Spatial patterns and influencing factors of soil SOC、DOC、ROC at initial stage of vegetation restoration in a karst area

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Vegetation restoration has always been the focus of ecological research, but the synergistic effect of the soil carbon cycle and vegetation restoration succession process in karst area is still unclear. In this study, the complete succession zones of non-karst, karst, and karst vegetation restoration landforms in a National Nature Reserve, Caohai (Guizhou Province, China), were compared. The content distribution characteristics of SOC, ROC and DOC were investigated, as well as the geomorphology, spatial location and interaction were studied by using GLMM. The results show that the soil types and vegetation coverage of different landforms lead to a decrease in SOC in karst area with an increase in depth. The soil content in karst area was low, and in order to maintain the normal growth of vegetation, the proportion of soil ROC and DOC in SOC must be high, which leads to the order of soil ROC content in unrepaired area > vegetation restoration area > non-karst area. In addition, the content of SOC in the surface layer of the vegetation restoration area was lower than that of the unrepaired area and the non-karst area. The soil microbial activity in the vegetation restoration area is stronger, and more organic carbon was fixed in the plant. The vegetation coverage and diversity increased obviously and markedly as a result of dominant plants changing (from Gramineae to Gramineae + Compositae) in the karst vegetation restoration area, but the soil in the karst area could not provide sufficient nutrition for plants, ultimately resulting in an inverse ratio between surface SOC and vegetation diversity. This study aims to enhance understandings of ecological functions and vegetation restoration in karst areas, as well as responses to regional carbon cycling.

KEYWORDS

vegetation restoration, karst, soil organic carbon, succession, vegetation community

1 Introduction

Karst area is typical of fragile ecology in China, with a domestic area of up to 3.44 million km² (Yuan, 2001; Wang, 2018). Due to special karst geographical and chemical properties, *in-situ* soils are characterized as having a low formation rate, weak water retention capacity, and imbalanced self-restoration (Lan et al., 2022; Yang et al., 2022). Up to 85% mountain coverage with steep terrain and thin soil layer, Guizhou province is regarded as an important karst areas in Southwest China (Zhao et al., 2017). Particularly, artificial disturbances aggravate soil erosion and rocky desertification as well as cause a significant reduction in soil coverage in the karst area (Zhou et al., 2020).

Soil organic carbon (SOC) serves as an indicator for soil properties, which improve nutrient cycling capacity and play an important role in soil and water conservation. In general, regional soil conditions (e.g., fertility and buffer capacity) are largely regulated by *in-situ* SOC (Ma et al., 2020). Active SOC can be directly utilized and transformed by plants and microorganisms, responding to regional carbon cycling and thus organic carbon balance (Cui et al., 2021; Wu et al., 2020). Readily oxidizable carbon (ROC), in particular, shows potential for capturing early SOC changes with high turnover rates (Zhang et al., 2019c). Dissolved organic carbon (DOC) is a carrier for element migration and transformation in soils, which highly affects nutrient cycles, microbial activities, and SOC transformation (Guo et al., 2020). Thus, it is necessary to unravel distinct organic carbon dynamics and influencing factors in soil environments (Bai et al., 2020; Gu et al., 2023).

Vegetation restoration is a common measure for soil and water conservation, which can also control rocky desertification in karst areas (Bastin et al., 2019; Jiang et al., 2014). Studies showed that vegetation restoration improved the ecological environment under the soil-plant complex system, promoting soil nutrient accumulation and improving rocky desertification (Gerhardt et al., 2017; Yadav et al., 2018; Huang et al., 2018). At present, some achievements made and widespread attentions on vegetation restoration in karst areas, however, researches were mostly focused on the corresponding restoration models and land use patterns. For example, previous reports examined the differences between natural and artificial restorations (Hu et al., 2018; Hu et al., 2020), the relationships between vegetation restoration measures and soil quality *via* model calculations (Zhang et al., 2019b), and the effects of different vegetation types on soil nutrients (Guan and Fan, 2020). Nevertheless, the mechanisms of vegetation restoration on soil property variability and the synergistic carbon cycle in karst areas have yet to be revealed (Rubino et al., 2010; Wu et al., 2022b). Soil SOC participates in the succession of vegetation restoration, linking soil and vegetation systems during the material cycle and accumulation. In this context, the heterogeneous organic carbon components generally trace the SOC pool and reflect its dynamics. As a result, plant communities stimulated organic carbon sequestration into soils *via* photosynthesis, contributing large amounts of SOC to terrestrial ecosystems (Wang et al., 2022). Therefore, studies on the variability of SOC components in response to vegetation restoration as well as their inherent links to soil nutrients are merited.

In this study, spatiotemporal substitution method (Sun et al., 2021) was used to compare variability of characteristic in the karst (Jiangjiawan) regional after vegetation restoration soil, unrepaired soil in the same region and non-karst soil (Yangguanshan) in a National Nature Reserve Caohai, Southwest China (the selected sample belt has spatial differences and can reflect the state of plant succession in different periods.). We explored SOC variety characteristics constrained by vegetation restoration during distinct landforms. The purposes are to provide theoretical support for further understandings of the regional carbon cycle, ecological functions, and vegetation restoration in karst areas, which hope to provide a scientific basis for vegetation selection after ecological destruction.

2 Materials and methods

2.1 Study area

The study area was a National Nature Reserve Caohai (26°49′-26°53′N, 104°12′-104°18′E), situating in Guizhou Province, Southwest China (Figure 1). The Caohai was adjacent to the hinterland of the Wumeng Mountains in the central part of the Yunnan-Guizhou Plateau. It was a specific plateau wetland formed by geomorphologically stagnant water in the karst basin, which was also regarded as the largest karst artificial lake in China. Caohai was located in a subtropical monsoon area with discernible dry and wet seasons. Rainfall was concentrated in the wet season (summer and autumn) with sufficient light. The annual average temperature was 10.5°C. The soil types of the reserve mainly include yellow soil and calcareous soil with few plant species, which is typical of a plateau wetland ecosystem.

2.2 Research methods

2.2.1 Sample plot establishment and soil sample collection

The study area was within the scope of the 'ecological isolation corridor project of Caohai North Slope Mountain in Weining County', Guizhou Province. Through the vegetation restoration carried out by artificially planting Yunnan poplar (broad-leaved deciduous forest) on the upper-slope, the purpose of reducing soil and water loss was achieved. The project improves the regional ecological environment and increases the ecological carrying capacity of the region while increasing the diversity of biological species.

