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Influence of *Eucalyptus* Plantation on Soil Organic Carbon and Its Fractions in Severely Degraded Soil in Leizhou Peninsula, China

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Abstract: Effective vegetation restoration plays an important role in maintaining and improving soil nutrients and can promote the fixation of soil organic carbon (SOC) and its fractions in degraded soil areas. To understand the influence of *Eucalyptus* plantation on SOC and its fractions in severely degraded soil in Leizhou Peninsula, China, vegetation restoration with *Eucalyptus* (RE: *Eucalyptus*–shrub ES, *Eucalyptus*–grass EG, and *Eucalyptus*–*Dicranopteris* ED) was chosen as the research object, and natural vegetation restoration without *Eucalyptus* (RNE: shrub S, grass G, and *Dicranopteris* D) nearby was used as the control group. SOC and its fractions in different vegetation types were compared and analyzed after sample plot surveys and sample determination, and the driving forces of SOC and its fractions were discussed. SOC, dissolved organic carbon (DOC), microbial biomass carbon (MBC), easily oxidized organic carbon (EOC), and particulate organic carbon (POC) in RE were significantly different from those in RNE, increasing by 194.4%, 36.3%, 111.0%, 141.6%, and 289.9%, respectively. The order of SOC, EOC, DOC, MBC, and POC content in RE was ES > EG > ED. SOC and its fractions were positively correlated with leaf litter cover and biomass, and soil organic matter. SOC, total nitrogen, available nitrogen, total phosphorus, available phosphorus, and enzyme activities were negatively correlated with microbial diversity but were not significantly correlated with soil bulk density and microbial richness. Structural equation modeling analysis results showed that soil enzyme activity was a direct driving force of SOC and its fractions. The input of carbon sources from leaf litter and soil properties were indirect factors that affected SOC and its fractions by affecting microbial characteristics and enzyme activities. Thus, planting *Eucalyptus* in harsh environments, where natural restoration is difficult, can be an effective measure for early vegetation restoration.

Keywords: Leizhou Peninsula; red soil degradation area; *Eucalyptus* plantation; vegetation restoration; SOC fractions

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1. Introduction

Soil carbon is the core component of the terrestrial carbon pool, and its reserves are twice those of the atmospheric carbon pool and two to three times more than those of the vegetation carbon pool [1]. SOC accounts for more than 50% of the total soil carbon [2], which is an essential factor of soil fertility, and an important indicator of soil quality and ecosystem productivity [3] it also has a great influence on soil properties [4] and ecosystem services such as climate regulation [5], soil carbon sequestration [6], and nutrient cycling [7].

SOC content is determined by the long-term balance between organic carbon input from litterfall, roots, and organic carbon loss by processes such as decomposition, leaching, and dissolved carbon export [8,9]. It is difficult to respond to short-term ecosystem disturbances and can't well reflect short-term changes in soil quality and organic carbon conversion rate [2,10–12]. Soil labile organic carbon (LOC) accounts for only a small part of the total organic carbon pool, but it is more sensitive to ecosystem disturbances than

soil organic carbon (SOC) [13,14]. LOC, an important index of soil quality, can reflect the availability of SOC and soil quality in different degrees [15]. It can also reflect a slight change in the organic carbon pool caused by ecosystem disturbance [16], especially the dynamic change of SOC during the early restoration of degraded ecosystems. LOC is mainly classified into dissolved organic carbon (DOC), microbial biomass carbon (MBC), easily oxidized organic carbon (EOC), and particulate organic carbon (POC). The content, distribution, and dynamics of SOC fractions in different ecosystems may be different [17]. The status of SOC fractions in different ecosystems helps to understand the carbon nutrient cycle of ecosystems and maintain the sustainable development of ecosystems [18].

