	154.71 ± 29.13Aa	0.33 ± 0.02Dc	6.28 ± 0.32Ca	17.93 ± 0.25Ca	20.52 ± 1.21Bc
	30–60	154.76 ± 21.37Aa	0.35 ± 0.06Db	6.27 ± 0.19Ca	15.03 ± 1.3Cb	28.99 ± 3.22Ab
	60–90	170.48 ± 15.18Aa	0.38 ± 0.04Ca	5.7 ± 0.32Cb	11.89 ± 1.25Dc	35.98 ± 4.49Aa
Ⅱ	0–30	91.22 ± 10.44Bb	0.39 ± 0.06Ca	6.58 ± 0.46Bb	18.64 ± 0.31Ba	20.44 ± 1.63Ac
	30–60	60.78 ± 13.77Bc	0.41 ± 0.08Ca	6.85 ± 0.15Ba	16.47 ± 0.55Bb	24.15 ± 2.17Bb
	60–90	111.79 ± 25.89Ba	0.42 ± 0.06Ca	6.32 ± 0.3Bc	12.97 ± 0.84Cc	36.24 ± 2.64Aa
Ⅲ	0–30	32.17 ± 4.55Cb	0.48 ± 0.07Bb	7.03 ± 0.39Aa	19.12 ± 0.46Aa	14.79 ± 1.47Cb
	30–60	18.84 ± 2.1Cc	0.51 ± 0.03Bb	7.02 ± 0.11Aa	18.39 ± 0.25Ab	13.77 ± 1.52Cb
	60–90	61.78 ± 9.97Ca	0.58 ± 0.07Ba	6.51 ± 0.26ABb	17.23 ± 0.38Bc	25.44 ± 3.07Ba
Ⅳ	0–30	18.19 ± 2.98Db	0.6 ± 0.09Aa	7.17 ± 0.42Aa	19.21 ± 0.7Aa	7.94 ± 0.55Db
	30–60	11.39 ± 2.89Dc	0.62 ± 0.10Aa	7.14 ± 0.24Aa	18.76 ± 0.97Aab	6.4 ± 0.86Dc
	60–90	30.28 ± 4.63Da	0.65 ± 0.07Aa	6.59 ± 0.34Ab	18.38 ± 0.54Ab	10.29 ± 2.96Ca

SWC: Soil water content; BD: Bulk density; ST: Soil temperature. Capital letters indicate the differences among sample plots, lowercase letters indicate the differences among layers ($p \leq 0.05$).

3.3 Horizontal and Vertical Differentiation Patterns of SOC Content

The results of ANOVA showed that SOC content differed horizontally and vertically ($p \leq 0.05$) (Fig. 2). On the horizontal gradient, the SOC content in 0-90cm soil layer of Sample plot Ⅰ was the highest (311.41 g/kg), from Sample plot Ⅰ to Ⅳ, the SOC content showed a decreasing trend, and in Sample plot Ⅳ was the lowest (53.21 g/kg). The SOC content in each layers showed a trend of undrained peatlands (Sample plot Ⅰ) > slightly drained peatlands (Sample plot Ⅱ) > moderately drained peatlands (Sample plot Ⅲ) > heavily drained peatlands (Sample plot Ⅳ). The SOC content in the upper layer decreased from 332.28 ± 8.62 g/kg to 55.68 ± 1.07 g/kg, in the middle layer decreased from 310.29 ± 24.41 g/kg to 38.63 ± 4.53 g/kg, and in the lower layer decreased from 291.67 ± 13.67 g/kg to 65.34 ± 10.33 g/kg, with reductions of 83.23%, 87.46%, and 77.59% respectively.

On the vertical gradient, in Sample plot Ⅰ, the SOC content showed a distribution pattern of upper layer > middle layer > lower layer, reduction of 12.22%. In Sample plot Ⅱ, Ⅲ, and Ⅳ showed a distribution pattern of lower layer > upper layer > middle layer.

3.4 Response of SOC Content to Vegetation Community Characteristics and Soil Factors

3.4.1 Correlation Analysis of SOC Content and Community Characteristics

Through the two-factor ANOVA analysis of the influence of vegetation community characteristics and soil factors on SOC content, the results showed that the interaction between vegetation community characteristics and soil factors was not significant ($P > 0.05$). Therefore, vegetation community characteristics and soil factors were analyzed separately.