Soil samples were collected in August 2021. Considering that the vegetation succession in the non-karst area was relatively perfect and the vegetation types are different in different slope positions. A sample belt was selected in a non-karst area locating on the upper-slope, middle-slope and lower-slope (three sample squares are arranged in each slope). Soil samples were randomly selected for analysis from five sampling points. In the karst area (Jiangjiawan), two sample zones before and after vegetation restoration were selected, all of which were in the same habitat, half of which were restored by vegetation and the other half as a comparative study. According to the present situation of vegetation succession, each sample zone is divided into two parts (uphill and downhill), and samples are taken according to different dominant communities of plants. Three sample squares were selected in each area, and five sample points were randomly selected for sampling and analysis (as shown in Figure 1). The age of the vegetation restoration transect was 3–4 years, and the natural vegetation was mainly herbaceous. The soil type in the Jiangjiawan area was calcareous, and the vegetation community was relatively uniform before restoration: including elm seedlings and herbaceous plant communities such as Elymus, pennisetum, and sage millet (Zhang et al., 2013; Wu et al., 2013). The basic situation was shown in Table 1.

The SOC content in three sample zones was analyzed using "spatio-temporal substitution method". Soil samples were collected, and indeed, the community composition characteristics at each sample site were documented. The sampling profile was 50 cm deep with 10 cm intervals. Before laboratory analysis, soil samples
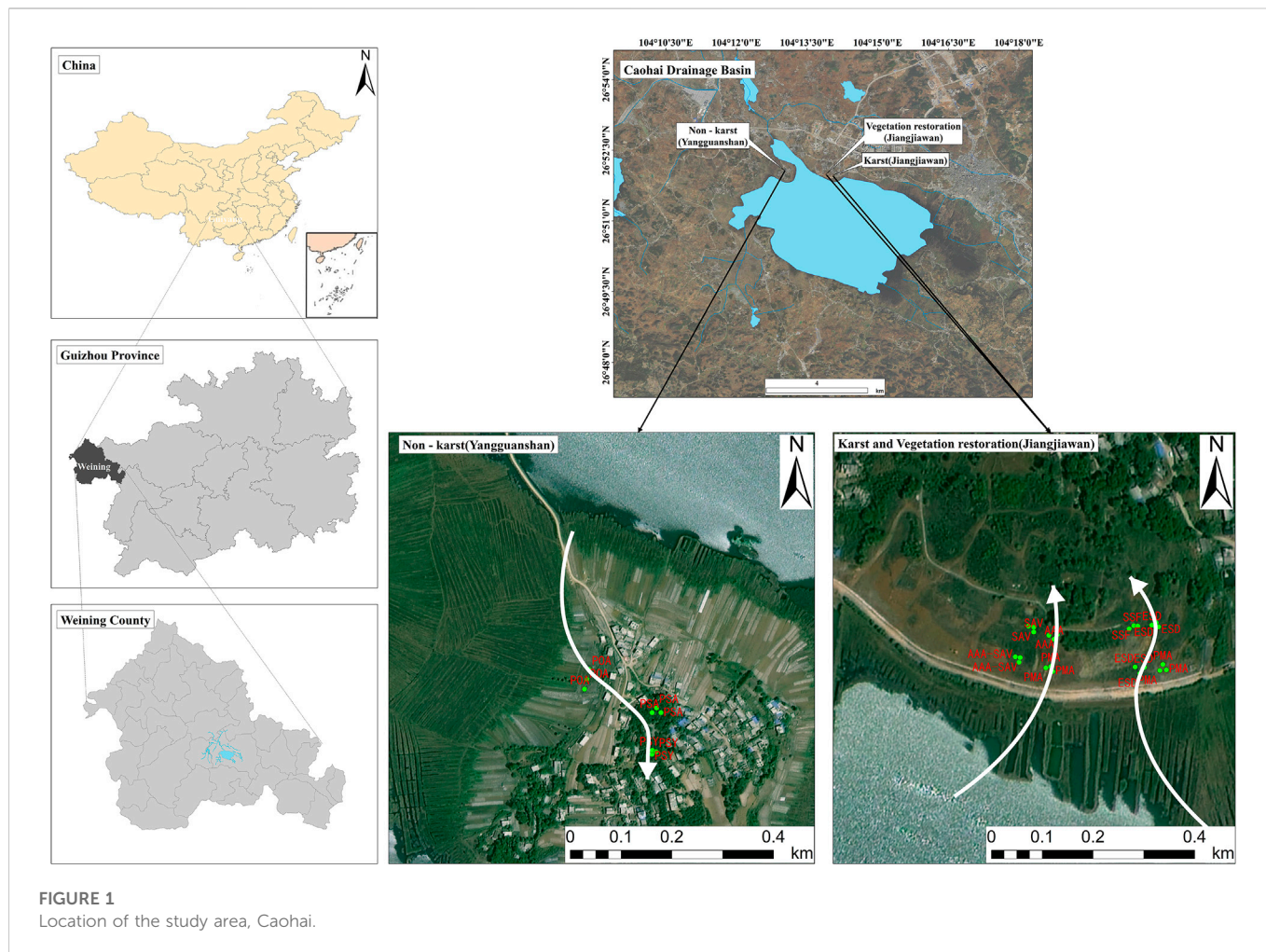
FIGURE 1
Location of the study area, Caohai.

TABLE 1 Location and vegetation status of the transec.

Transect	Latitude longitude	Altitude/m	Vegetation coverage/%	Soil type	Phytocoenosium
Non-karst	104°12′1.82″-104°13′1.82″E 26°52′3.10″-26°52′20.60″N	2,174–2,196	85	Yellow soil	Tree community: Pinus Yunnanensis. Herbaceous plants: The main species are Phyllostachys sulphurea, Plantago asiatica
Karst	104°14′0.33″-104°14′2.81″E 26°51′51.11″-26°52′0.38″N	2,182–2,188	45	Calcareous soil	Herbaceous plants: Elymus dahuricus, Pennisetum alopecuroides and Sporobolus fertilis
Vegetation restoration	104°13′53.40″-104°13′7.0″E 26°51′56.86″-26°52′0.81″N	2,182–2,188	65	Calcareous soil	Tree community: Mainly Ulmus pumila. Herbaceous plants: Artemisia argyi, Pennisetum alopecuroides

were cryopreserved in a self-sealed bag. According to the experimental requirements, the collected samples were treated by air drying, crushing, and sieving.

2.2.2 Treatment and determination

SOC was determined by the potassium dichromate oxidation-external thermal method (Nelson and Sommers, 1982). ROC was determined by 333 mol/L $KMnO_4$ oxidation-colorimetry (Blair et al., 1995). DOC was determined by 0.2 mol/L $FeSO_4$ titration (Raber et al., 1998; Walkley and Black, 1934).

The total phosphorus (TP) content of soil was determined using NaOH. melting-molybdenum-antimony anti-chromogenic-ultraviolet spectrophotometry. Soil available phosphorus (AP) was

determined by 0.5 mol/L $NaHCO_3$ extraction-molybdenum-antimony anti-chromogenic-UV spectrophotometry. Ultraviolet spectrophotometry was employed to assess nitrate nitrogen and ammonium nitrogen. And the 2 mol/L potassium chloride-indophenol blue colorimetric method, respectively. All determinations used deionized water to measure soil pH at a ratio of 1 wt/vol (2.5) (Wu et al., 2022a). Samples for soil bulk density analysis were collected using steel cylinders (5 cm diameter and 5 cm height) with a volume of 100 cm^3. Soil moisture content was obtained from weight loss by drying moist soil in the field at 105°C to a constant weight for at least 6 h. Determination of soil aggregates by the wet sieve method. All superior purity reagents were purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China) including sulfuric acid,

TABLE 2 Physical and chemical properties of surface soil from the different transect.