The factors affecting the content and spatial distribution of SOC and its fractions are complex. Without considering human disturbance, the distribution and dynamics of SOC and its fractions are not only affected by abiotic factors such as climate [17], soil erosion [19], and physicochemical properties [17] but also by biotic factors such as vegetation types [20] and soil microbial characteristics [21]. However, environmental factors are dynamic during material circulation in the ecosystem [22]. In different ecosystems, the factors driving carbon distribution and dynamics are different [19]. Therefore, the main factors affecting the distribution and dynamics of SOC and its fractions may be different in different ecosystems.

Red soil derived from the parent material layer is poor and often seriously degraded [23], particularly in the overuse of land for human activities of breeding animals, brick burning, digging, mining, etc., which massively destroy the original ecological structure of the soil surface layer in the degraded red soil area. Under the combined action of external forces such as high temperature and heavy rainfall, the soil layer is rapidly eroded and lost, and the red bedrock or its weathered crust is exposed, resulting in a red desert landscape [24]. Due to land degradation, soil nutrients are also lost, making the ecological environment fragile [25]. Therefore, ecological restoration of degraded areas needs urgent attention. Effective vegetation restoration is considered the most effective way to repair degraded soil and improve ecosystem services [26,27].

Vegetation restoration models include plantation restoration and natural vegetation restoration [28]. Plantation restoration is a mode of planting vegetation and implementing closure management to achieve vegetation restoration. In southern China, *Eucalyptus* and pine trees are widely planted as the main tree species for plantation vegetation restoration because of their rapid growth characteristics [29,30]. Natural vegetation restoration is a restoration mode in which natural vegetation can be regenerated without plantation measures. In vegetation restoration, different vegetation types may be developed as the understory vegetation of the plantation or as the main vegetation at the initial stage of natural restoration. What are the content and dynamics of SOC and its fractions in different vegetation types, especially in the tropical areas of southern China with heavy rainfall and eroded red soil? Which vegetation type is more conducive to organic carbon availability and stability? At present, research on these aspects is lacking.

In this study, vegetation restoration with *Eucalyptus* (RE: *Eucalyptus*–shrub ES, *Eucalyptus*–grass EG, and *Eucalyptus*–*Dicranopteris* ED) was chosen as the research object, and natural vegetation restoration without *Eucalyptus* (RNE: shrub S, grass G, and *Dicranopteris* D) nearby was taken as the control group. The content and dynamic characteristics of SOC and its labile fractions in restored vegetation types in the degraded red soil area in Leizhou Peninsula, China, were compared and analyzed after sample plot surveys and sample determination, and their driving forces were discussed. The objective of this study was to explore an effective vegetation restoration model for the degraded red soil area in Leizhou Peninsula, providing a theoretical reference for vegetation restoration and sustainable management of *Eucalyptus* plantations in degraded red soil areas.

2. Materials and Methods

2.1. Study Site

Leizhou Peninsula (20°12′–21°35′ N, 109°30′–110°55′ E) in the southernmost tip of the Chinese mainland, with an area of 12,470 km^2, is the third largest peninsula in China. It

experiences the marine monsoon climate of the northern tropics. It is sunny and hot all year round, with annual average temperature range from 22.8 °C to 23.5 °C, a maximum temperature of 38.8 °C, and a minimum temperature of 2.2 °C [31,32].

East and southeast winds prevail throughout the year. The annual rainfall is 1400–1600 mm, but the distribution is uneven, and the wet and dry seasons are obvious. The rainy season from May to September accounts for 85% of the annual rainfall. Drought is a serious issue in winter and spring. The study area is relatively flat, with an inverted turtle-back terrain from north to south. The terrain is high in the north, low in the middle, and high in the south. The soil types are mainly latosol developed from basalt and coastal and tidal sandy soil [32].