From the correlation analysis between SOC content and community characteristics at different drainage gradients in peatlands (Fig. 3). The SOC content showed highly significant positive correlations with community total biomass (TB), litter count (LC), and root/shoot (R/S) ($p < 0.01$), with correlations reaching 0.91, 0.87, and 0.43, indicating that community TB, LC, and R/S positively contributed to SOC accumulation.

3.4.2 Path Analysis of SOC Content and Soil Factors

The results of correlation analysis showed that there were differences in the correlations between SOC content and soil factors at different drainage gradients ($p < 0.05$) (Fig. 4). In Sample plot I, the SOC content showed highly significant positive correlation with pH and ST ($p < 0.01$), highly significant negative correlation with BD and C/N ($p < 0.01$), and no significant relationship with SWC. In Sample plot II, III, and IV, the SOC content showed highly significant positive correlation with SWC and C/N ($p < 0.01$), negative correlation with pH and ST, indicating that the soil factors affecting SOC content changed with the drainage degree increased.

Stepwise regression analysis was performed using SPSS based on correlation analysis. The dependent variable SOC was labeled as Y_1 , the soil factors SWC, BD, pH, ST, and C/N were labeled as the independent variables $x_1 \sim x_5$ in that order. The path coefficients of the respective variables with significant effect on the dependent variables were obtained, according to the results of significance test, the factors whose path coefficients reached the significance level ($p < 0.05$) were retained, and the non-significant factors were excluded (Table 3). In the regression analysis of Y_1 , it was found that x_1 , x_2 , x_4 and x_5 were retained, x_3 was excluded. The optimal regression equation of soil factors on Y_1 was obtained as follows:

$$Y_1 = -53.199 + 99.05x_1 - 192.386x_2 + 11.103x_4 + 4.682x_5, R^2 = 0.924$$

Where R^2 is the proportion that reflects the total variation of the dependent variable can be explained by the independent variable through the regression relationship. In the regression equation for Y_1 , $R^2 = 0.924$, indicating that the contributions of x_1 , x_2 , x_4 and x_5 to the variation of Y_1 are 92.4%.

Table 3
Regression coefficient test of soil physicochemical properties on SOC

Dependent variable	Constant	Regression coefficient	S. E.	t test value	p value
Y_1	Intercept	-53.199	51.894	-1.025	0.306
	x_1	99.050	6.559	15.102	0.000
	x_2	-192.386	22.181	-8.674	0.000
	x_3	-4.200	5.560	-0.755	0.451
	x_4	11.103	1.477	7.519	0.000
	x_5	4.682	0.419	11.174	0.000

Based on the regression analysis, the soil factors with non-significant differences were excluded, and the path coefficients of each factors to SOC were calculated, thereby clarifying their influences on SOC. It can be known from Table 4, there are four independent variables have direct effect on SOC (Y_1), the ranking of the determination coefficients for each factors affecting SOC is SWC > C/N > ST > BD. SWC (x_1) has the largest direct effect of 0.566, C/N (x_5) has the second largest direct effect of 0.456, followed by ST (x_4) with 0.266, and BD (x_2) has the smallest direct effect, is -0.234. Indicating that these four soil factors and their interactions are the dominant factors affecting SOC, and they jointly control the direction

and intensity of SOC conversion processes. From the indirect effect results, the indirect effect of ST on SOC is the largest, therefore, the indirect effect of ST should also be paid attention to when analyzing the changes of SOC.

Table 4
Path analysis of soil physicochemical properties on SOC

Dependent variable	Constant	Relative coefficient	Direct effect	Indirect effect					Determination coefficients
				x_1	x_2	x_4	x_5	Σ	
Y_1	x_1	0.912	0.566	—	0.1578	-0.1744	0.3491	0.3325	0.3360
	x_2	-0.781	-0.234	-0.3962	—	0.1165	-0.2704	-0.5500	0.0533
	x_4	-0.609	0.266	-0.3864	-0.1028	—	-0.3813	-0.8705	0.0684
	x_5	0.818	0.456	0.4422	0.1364	-0.2180	—	0.3606	0.2094