Transect		Dominant community	Coverage (%)	pH	SWC(%)	BD (g/cm^3)	EC (μs/cm)	NH$_4^+$-N (mg/kg)	NO$_3^-$-N (mg/kg)	TN (g/kg)	AP (mg/kg)	TP (g/kg)
Non-karst	US	PSY	85	5.53 ± 0.21c	23.50 ± 3.62b	1.37 ± 0.22a	32.47 ± 9.44cd	7.18 ± 2.36bc	16.05 ± 8.99a	1.62 ± 0.98abc	8.10 ± 3.76a	0.13 ± 0.07c
	MS	PSA	65	5.79 ± 0.12c	33.19 ± 8.47ab	1.17 ± 0.09a	20.33 ± 3.97d	18.38 ± 10.51 ab	17.68 ± 4.13a	2.32 ± 0.12a	19.61 ± 18.16a	0.33 ± 0.09 ab
	LS	POA	50	7.02 ± 0.60b	29.36 ± 6.84ab	1.45 ± 0.14a	81.03 ± 18.14a	4.45 ± 2.14c	10.30 ± 3.83a	1.88 ± 0.72 ab	23.83 ± 15.45a	0.37 ± 0.06 ab
Karst	US	ESD	8	7.83 ± 0.15a	32.51 ± 2.76ab	1.42 ± 0.04a	44.90 ± 17.25bc	9.82 ± 8.64abc	8.20 ± 3.83a	1.18 ± 0.27bc	11.07 ± 6.75a	0.14 ± 0.07c
	US	SSF	40	7.40 ± 0.41ab	35.86 ± 7.81a	1.31 ± 0.13a	58.77 ± 8.73ab	13.59 ± 8.39abc	10.41 ± 6.07a	1.23 ± 0.39bc	13.85 ± 11.95a	0.13 ± 0.07c
	LS	ESD	30	7.42 ± 0.45ab	32.01 ± 4.87 ab	1.41 ± 0.10a	62.27 ± 6.87 ab	20.43 ± 8.77a	8.12 ± 1.95a	1.46 ± 0.13abc	6.37 ± 3.34a	0.26 ± 0.14bc
	LS	PMA	45	7.47 ± 0.05ab	25.34 ± 7.17ab	1.44 ± 0.14a	56.43 ± 4.61bc	2.74 ± 1.40c	11.26 ± 7.20a	1.06 ± 0.32bc	5.22 ± 0.60a	0.16 ± 0.03c
Vegetation restoration	US	AAA	50	7.01 ± 0.79b	24.12 ± 0.46b	1.35 ± 0.11a	42.60 ± 14.27bcd	5.77 ± 0.69c	10.38 ± 2.37a	0.99 ± 0.10c	22.77 ± 3.62a	0.44 ± 0.06a
	US	SAV	55	6.93 ± 0.36b	26.02 ± 2.40 ab	1.32 ± 0.05a	49.70 ± 15.95bc	4.06 ± 1.77c	8.11 ± 4.25a	1.07 ± 0.18bc	15.87 ± 9.03a	0.33 ± 0.07ab
	LS	AAA-SAV	80	7.57 ± 0.33ab	28.29 ± 0.29 ab	1.36 ± 0.05a	45.70 ± 10.52bc	11.14 ± 2.98abc	15.67 ± 8.16a	1.17 ± 0.40bc	21.62 ± 1.48a	0.44 ± 0.07a
	LS	PMA	60	7.10 ± 0.14ab	27.69 ± 0.54ab	1.39 ± 0.08a	48.43 ± 11.66bc	8.31 ± 6.38abc	11.64 ± 3.97a	0.90 ± 0.06c	24.59 ± 0.6a	0.42 ± 0.02a

Lowercase letters represent the significant differences between different dominant communities in the same zone ($p < 0.05$).
US: Upper-slope; MS: Middle-slope; LS: Lower-slope.
PSY:*pinus yunnanensis*; PSA:*phyllostachys sulphurea*; POA:*plantago asiatica*; ESD:*elymus dahuricus*; SSF:*sporobolus fertilis*; PMA:*pennisetum alopecuroides*; AAA:*artemisia argyi*; SAV: *setaria viridis*; AAA- SAV: *Artemisia argyi- Setaria viridis*.

hydrochloric acid, sodium hydroxide, etc. Soil physical and chemical properties are listed in Table 2.

2.2.3 Data analysis and processing

The data were analyzed by Excel 2021, and SPSS 26.0 software was used for generalized linear mixed model (GLMM) analysis. The principal component analysis (PCA) of all kinds of SOC as variables was tested by Canoco Software 5.0 software. The drawing was prepared using GraphPad Prism 9.0 software, and the correlation analysis of the two matrices was analyzed by R 4.1.0.

3 Results

3.1 Distribution of soil aggregates in different landforms

The particle size distribution of soil aggregates exhibited notable differences in distinct geomorphological types (Table 3). Except for *Pinus Yunnanensis* (upper-slope), the proportion of macroaggregates in non-karst areas was larger than that in karst areas, while the aggregates >5 mm in *Elymus dahuricus* (lower-slope) and *Pennisetum alopecuroides* (lower-slope) were significantly higher than those of *Artemisia argyi- Setaria viridis* (lower-slope) and *Pennisetum alopecuroides* (lower-slope) restored by vegetation.

However, vegetation restoration failed to cause obvious effects on the gap in microaggregates.