2.2. Experimental Design

After measuring the age of trees by extracting tree core samples with borers and visiting local forest landowners, seven typical degraded areas (slope < 5°) were selected as restoration study sites in Chikan District, Xiashan District, Hetou Town, Nanxing Town, Jijia Town, Longmen Town, and Yangjia Town in the Leizhou Peninsula. *Eucalyptus grandis* Hill ex Maiden was planted in all seven restoration study sites in 2013, with a row spacing of 3 m × 2 m. No fertilization or weed control treatment was performed after planting. After restoration, shrubs, grasses, or *Dicranopteris pedata* (Houttuyn) Nakaike were naturally restored in the plots with *Eucalyptus*, and the vegetation types were respectively corresponding to *Eucalyptus*-shrub (ES), *Eucalyptus*-grass (EG), *Eucalyptus*-*Dicranopteris* (ED). Shrubs, grasses, and *Dicranopteris pedata* were naturally restored in the plots without *Eucalyptus* near *Eucalyptus* plots, and the vegetation types were respectively corresponding to shrubs (S), grasses (G), and *Dicranopteris pedata* (D).

The investigation was performed from June to October 2021. According to the paired experiment, three pairs of paired plots were established ES and S, EG and G, and ED and D. A set of paired plots in each study site included a *Eucalyptus* plot (20 m × 20 m) and a non-*Eucalyptus* plot (10 m × 10 m). A total of 21 paired plots (21 *Eucalyptus* plots of RE and 21 non-*Eucalyptus* plots of RNE) were established in the seven study sites. To eliminate differences in background conditions between RE and RNE plots, the plots were maintained in the non-vegetation state before restoration as far as possible. In addition, to eliminate the influence of environmental conditions such as *Eucalyptus* litter and shade on RNE plots, the distance between a plot planted with *Eucalyptus* and a plot not planted with *Eucalyptus* in each set of paired plots was restricted to 50–300 m. Site conditions such as topography and soil were the same.

The growth indicators of all trees with diameter at breast height (DBH) ≥ 5 cm (woody plants with DBH < 5 cm were considered shrubs) in the sample plot were measured, including quantity, height, DBH, annual ring, and crown width. Five shrub quadrats (2 m × 2 m) and five herb quadrats (1 m × 1 m) were arranged in the sample plot to investigate the growth of shrubs and grasses using growth indicators such as the number of plants (clumps), basal (clumps) diameter, crown diameter, height, and cover.

Five litter quadrats (1 m × 1 m) were also set up in the plot, and the biomass of litter was investigated by the harvest method. General descriptions of vegetation restoration and soil physicochemical properties are shown in Tables 1 and 2, respectively.

Table 1. General description of vegetation restoration with *Eucalyptus* and natural vegetation restoration without *Eucalyptus*.

Vegetation Type	*Eucalyptus*			Understory Vegetation			Leaf Litter		
	DBH (cm)	Height (m)	Canopy Cover (%)	Cover (%)	Height (m)	Dominant Species	Cover (%)	Thickness (cm)	Biomass (g m^{-2})
ES	12.6 ± 2.1	12 ± 2	40–50	70–80	1.4	*Aporosa dioica (Roxb.)* Müll. Arg. *Litsea glutinosa (Lour.)* C. B. Rob. *Micromelum falcatum* (Lour.) Tan.	69 ± 5	3.5 ± 0.2	303.9 ± 5.9
S	-	-	-	15–20	0.7	*Aporosa dioica (Roxb.)* Müll. Arg. *Antidesma ghaesembilla* Gaertn.	9 ± 1	0.5 ± 0.1	16.1 ± 2.7
EG	10.9 ± 2.7	10 ± 2	40–50	70–80	0.8	*Miscanthus sinensis* Anderss. *Imperata cylindrica* (L.) Beauv.	79 ± 7	6.7 ± 1.6	398.9 ± 4.7
G	-	-	-	15–25	0.5	*Miscanthus sinensis* Anderss. *Imperata cylindrica* (L.) Beauv.	2 ± 0	0.4 ± 0.1	2.3 ± 0.4
ED	9.4 ± 2.6	9 ± 2	40–50	75–85	1.1	*Dicranopteris pedata* (Houtt.) *Nakaike*	92 ± 1	16.5 ± 1.7	921.0 ± 17.1
D	-	-	-	25–35	0.4	*Dicranopteris pedata* (Houtt.) *Nakaike*	38 ± 5	1.5 ± 0.2	58.8 ± 2.8

ES, EG, and ED represent *Eucalyptus*–shrub, *Eucalyptus*–grass and *Eucalyptus*–*Dicranopteris* respectively. Vegetation restoration with *Eucalyptus*; S, G and D represent shrub, grass, and *Dicranopteris* respectively, natural vegetation restoration without *Eucalyptus*; DBH, diameter at breast height. Data are mean ± SD. The same as below.