4 Discussion

Accumulation of carbon pool in alpine peatlands is a complex problem combining exogenous inputs and internal decomposition. Water migration and community succession are the main ecological processes affecting soil organic carbon (SOC) content(Whitaker et al., 2020; Stuart et al., 2022). The difference of hydrothermal pattern, and frequent freeze-thaw action within Zoige alpine peatland, have altered the peatland microtopography and created unique microhabitats. Directly affected the vegetation communities spatial distribution and biomass allocation patterns, as well as influenced the SOC spatial differentiation in the peatlands. In this study, with the continuous loss of water from peatlands, soil water content (SWC) and C/N decreased, soil bulk density (BD), pH, and temperature (ST) increased (Table 2), the dominant species succession from *Carex muliensis* to *Kobresia tibetica*, the community root/shoot (R/S), total biomass (TB) and litter count (LC) decreased (Table 1). These altered the input and decomposition of organic matter, affected the horizontal and vertical patterns of SOC, reflected the influence mechanism of water migration and material conversion on the soil carbon pool stability of alpine peatlands.

4.1 Alpine Peatland Community Succession and its Influencing Factors

The grass hummocks in the alpine peatlands increase the surface roughness, trapping of mineral nutrients, providing more habitat and competitive resources for peatland plants. Vegetation communities by adjusting spatial distribution, as well as intraspecific and interspecific relationships, have formed species composition and community structure suitable for their habitats (Peichl et al., 2018; Sieben, 2018). The rapid replacement of dominant species means that the environmental changes may lead to ‘ecological collapse’(MacDougall et al., 2013). From Sample plot I to IV, the SWC decreased, the peatland microtopography transitioned from spotted grass hummocks to massed grass hummocks, the peatland community dominant species changed from *Carex muliensis* to *Blysmus sinocompressus* and *Kobresia tibetica*, the proportion of peat-forming plants and community biomass decreased (Table 1).

(1) Sample plot I is primitive peatlands undisturbed by drainage, with perennial waterlogging on the surface, and obvious freeze-thaw effect, resulting in the spotted grass hummocks developed, a wide range of thin waterlogged environment between hummocks limited the species diversity(Wang et al., 1997). The *Carex muliensis* tolerant of infertility and flooding became the dominant species in the peatland community, with better hydrological conditions for plant growth, the community biomass highest. (2) In Sample plot II and III, the surface stagnant water seeped down and the inundation

range was reduced, massed grass hummocks are main microtopography. The living space of *Carex muliensis* was compressed, and the habitat suitability of *Blysmus sinocompressus* growing on top or edge of the hummocks was increased, replacing *Carex muliensis* become the dominant species in the wetland community. The proportion of forb herbaceous such as Rosaceae and Gentianaceae increased in the community, the proportion and biomass of peat-forming plants decreased gradually. (3) Sample plot IV is located near the erosion gully, where the peatlands has been further drained, the groundwater level decreased, scattered and low massed grass hummocks have developed on the surface. The more drought-tolerant *Kobresia tibetica* has expanded its distribution range and dominated the community. With the succession of the wetland from humid habitat to mesic habitat, the colonization of the forb herbaceous was further strengthened, the proportion and biomass of peat-forming plants in the community decreased to the lowest level.

4.2 Horizontal Gradient SOC Distribution and its Influencing Factors

Peatlands SOC accumulation is attributed to carbon production during the plant life cycle and carbon storage under low decomposition environment(Li et al., 2023; Liu et al., 2023). The peat-forming processes mainly preserves the underground roots and stems parts of fiber-developed perennial peat-forming plants(Wang et al., 2012). This study found that the SOC content showed a trend of Sample plot I > Sample plot II > Sample plot III > Sample plot IV (Fig. 2).

(1) At the level of organic matter input, Sample plot Ⅰ is peat-forming plants community dominated by *Carex muliensis*, with the highest biomass and largest R/S (Table 1), which provided abundant and stable material source for peat accumulation(Cong et al., 2015). From Sample plot Ⅰ to Ⅳ, with the surface waterlogging condition gradually decreased until disappeared, plant diversity increased, causing changes in community composition structure and species growth characteristics. The proportion of peat-forming plants in the community declined gradually. With interspecific competition increased, plants allocated more biomass to above-ground parts, the R/S declined. The quantity and quality of organic matter inputs showed a decreasing trend(Goud et al., 2018; Qi et al., 2019). (2) At the level of organic matter decomposition, Sample plot I sustained high water level to form anaerobic environment, with higher soil C/N and lower ST (Table 2), the organic matter decomposition rate at low level, the SOC content was the highest. From Sample plot II to IV, the environmental factors determining peat sequestration developed in the opposite direction. With the water level decreasing, the peatlands shifted from anaerobic to aerobic environment, soil C/N and ST gradually increased, microorganisms increased the rate of converting organic matter(Xue et al., 2021; Szatylowicz et al., 2024). Under the condition of reduced primary production input and enhanced decomposition, the SOC content of the drainage-disturbed peatlands gradually decreased. At the edge of the gully (Sample plot Ⅳ), the SOC content was already lower than 10%, the peatland characters changed qualitatively.