3.2 Distribution characteristics of soil carbon in different landforms

3.2.1 Distribution characteristics of soil organic carbon in different landforms
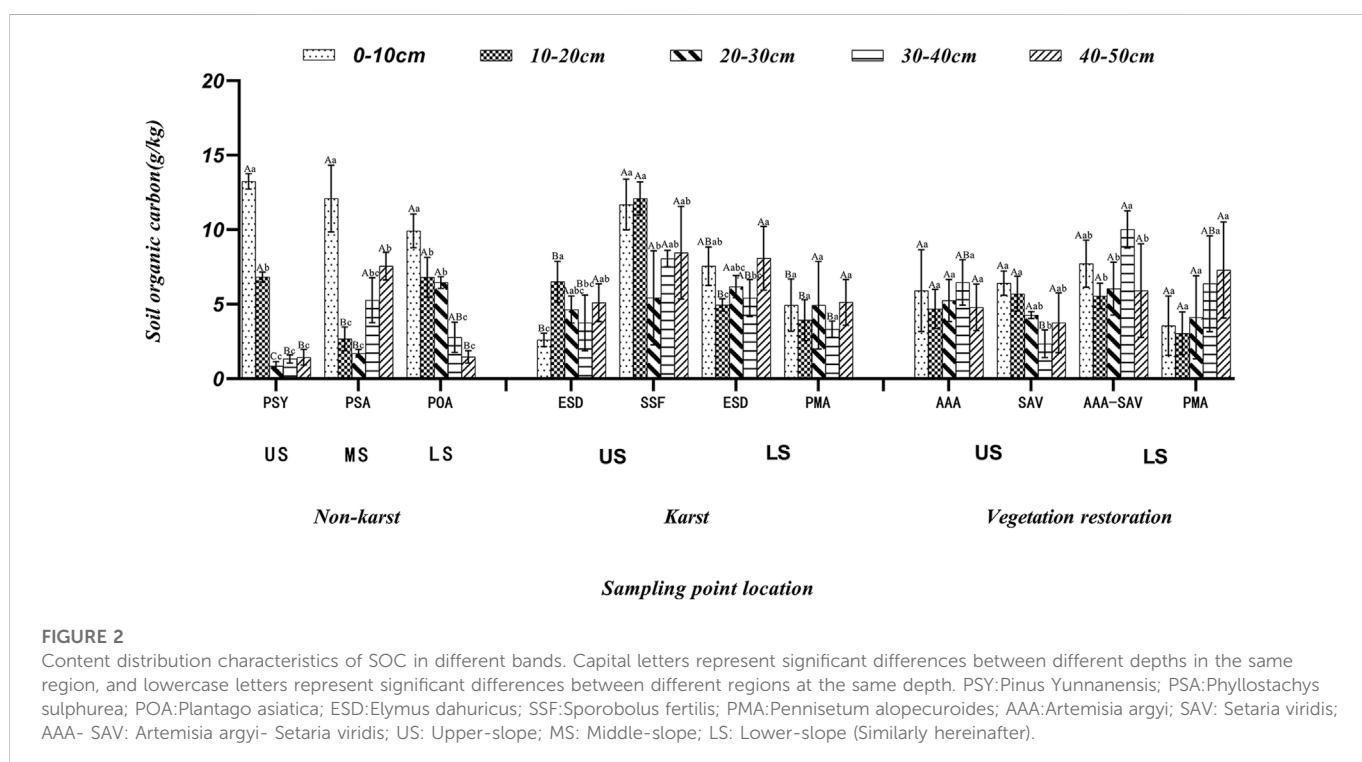
The distribution of SOC content in three sample zones is shown in Figure 2. In non-karst area, SOC content of *Pinus Yunnanensis* (upper-slope) was significantly higher than that of other depths, while SOC content of *Phyllostachys sulphurea* (middle-slope) fluctuated in different depths. In comparison, the SOC content of *Plantago asiatica* (middle-slope) decreased gradually. In karst areas, the distributions of SOC of *E. dahuricus* (upper-slope), *Pennisetum alopecuroides* (lower-slope), and *E. dahuricus* (lower-slope) were more uniform, and SOC of *Sporobolus fertilis* (upper-slope) decreased gradually. After vegetation restoration, SOC content of *S. viridis* (upper-slope) increased gradually with the increased depth, whereas SOC content of *Pennisetum alopecuroides* (lower-slope) exhibited insignificant changes.

The generalized linear mixed model (GLMM) was performed in the non-normal analysis of SOC, as well as to evaluate geomorphology, spatial location, and their interactions (the dominant vegetation

TABLE 3 Particle size composition of surface soil aggregates in different zones.

Transect		Dominant community	Aggregate particle size %						
			>5 mm	3 mm	2 mm	1 mm	0.5 mm	0.25 mm	<0.25 mm
Non-karst	US	PSY	6.68 ± 3.01c	5.68 ± 2.21bc	5.31 ± 1.66bc	9.23 ± 8.38a	11.53 ± 11.15cd	12.76 ± 3.04a	48.80 ± 23.37a
	MS	PSA	25.69 ± 16.82bc	11.13 ± 3.44ab	9.19 ± 2.94a	16.44 ± 5.06a	15.45 ± 5.60bcd	7.81 ± 1.47 ab	14.29 ± 3.80b
	LS	POA	48.34 ± 11.51ab	12.40 ± 3.90a	6.78 ± 2.10abc	6.57 ± 1.62a	4.39 ± 0.97d	6.30 ± 5.39b	15.22 ± 9.85 b
Karst	US	ESD	18.08 ± 14.99c	7.36 ± 2.82abc	6.97 ± 1.30abc	12.74 ± 5.14a	20.07 ± 6.31abc	11.39 ± 4.39 ab	23.39 ± 14.41 ab
	US	SSF	14.29 ± 13.65c	9.39 ± 3.92abc	7.26 ± 1.79abc	18.58 ± 14.86a	17.37 ± 8.69bcd	8.01 ± 1.57 ab	25.10 ± 14.62ab
	LS	ESD	56.61 ± 33.03a	6.70 ± 3.73abc	5.16 ± 2.38c	5.88 ± 5.20a	7.18 ± 6.07cd	5.78 ± 4.16 b	12.69 ± 14.31b
	LS	PMA	15.42 ± 10.44c	9.36 ± 3.17abc	8.73 ± 0.41 ab	16.33 ± 2.96a	18.12 ± 7.95abcd	7.81 ± 0.21 ab	24.24 ± 2.88ab
Vegetation restoration	US	AAA	3.71 ± 1.37c	7.05 ± 2.77abc	6.35 ± 1.39abc	16.39 ± 1.79a	29.24 ± 1.00ab	10.07 ± 0.49ab	27.18 ± 3.22ab
	US	SAV	14.47 ± 18.60c	4.93 ± 1.87c	5.05 ± 0.63c	9.79 ± 1.48a	26.01 ± 9.21ab	11.82 ± 1.87ab	27.93 ± 11.08ab
	LS	AAA-SAV	2.74 ± 0.42c	4.38 ± 1.43c	5.40 ± 0.94bc	19.00 ± 7.37a	32.58 ± 6.91a	13.01 ± 3.19a	22.89 ± 12.01ab
	LS	PMA	4.11 ± 1.09c	4.71 ± 0.39c	5.25 ± 0.60bc	9.84 ± 2.78a	27.39 ± 8.15ab	11.28 ± 1.72ab	37.41 ± 9.97ab

Lowercase letters represent the significant differences between different dominant communities in the same zone ($p < 0.05$).

FIGURE 2
Content distribution characteristics of SOC in different bands. Capital letters represent significant differences between different depths in the same region, and lowercase letters represent significant differences between different regions at the same depth. PSY:Pinus Yunnanensis; PSA:Phyllostachys sulphurea; POA:Plantago asiatica; ESD:Elymus dahuricus; SSF:Sporobolus fertilis; PMA:Pennisetum alopecuroides; AAA:Artemisia argyi; SAV: Setaria viridis; AAA- SAV: Artemisia argyi- Setaria viridis; US: Upper-slope; MS: Middle-slope; LS: Lower-slope (Similarly hereinafter).

community as a random factor) in the conditions of spatial location, deep soil geomorphology, and the corresponding interaction in non-karst area, karst area, and vegetation-restored karst area (Table 4). We observed significant differences in SOC content between karst and non-karst topography (0–20 cm). There is a very significant difference in topsoil between karst vegetation restoration area and non-karst area, and the spatial location of deep soil has a significant effect on SOC content.