Table 2. Soil physicochemical properties in vegetation restoration with Eucalyptus and natural vegetation restoration without Eucalyptus.

Vegetation Type	Soil Layer	SW (%)	BD (g m^{-3})	pH	TN (g kg^{-1})	TP (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	SOM (g kg^{-1})
ES	0–10 cm	10.21 ± 2.01	1.39 ± 0.08	5.2 ± 0.2	1.49 ± 0.22	0.85 ± 0.10	238.2 ± 0.39	3.70 ± 0.58	32.49 ± 2.84
S		8.19 ± 0.12	1.35 ± 0.07	4.7 ± 0.1	0.40 ± 0.10	0.36 ± 0.07	44.25 ± 3.88	0.92 ± 0.12	7.9 ± 0.89
EG		13.51 ± 0.56	1.37 ± 0.1	4.9 ± 0.4	1.00 ± 0.11	0.61 ± 0.05	131.4 ± 4.28	2.14 ± 0.31	23.16 ± 2.91
G		7.97 ± 0.58	1.35 ± 0.13	4.7 ± 0.2	0.54 ± 0.07	0.36 ± 0.04	47.81 ± 6.44	1.02 ± 0.14	7.09 ± 1.16
ED		14.90 ± 0.78	1.37 ± 0.02	4.5 ± 0.2	0.76 ± 0.06	0.49 ± 0.03	94.8 ± 9.85	1.47 ± 0.29	19.39 ± 1.67
D		8.26 ± 0.15	1.38 ± 0.18	4.6 ± 0.1	0.37 ± 0.05	0.34 ± 0.05	51.82 ± 6.03	1.12 ± 0.13	8.27 ± 0.93
ES	10–20 cm	10.98 ± 1.55	1.42 ± 0.05	4.8 ± 0.1	0.84 ± 0.08	0.51 ± 0.07	125.2 ± 8.12	1.87 ± 0.38	15.09 ± 1.86
S		10.40 ± 0.25	1.44 ± 0.05	4.6 ± 0.1	0.4 ± 0.07	0.34 ± 0.08	54.07 ± 2.80	1.16 ± 0.1	6.55 ± 0.33
EG		13.53 ± 0.71	1.4 ± 0.09	4.5 ± 0.1	0.69 ± 0.13	0.37 ± 0.03	76.19 ± 5.13	1.13 ± 0.16	12.42 ± 0.91
G		10.11 ± 0.44	1.42 ± 0.04	4.8 ± 0.2	0.42 ± 0.06	0.43 ± 0.04	46.50 ± 5.48	1.30 ± 0.05	4.26 ± 0.54
ED		15.22 ± 0.85	1.42 ± 0.08	4.5 ± 0.1	0.48 ± 0.07	0.40 ± 0.04	63.48 ± 3.14	1.21 ± 0.14	9.85 ± 0.84
D		10.96 ± 0.83	1.37 ± 0.13	4.5 ± 0.1	0.31 ± 0.06	0.34 ± 0.07	36.91 ± 6.61	1.4 ± 0.19	4.35 ± 0.34

SW denotes soil water.

2.3. Sample Collection

Soil samples were collected from the 0–10 cm and 10–20 cm soil layers. Five soil cores were taken from each quadrat along an S-shaped route, and the soil samples of the same soil layer were mixed into one soil sample after removing stones and roots. This homogenized soil sample was put into a plastic self-sealing bag and taken to the laboratory for processing. After sieving through a 2-mm sieve, fresh soil was divided into three parts. The first part was air-dried and used to determine SOC and its fractions and soil physicochemical properties. The second part was stored in a refrigerator at 4 °C for the measurement of soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), microbial biomass phosphorus (MBP), and soil enzyme activity. The third part was stored at −80 °C for DNA extraction and analysis.