Integrating the changes in hydrological environment, microtopography, and the trend of dominant species succession(Whitaker et al., 2020; Kolari & Tahvanainen, 2023). Sample plot Ⅰ is primary peatlands, Sample plot Ⅱ, Ⅲ, and Ⅳ are degraded peatlands disturbed by drainage, which may trigger the peatland carbon behavior changed from net uptake to net release, leading to ecosystem carbon loss(Li et al., 2023). This is consistent with the study of Zhong et al. on the vulnerability of degraded peatland SOC to water level fluctuations(Zhong et al., 2020; Xue et al., 2021).

4.3 Vertical Gradient SOC Distribution and its Influencing Factors

The retention and turnover of modern peat and ancient peat are jointly affected by biological and environmental factors. In the vertical gradient, there are significant differences in soil environmental characteristics and physicochemical properties, as well as different responses to external environmental changes and carbon dynamic processes(Dorji et al., 2014; Manies et al., 2021). This study found that from Sample plot I to IV, the SOC content of the upper, middle and lower layers showed a decreasing trend. In Sample plot I, the SOC content was upper layer > middle layer > lower layer. In Sample plot II, III and IV, the SOC content was lower layer > upper layer > middle layer (Fig. 2).

(1) From Sample plot I to IV, water level fluctuations and community succession disrupted the peat accumulation balance processes. The disappearance of water-saturated anaerobic environment accelerated the decomposition of organic

materials, and the reduction of community biomass reduced the input of organic materials. With the degree of drainage disturbance increased, the SOC content in the upper, middle and lower layers of the peatlands showed a decreasing trend. (2) Sample plot I surface waterlogging, and the abundant community litter and root biomass provided abundant material base for the SOC accumulation in the upper layer (Yakovleva et al., 2020). Under the low-temperature and anaerobic environments, SOC was stably preserved and had obvious 'surface accumulation' character (Liu et al., 2019; Zhang et al., 2023). While the input of litter debris and plant residues from the surface layer to the deeper soil gradually decreases, meanwhile, the deeper peat is undergoing slow but continuous decomposition. Consequently, in Sample plot I, the SOC content gradually decreases with the increase of soil depth (Ruiz Sinoga et al., 2012; Tfaily et al., 2014). (3) In upper layer, with the drainage intensity increased, the surface stagnant water in peatlands migrated and transformed into underground runoff, the water level depth decreases, the air permeability of the upper soil increased. The organic matter was subjected to stronger oxidation and decomposition, and the organic matter preservation capacity was weak. However, abundant litter of the wetland vegetation community still provided decomposable organic matter for upper layer soil, this 'dynamic compensatory' maintained high SOC content in the upper layer (Billings et al., 2010; Chaudhary et al., 2017). In middle layer, the soil aerobic and anaerobic environments are constantly switching with water migration and groundwater rise and fall, the historical period peat gradually decomposed. Meanwhile, the litter debris input from the surface decreased. In the high decomposition and low input environment, the middle layer SOC content maintained at the lowest level (Broder et al., 2012; Tfaily et al., 2014; Liu et al., 2022). In lower layer, because water seepage and close to the permafrost layer, the peat formed during the stable climate period decomposes slowly. Although the material input is the least, the SOC content remains at the highest level (Lee et al., 2011). Therefore, in Sample plot II, III and IV, the SOC contents in the vertical direction shows a trend of lower layer > upper layer > middle layer, reflecting the stability maintenance mechanism of the peatland carbon pool in the carbon cycle.