TABLE 4 Generalized linear mixed model (GLMM) analysis of SOC.

Spatial location	Karst - non-karst				Karst - vegetation restoration				Vegetation restoration - non-karst			
	0–20 cm		20–50 cm		0–20 cm		20–50 cm		0–20 cm		20–50 cm	
	F	P	F	P	F	P	F	P	F	P	F	P
landform	9.644	0.004	0.443	0.509	0.570	0.454	0.443	0.509	85.859	0.000	0.513	0.477
Location	0.817	0.373	2.242	0.141	0.878	0.354	2.242	0.141	2.000	0.167	10.593	0.002
landform * Location	0.000	0.992	2.999	0.089	0.293	0.591	2.999	0.089	0.965	0.333	1.454	0.234

$p < 0.05$: Significant, $p < 0.01$: very significant.

FIGURE 3
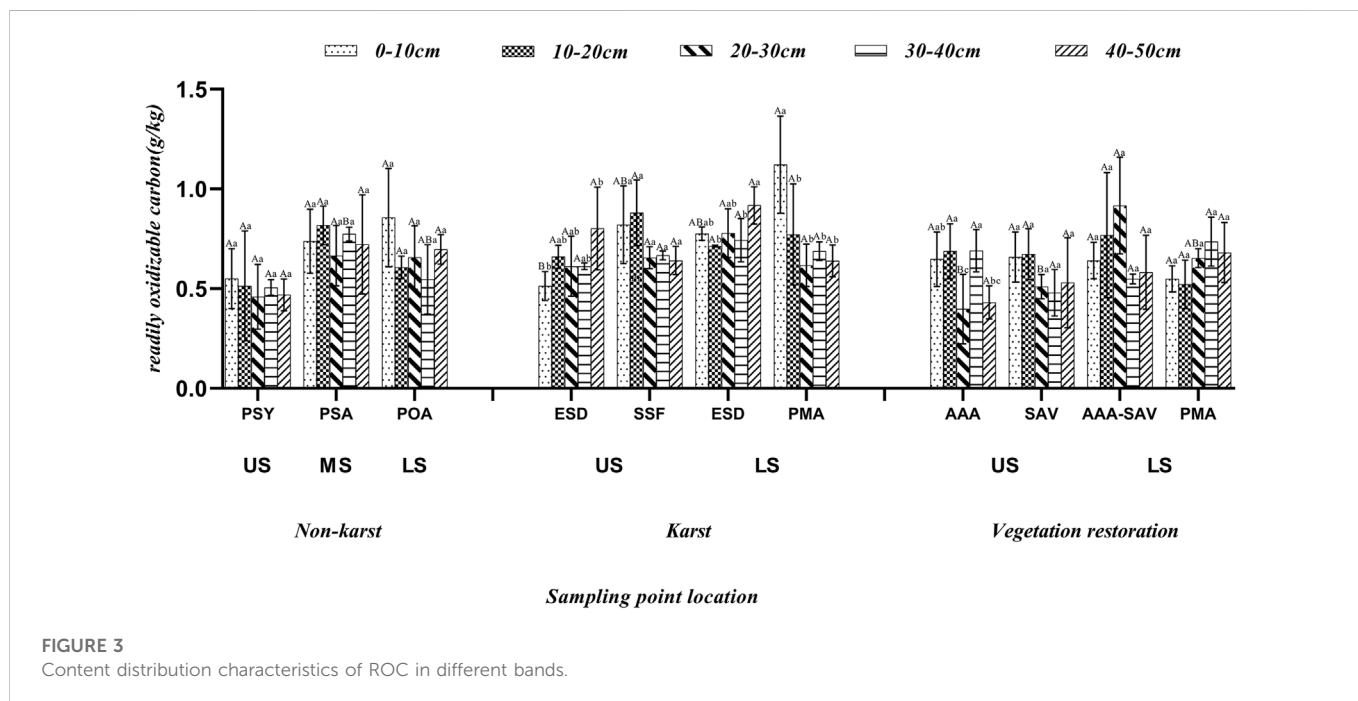Content distribution characteristics of ROC in different bands.

TABLE 5 Generalized linear mixed model (GLMM) analysis of soil ROC.

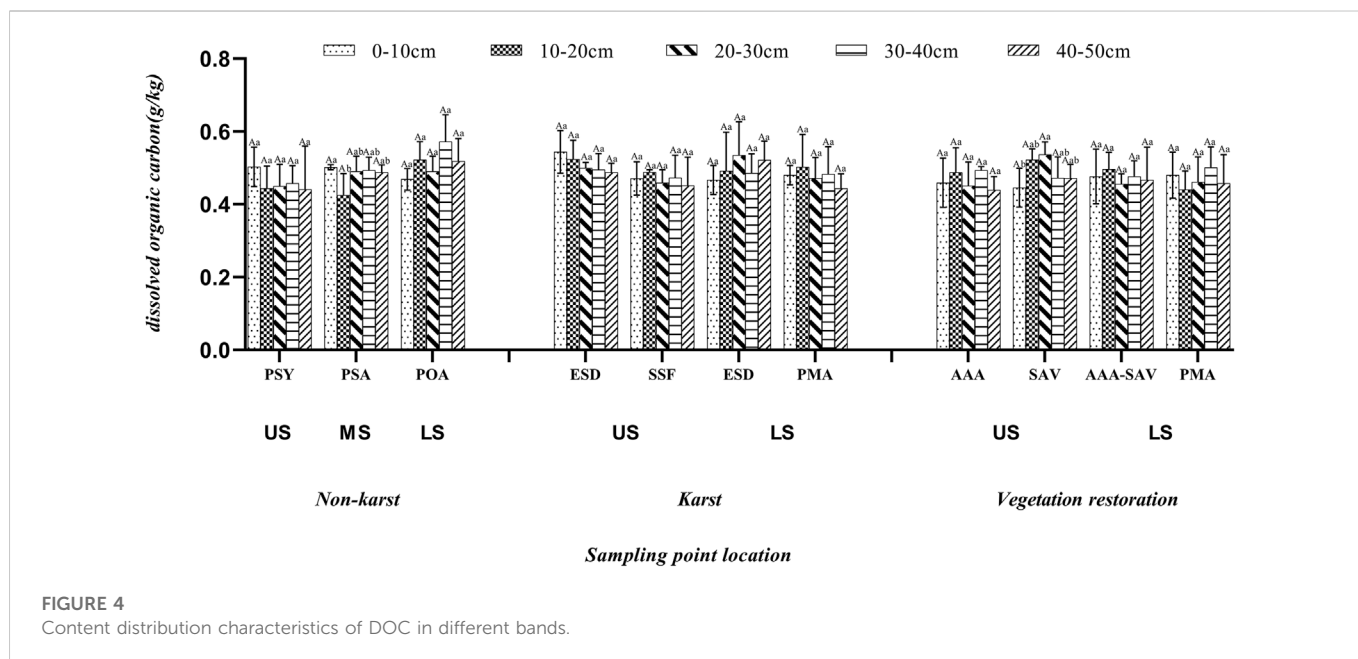| Spatial location	Karst - non-karst				Karst - vegetation restoration				Vegetation restoration - non-karst			
	0–20 cm		20–50 cm		0–20 cm		20–50 cm		0–20 cm		20–50 cm	
	F	P	F	P	F	P	F	P	F	P	F	P
landform	0.536	0.470	1.544	0.220	2.512	0.120	5.799	0.019	3.637	0.066	0.141	0.709
Location	1.781	0.191	4.586	0.037	0.235	0.631	9.002	0.004	0.536	0.470	38.345	0.000
landform * Location	0.000	0.987	0.481	0.491	3.308	0.076	0.665	0.418	4.240	0.048	0.220	0.641