In addition, beside each sampling point of the soil core, a cutting ring was used to collect soil to measure soil bulk density (BD) at the laboratory, and an aluminum box was used to collect soil to measure the soil water content by oven drying at the laboratory.

2.4. Sample Analysis

Soil pH was estimated by the potentiometric method. Soil organic matter (SOM) was measured by the potassium dichromate oxidation-external heating method, and SOM was converted to SOC with a conversion factor of 1.724. Soil total nitrogen (TN) was determined by the semi-micro Kjeldahl method. Soil available nitrogen (AN) was quantified by the

alkaline hydrolysis nitrogen diffusion method. Total phosphorus (TP) in soil was determined by sodium hydroxide melting–molybdenum antimony anti-colorimetry. Available phosphorus (AP) in soil was determined by the 0.03 mL NH4F–0.025 mL HCl extraction method. The specific determination method used was as described by Bao [33].

Soil MBC, MBN, and MBP were fumigated with chloroform, and the specific determination method used was as described by Manral et al. [34–36].

Soil sucrose activity was determined by 3,5-dinitrosalicylic acid colorimetry; catalase (CAT) activity was determined by potassium permanganate titration; cellulase activity was determined by 3,5-dinitrosalicylic acid colorimetry, and the specific determination method used was as described by Guan et a [37]. β-Glucosidase was determined according to the method by Saiya-Cork et al. [38].

Genomic DNA extraction, DNA sample detection, sequencing library construction, and library inspection were performed for Soil metagenomic DNA sequencing. The genome was sequenced by using the Illumina NovaSeq PE150 platform.

2.5. Statistical Analysis

Data were analyzed using IBM SPSS statistics 20.0 (IBM Crop., Armonk, NY, USA). The paired sample t-test was used to compare differences in paired vegetation indicators, and a one-way analysis of variance was performed to compare differences in unpaired vegetation indicators. Pearson correlation coefficient was used to calculate the correlation between SOC, its fractions, and environmental factors.

Structural equation modeling (SEM) was used to study the direct and indirect effects of environmental factors on SOC and its fractions during vegetation restoration. The fitting indices chi-square fit statistics/degree of freedom (χ^2/df) and root mean square error of approximation (RMSEA) were used to explain the model. $\chi^2/df < 3$ indicates that the fitting is reasonable [39], while an RMSEA value of less than 0.08 suggests an adequate model fit [40]. Chao1 and Shannon indices were calculated by measuring the alpha diversity of soil microorganisms [41,42]. Origin 2021 (Origin Lab, Northampton, MA, USA) was used to draw the heatmap. The significance level was set at $p < 0.05$.

3. Results

3.1. SOC and Its Fractions in Different Vegetation Types

SOC, DOC, MBC, EOC, and POC in RE were significantly different from those in RNE (Figure 1), increasing by 194.4%, 36.3%, 111.0%, 141.6% and 289.9%, respectively, reflecting that the input of SOC was higher in RE than in RNE. SOC, DOC, MBC, EOC, and POC were significantly higher in ES than in EG and ED, which indicated that the organic carbon source input was higher in ES. SOC, DOC, MBC, EOC, and POC were also significantly higher in EG than in ED (Figure 1a–e), indicating that the organic carbon source input was higher in EG than in ED.

Except for DOC, which increased with soil depth, SOC and its other fractions such as MBC, EOC, and POC decreased with soil depth in each vegetation type, indicating that SOC and its fractions were mostly concentrated in the topsoil.

3.2. Ratio of SOC Fractions to SOC in Different Vegetation Types

In each vegetation type, DOC/SOC (0.1%–0.8%) was low, whereas EOC/SOC (69.9%–90.3%) was high, both of which increase with soil depth (Figure 2). DOC/SOC, EOC/SOC, and POC/SOC were significantly higher in RE than in RNE in the 0–10 cm layer. MBC/SOC in RE was significantly lower than that in RNE. In the 10–20 cm soil layer, DOC/SOC, MBC/SOC, EOC/SOC, and POC/SOC were significantly higher in RNE than in RE (Figure 2).