Conclusions

Global warming causes perennial permafrost warming and thawing, the phenomenon of erosion gullies drainage produced by thaw slump has declined the water level of peatlands, changed the anaerobic environment and microtopography of peatlands, resulted in the succession of vegetation community dominant species from peat-forming plants to Gramineae and forb herbaceous. With the quality and quantity of material inputs decreased, as well as the decomposition of organic residues increased, the SOC distribution pattern on the horizontal and vertical gradients changed, resulting in the degradation of peatlands. This study from the perspective of material input and output, explored the influence of community succession on the SOC differentiation pattern in the drainage processes of alpine peatlands. However, the analysis of SOC components were not comprehensive, therefore, further research will focus on the migration processes of SOC components in alpine peatlands.

Declarations

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Competing Interests

All authors disclosed no relevant relationships. The authors have no relevant financial or non-financial interests to disclose. We thank Robert McKenzie, PhD, from Liwen Bianji, Edanz Group China (www.liwenbianji.cn/ac), for editing the English text of a draft of this manuscript.

Author Contributions

All authors contributed to the study conception and design. The conceptualization, methodology, formal analysis, investigation, information, data compilation, writing-original draft, and visualization were done by Xinyu Ma; the validation, writing-review, and editing were done by Prof. Chengzhang Zhao. We are grateful to Lu Zhang, Haolin Li, Yan Wang and Xiawei Zhao for their assistance in the field and laboratory work.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