$p < 0.05$: Significant, $p < 0.01$: very significant.

3.2.2 Distribution characteristics of easily oxidizable organic carbon in soils with different landforms

The distribution of soil ROC content in the three sample zones is shown in Figure 3. Soil ROC content in non-karst areas basically conformed to the law of decreasing with increased depth. Before vegetation restoration, *S. fertilis* (upper-slope) and *Pennisetum alopecuroides* (lower-slope) decreased with the increased soil depth in karst area, while the distribution of *E. dahuricus* (upper-slope) and *E. dahuricus* (lower-slope) showed the opposite observations.

However, after vegetation restoration, the soil ROC content of *A. argyi- S. viridis* (lower-slope) increased at first and then decreased with depth. The soil ROC of *S. viridis* (upper-slope) decreased with the depth, while *Pennisetum alopecuroides* (lower-slope) showed a contrary trend.

The GLMM showed that topsoil geomorphology, spatial location, and their interaction had no significant effect on soil ROC content in karst and non-karst areas, while deep soil spatial location had significant effects on soil ROC content in karst and non-karst areas

FIGURE 4
Content distribution characteristics of DOC in different bands.

TABLE 6 Generalized linear mixed model (GLMM) analysis of soil DOC.

Spatial location	Karst - non-karst				Karst - vegetation restoration				Vegetation restoration - non-karst			
	0–20 cm		20–50 cm		0–20 cm		20–50 cm		0–20 cm		20–50 cm	
	F	P	F	P	F	P	F	P	F	P	F	P
landform	0.221	0.641	0.625	0.433	1.341	0.253	0.972	0.328	0.299	0.588	0.692	0.409
Location	0.005	0.942	9.314	0.004	0.307	0.582	0.024	0.877	0.012	0.914	4.304	0.043
landform * Location	0.615	0.439	4.780	0.034	0.080	0.778	0.226	0.636	0.009	0.925	6.401	0.015

$p < 0.05$: Significant, $p < 0.01$: very significant.

(Table 5). The interaction of topsoil geomorphology and spatial location between karst vegetation restoration area and non-karst area has a significant impact on soil ROC, while the deep soil spatial location has a very significant impact on soil ROC. The influence of upper-slope sample points on soil ROC in karst vegetation restoration area was significantly higher than that in non-karst area, and the geomorphology and spatial location of deep soil in karst area and karst vegetation restoration area had a significant influence on soil ROC content.

3.2.3 Distribution characteristics of soil dissolved organic carbon in different landforms

Figure 4 demonstrates the distribution of soil DOC content across three sample zones. The DOC content of the topsoil of *Pinus Yunnanensis* (upper-slope) in non-karst area was higher than that of other depths. *Plantago asiatica* (lower-slope) increased as the depth increased. The SOC content of *E. dahuricus* (upper-slope), *S. fertilis* (upper-slope), and *Pennisetum alopecuroides* (lower-slope) gradually decreased with the depth, while that of *E. dahuricus* (lower-slope) gradually increased. After vegetation restoration, the soil DOC content of *A. argyi* (upper-slope), *S. viridis* (upper-slope), and *A. argyi- S. viridis* (lower-slope) increased at first and then decreased, while that of

Pennisetum alopecuroides (lower-slope) decreased at first and then increased.

The GLMM revealed that the spatial location of the soil profile in karst and non-karst areas has a major impact on the soil DOC content. Meanwhile, the interaction in the karst area (upper-slope) the effect of the interaction of geomorphology and spatial location on soil DOC content was also significantly higher than that of non-karst landforms. The spatial location and interaction of deep soil in karst vegetation restoration area and non-karst area have a significant impact on soil DOC, and the influence of non-karst landform (lower-slope) on soil DOC is greater than that of restored karst landform as shown in Table 6.

3.3 Correlation analysis between carbon component content and soil physical and chemical properties

3.3.1 PCA analysis

Figure 5 depicts the PCA analysis of the physical and chemical properties of topsoil based on three samples. The findings revealed that the chemical and physical characteristics of the soil surface layer
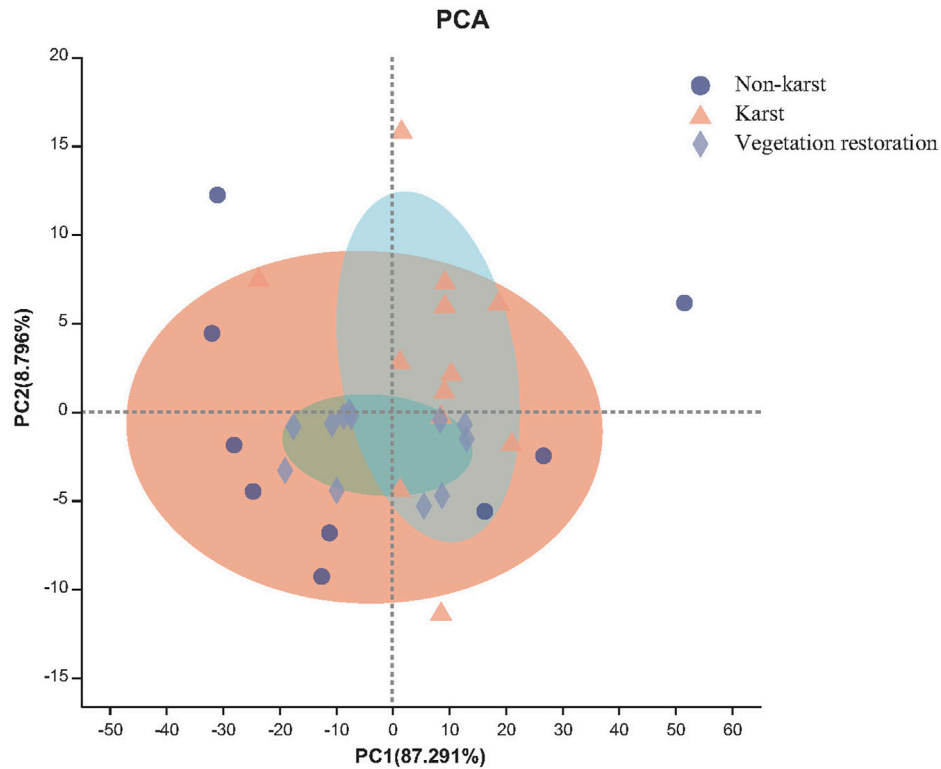
FIGURE 5
Principal coordinate analysis of soil physical and chemical properties. PC1: major coordinates of the largest possible explain data changes; PC2: the rest of the degree of change in the proportion of the largest main coordinate components.