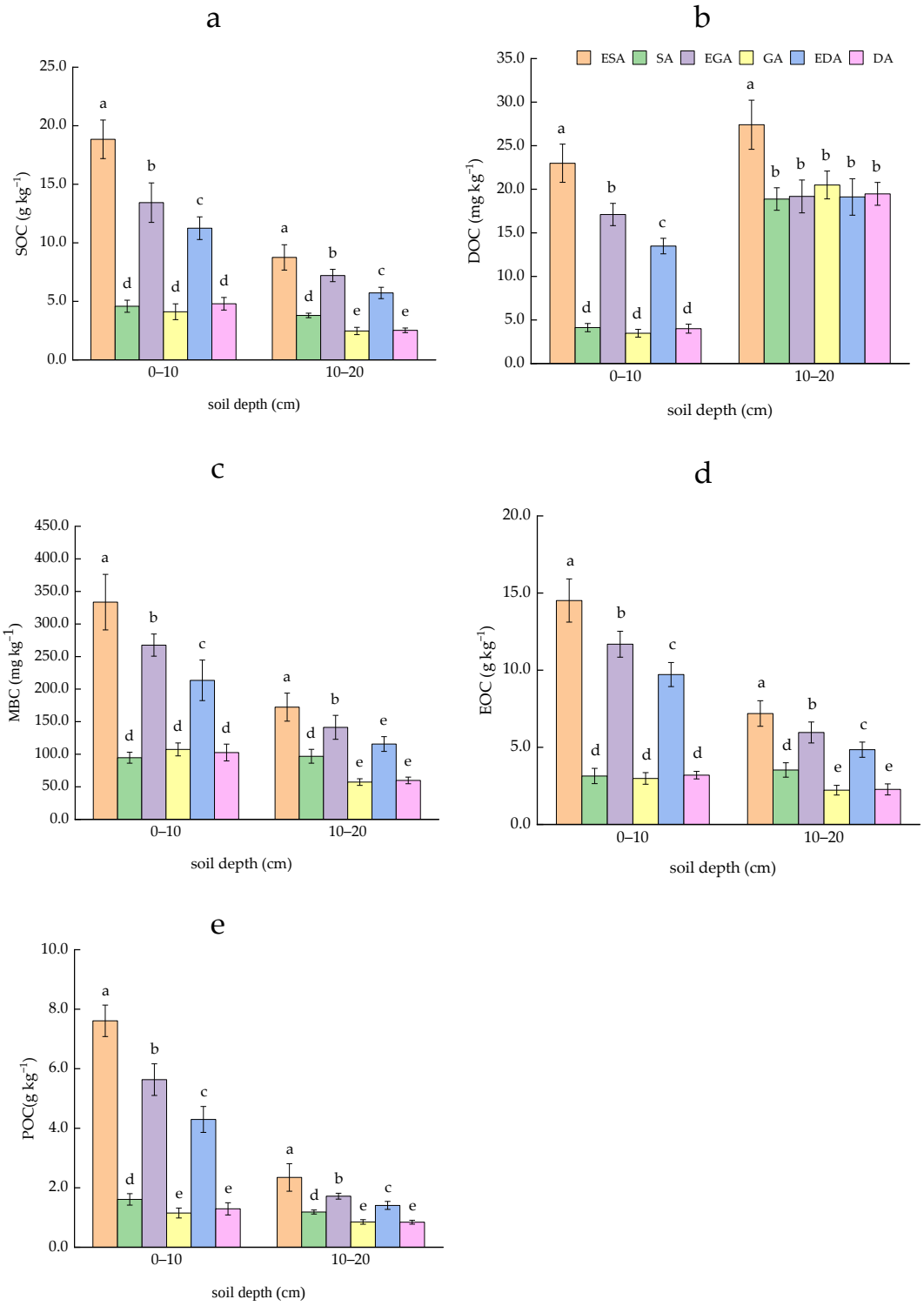

Figure 1. SOC and its fractions in different vegetation types. (**a**) SOC, soil organic carbon; (**b**) DOC, dissolved organic carbon; (**c**) MBC, Microbial biomass carbon; (**d**) EOC, Easily oxidized organic carbon; (**e**) POC, Particulate organic carbon. Different lowercase letters indicate significant differences between different forest types ($p < 0.05$).