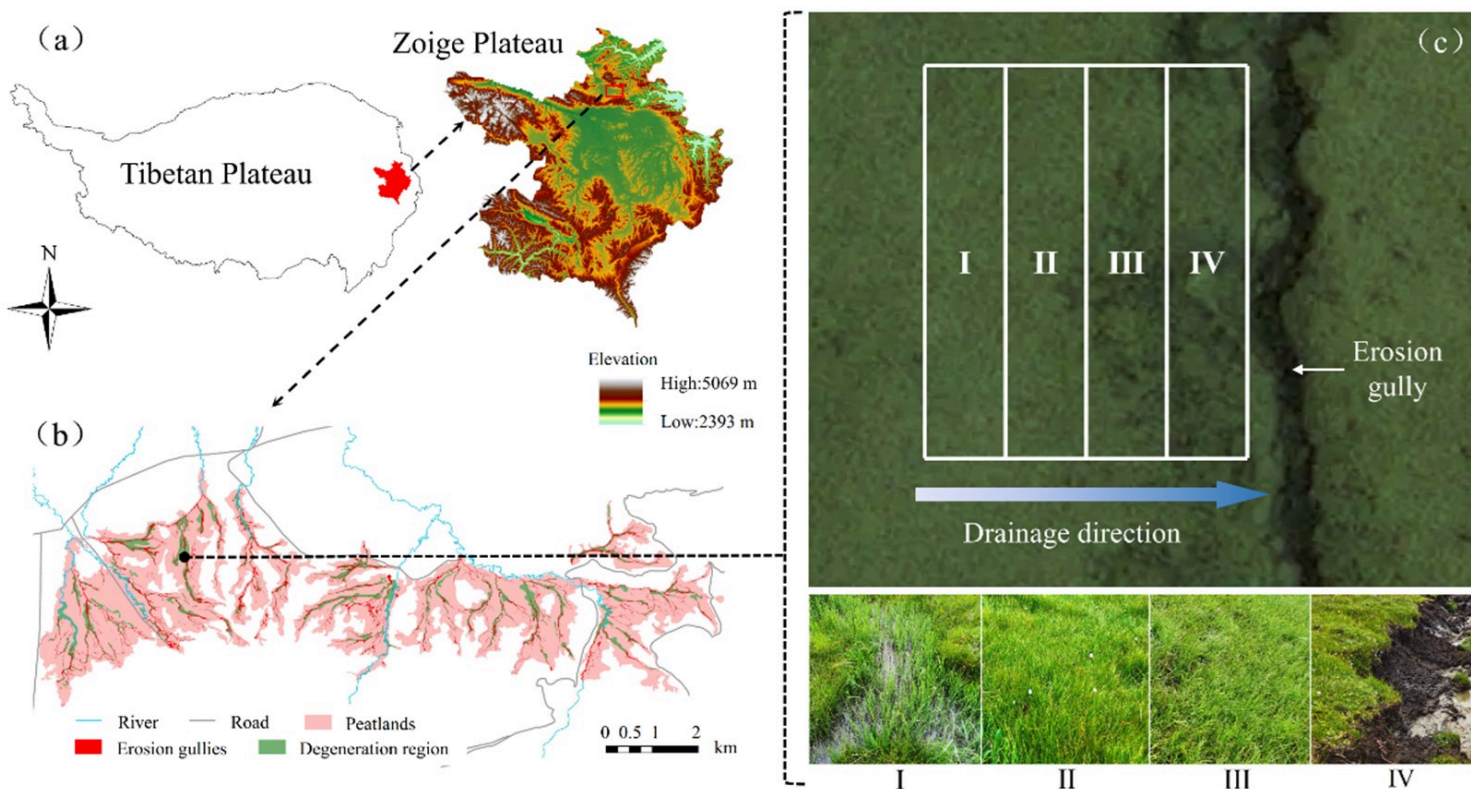


Figure 1

Information of the study area. (a) Zoige Plateau in Tibetan Plateau; (b) Spatial distribution of peatlands and gullies in Zoige Plateau; (c) The Google Earth imagery of peatlands affected by thaw slump erosion gully and photos of sample plots setting (mid-August 2023).