were primarily driven by two principal components (PCs) in different regions, with a cumulative total variance of 96.087%.Among them, the PC1 spindle exhibited the greatest influence, explaining 87.291% of the data variation. PC2 spindle explained 8.796% of the data variation. The non-karst area is mainly located at the negative end of the PC1 and PC2 axis, and the karst area is mainly located at the positive end of the PC1 and PC2 axis. The karst vegetation restoration area had both positive and negative PC1 axis and negative PC2 axis. Physical and chemical properties differed significantly between non-karst and karst areas. However, soil physical and chemical properties were closer to non-karst areas with no significant differences after vegetation restoration.

3.3.2 Correlation analysis of two matrices

In this study, two matrix Spearman correlation analyses and average clustering (class average method) were used to examine the correlations between soil environmental factors and organic carbon (SOC, DOC, and ROC), as shown in Figure 6. In non-karst areas, ROC and TN, ROC and AP, pH and TP were respectively positively correlated. Cluster analysis could be divided into four groups: 1) pH; 2) SWC; 3) BD, EC, NH_4^+-N and TN; 4) SOC, DOC, ROC and NO_3^--N, AP and TP were clustered together. For unrepaired karst areas, SWC was positively correlated with NH_4^+-N and negatively correlated with BD. Cluster analysis could be divided into three groups: 1) pH; 2) SWC, BD, EC, NH_4^+-N and TN; 3) SOC, DOC, ROC and NO_3^--N, AP and TP. For karst restoration areas, there was a significant positive correlation between NH_4^+-N and NO_3^--N and a significant negative correlation between TN and AP. Cluster analysis

could be divided into three groups: 1) pH; 2) SWC, BD and EC; 3) SOC, DOC, ROC, NH_4^+-N, TN, NO_3^--N, AP and TP.

4 Discussion

4.1 Effect of karst geomorphology on soil carbon content

The ecological environment of karst soils was more fragile than that in non-karst areas due to the limitations of the soil formation mechanism and its special three-dimensional structure above ground and underground (Xiong and Chi, 2015). The study showed that top soil organic carbon content in karst area was significantly lower than that in non-karst area, while deep soil organic carbon content was higher than that in non-karst area, SOC generally exhibits the spatial distribution characteristics of up-slope < down-slope. First, the top soil organic carbon content was related to the accumulation of litter and root biomass on the soil surface and SOC degradation. Soil surface accumulation of litter and root biomass were the main sources of SOC input (Long et al., 2022). The soil in karst area was limestone, and the weathered soil dissolves in weak acid, most of which was washed away by rainwater, The development of the soil parent material layer was slow, which was not conducive to plant growth, and the plant coverage was low (Wang et al., 2020). The soil in the non-karst area was yellow soil, and the soil parent material layer was well developed. In addition to herbs, there were a large number of shrubs and trees covered by vegetation in non-karst areas, and thick plant litter was accumulated
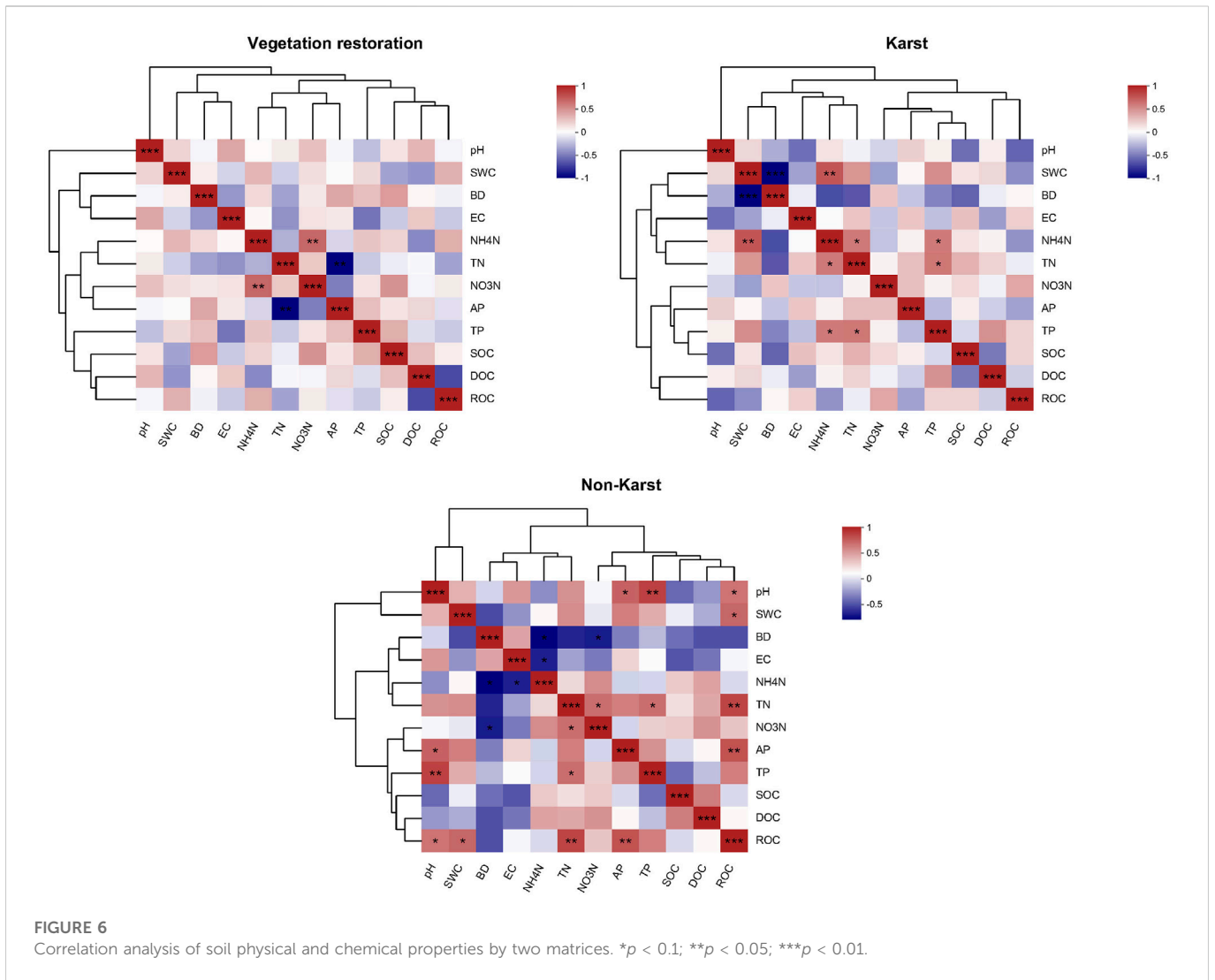
FIGURE 6
Correlation analysis of soil physical and chemical properties by two matrices. *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