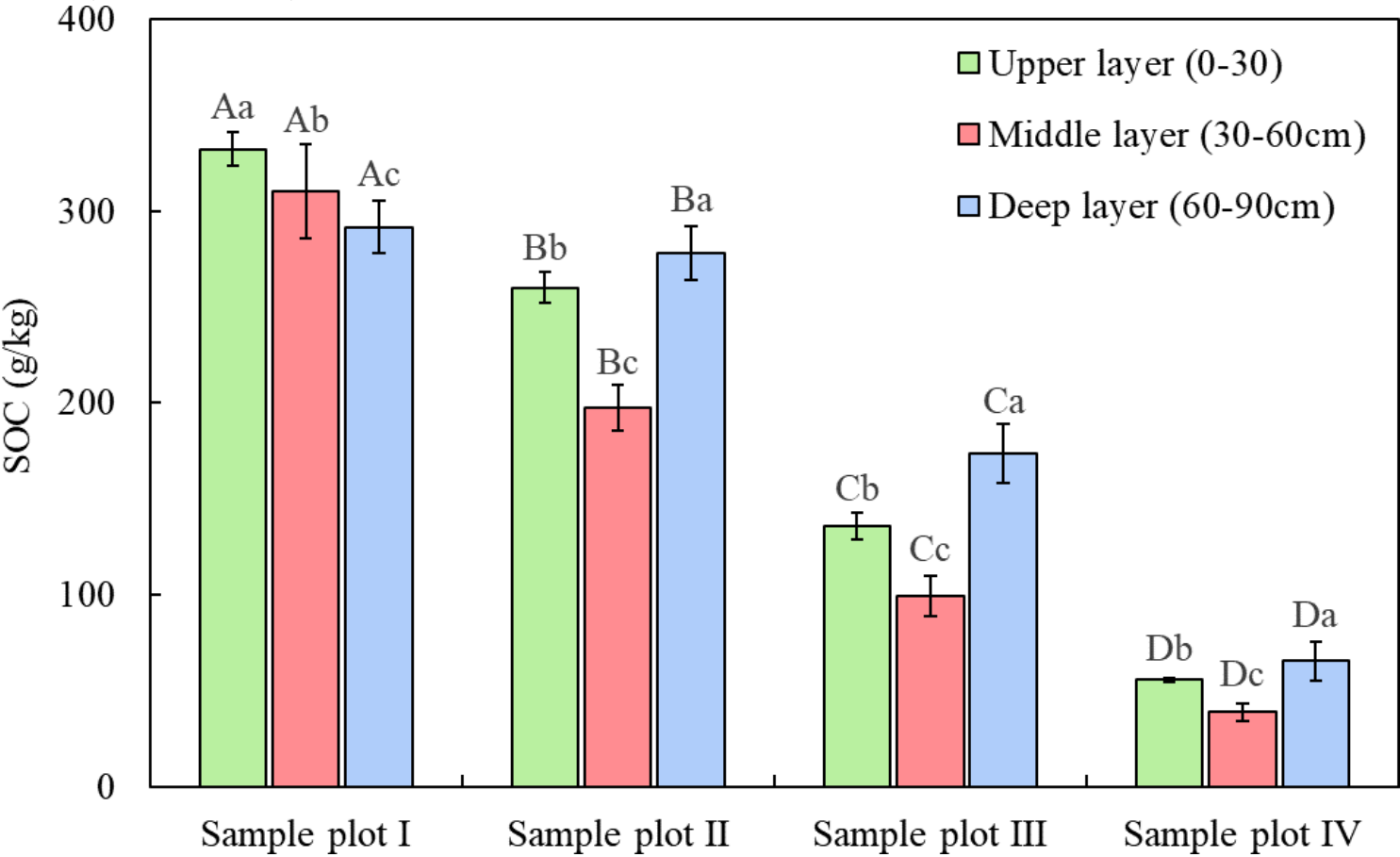


Figure 2

The SOC content in horizontal and vertical gradients. Capital letters indicate the differences among sample plots, lowercase letters indicate the differences among layers ($p \leq 0.05$).

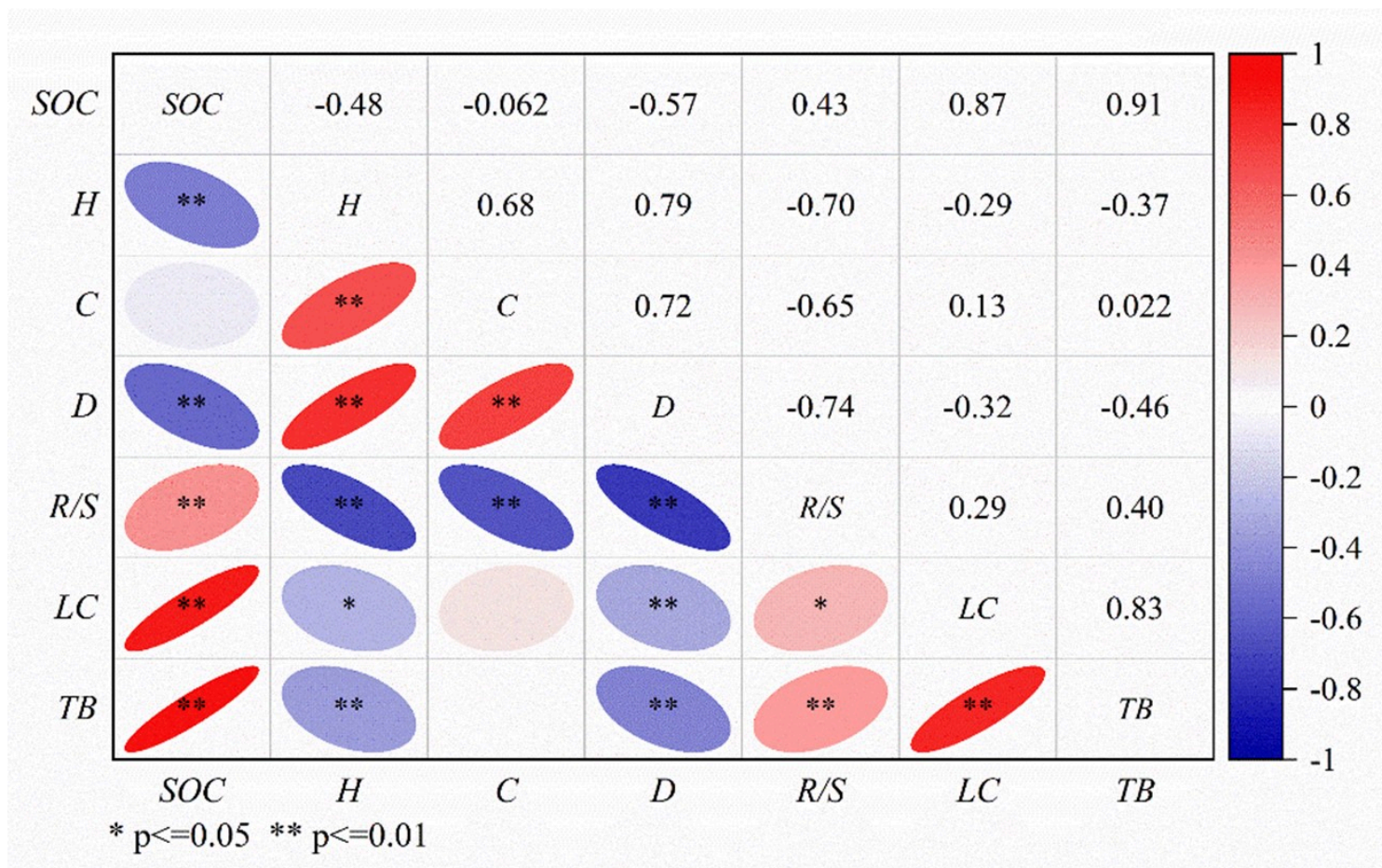


Figure 3

Correlation analysis of SOC content and vegetation community characteristics

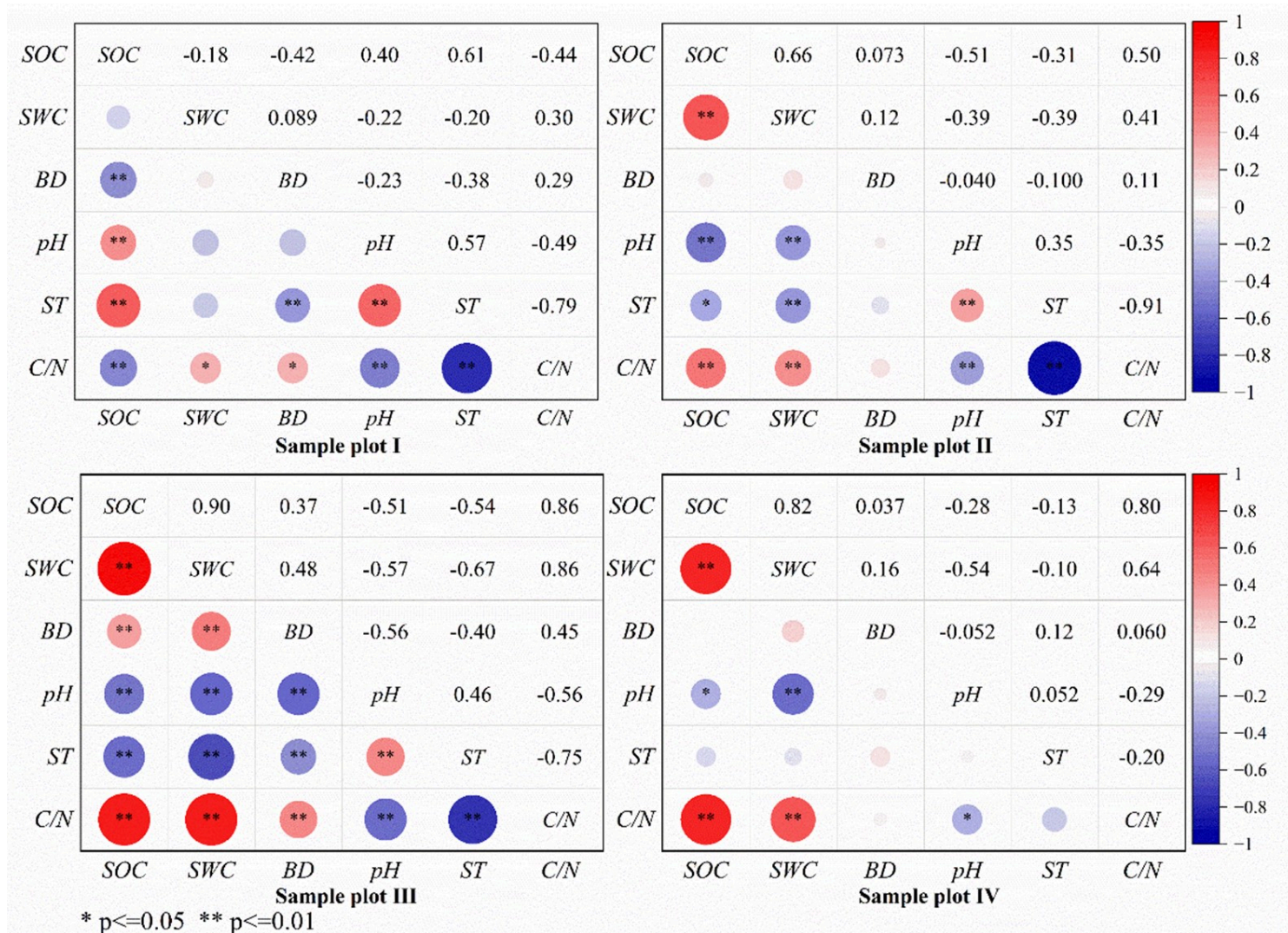


Figure 4

Correlation analysis of SOC content with soil factors in different drainage gradients