on the soil surface. Higher plant coverage and species richness maintain a high level of root biomass, and the decomposition of surface vegetation litter, plant roots, and litter releases a large number of nutrient elements needed for plant growth. Accumulate a large amount of nutrients, such as organic matter and humus in the surface layer (Chen et al., 2022a). Secondly, calcareous soil was developed from carbonate rock, resulting in a weakly alkaline pH and a high dissolution rate for supplementing lost calcium and related SOC (Li et al., 2015). In comparison, yellow soil belongs to zonal soil (acidic pH) with large leached calcium and magnesium; acid hydrolysis removes the components rich in proteins, nucleic acids, and polysaccharides from soil organic matter, which makes soil organic matter low (Wang et al., 2013; Zhu et al., 2007). Bacteria, actinomycetes, and other microorganisms were extremely active in calcium-rich calcareous soil, causing organic matter to decompose to form humus and rapid turnover, so that the SOC content of yellow soil in deep soil was significantly lower than that of calcareous soil (He et al., 2019; Yang et al., 2019); In addition, serious soil erosion also leads to the loss of SOC, and the SOC lost on the upper-slope accumulates on the down-slope, so that the SOC on the downslope is larger than that on the upper-slope (Liu et al., 2020).

Some studies reported a significant positive correlation between soil ROC, DOC, and SOC contents in brick red soil environments (Huang et al., 2015; Guan and Fan, 2020). However, we observed a higher ROC content in the karst area than the non-karst area with extremely significant effects of geomorphology and spatial location on soil ROC. This was due to low soil content in karst landforms (rock was exposed and the rock fragment content was high) with high sensibility in response to the surrounding environments. Soil must maintain a high proportion of soil ROC and DOC in order to maintain the normal growth of vegetation (Huang et al., 2013). This was supported by the results of the GLMM model. In this study, the results show that in karst areas, the DOC/SOC proportion was much higher than in non-karst areas. Due to the significant positive correlation between the content of large soil aggregates and the content of iron and aluminum compounds in the soil, the content of large aggregates (>5 mm) in karst areas was substantially lower than that in non-karst areas, according to Table 3. (Xue et al., 2019). The increase in the adsorption of iron-aluminum compounds will affect the soil DOC/SOC ratio, and the two are inversely proportional (Ren et al., 2018). SOC in karst area was more active and easier to be leached and eroded by wind than that in non-karst area (Chen et al., 2022b),

which indirectly explained the distribution characteristics of active organic carbon in karst area.

4.2 Effect of vegetation restoration on soil carbon composition

As an important measure to control soil erosion, vegetation restoration plays a vital role in the process of ecological restoration, which is also helpful to promote the development of eroded soil, improve soil quality and fertility (Liang et al., 2021). In this study, the vegetation types in karst area were mainly perennial herbaceous plants, while the roots of herbaceous plants were mainly concentrated in the soil surface layer. Thus, effects on SOC and TN were mainly concentrated in surface soil (Lei et al., 2021). Surface SOC in the karst vegetation restoration area was lower than that in the same spatial position in the karst unrepaired area, which might be attributed to the early stage of vegetation restoration in this area. Microbial activity was relatively strong, causing less SOC to accumulate due to its fixation in the vegetation (Xiao et al., 2022). Soil ROC in the restored area was lower than that in the karst area with an insignificant change in soil DOC, whereas surface soil ROC/SOC and DOC/SOC in the restored area were higher than those in the karst area. The proportion of surface soil aggregates (>5 mm) decreased significantly after vegetation restoration. The GLMM model showed that vegetation restoration had a significant effect on surface soil ROC. This indicated that rhizosphere activity weakened SOC stability and increased its activity despite vegetation restoration having significant carbon sequestration benefits (Zhang et al., 2019a; Hu et al., 2021b). In addition, we also found that the SOC content of the surface soil on the upper-slope was higher than on the lower-slope in both the karst area and the karst vegetation restoration area. Understandably, the erosion degree of surface runoff in the karst area was weaker than that in other areas, and the loss of SOC in surface runoff was relatively less. Coupled with specific karst landforms, the bare degree of rock on the upper-slope was higher than that on the lower-slope, suggesting a certain interception effect on SOC (Liang et al., 2018).

After vegetation restoration, the vegetation coverage was significantly improved. For instance, vegetation types developed from a single Gramineae to enriched Gramineae and Compositae. Soil surface TP increased and N:P decreased greatly after vegetation restoration (yet plant growth exhibited nitrogen limitation) (Li et al., 2015). Compositae plants with dicotyledons were more adaptable to environments, and Compositae plants spread rapidly with strong reproductive ability, which preempted the growth space of originally Gramineae and increased plant diversity (Jin et al., 2022; Gao et al., 2022). Studies reported that species diversity and richness could cause SOC sequestration by affecting soil microbial biomass and activity (Dawud et al., 2016; Hu et al., 2021a). However, here we showed that vegetation diversity was inversely proportional to soil surface carbon content, which might be related to the role of "plant-soil feedback (PSF)". Insufficient soil fertility in karst areas led to decreased soil microbial activity and failed to provide enough nutrition for plants. Strong competition occurred among plant populations in the condition of soil nutrients fixed or depleted, leading negative feedback from soil to plants. Current researches on the process and mechanism of "PSF", especially at the community level, remain limited (Wang, 2020; Conrad et al., 2016). Further works for the corresponding knowledge were thus merited.

5 Conclusion

Vegetation restoration was regarded as an important measure for soil and water conservation. Here we investigated spatial patterns of SOC and its influencing factors in a karst area at the initial stage of vegetation restoration. Significant differences in SOC were found among different landforms. Surface SOC was substantially lower in karst areas than in non-karst areas, and ROC/SOC and DOC/SOC in surface soil were higher than that in non-karst area. Vegetation restoration changed soil active organic carbon pool and enhanced soil carbon sequestration capacity. However, SOC was unstable without upward trends due to the influence of soil stability and dominant plant communities in the early stage of vegetation restoration. Spatial location, plant richness, ROC/SOC and DOC/SOC in surface soil were larger than those in karst area attributing to influence of topography. Soil physical and chemical indexes such as soil activity, plant coverage, and soil bulk density were improved compared with those before restoration, which evidenced a significant improvement of vegetation restoration on soil quality in karst area.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YW conceived, designed, and conducted the experiment; RW. analyzed the data and wrote the manuscript; MZ, PH, and XT performed the experiments and sorted out data; YW and JZ. assisted in the modification. All authors have revised the manuscript and approved the version submitted.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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