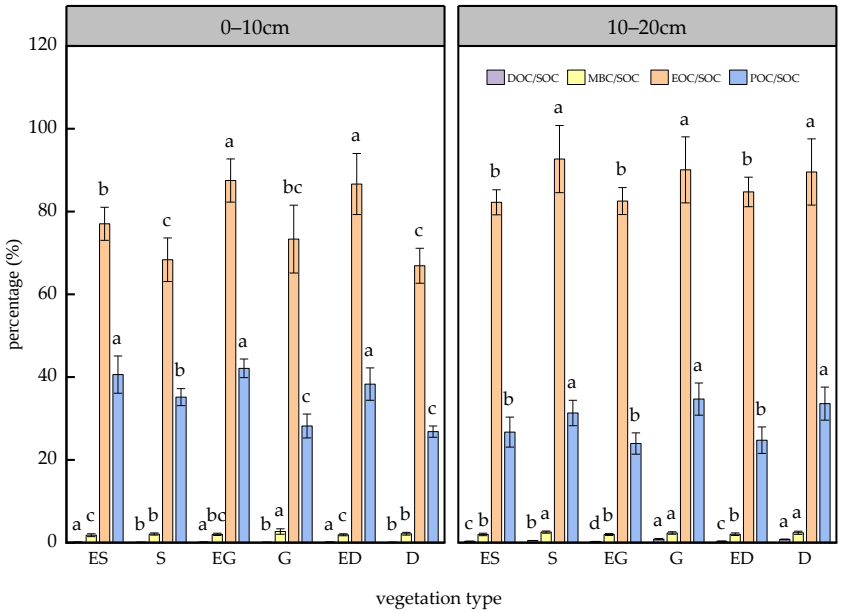

Figure 2. Ratios of SOC fractions to SOC in different vegetation types. Different lowercase letters indicate significant differences between different forest types ($p < 0.05$).

3.3. Relationship between SOC, Its Fractions, and Environmental Factors

SOC and its fractions were positively correlated with litter cover and biomass. SOM, SOC, TN, AN, TP, AP, and enzyme activities were negatively correlated with microbial diversity but were not significantly correlated with soil BD and microbial richness. Leaf litter thickness was positively correlated with MBC and EOC but was not significantly correlated with SOC and other fractions. Soil water content had no significant relationship with POC but had a positive correlation with SOC and other fractions ($p < 0.01$). The pH value and carbon to nitrogen ratio (C/N ratio) were not significantly correlated with DOC but were positively correlated with SOC and other fractions (Table 3). In addition, the correlation coefficients between DOC and various environmental factors were small, which reflected the instability of DOC.

Table 3. Pearson correlation coefficients between SOC, its fractions, and environmental factors.

		DOC	MBC	EOC	POC	SOC
Leaf litter	LC	**0.68**	**0.80**	**0.73**	**0.71**	**0.72**
	LT		0.40	0.38		
	LW	**0.40**	**0.57**	**0.55**	**0.48**	**0.51**
Soil physico-chemical properties	SW	**0.37**	0.28	0.28		0.29
	BD					
	pH		**0.56**	**0.49**	**0.43**	**0.57**
	SOM	0.28	**0.92**	**0.93**	**0.92**	**1.00**
	TN	0.31	**0.86**	**0.77**	**0.79**	**0.82**
	TP	0.33	**0.79**	**0.68**	**0.72**	**0.74**
	AN	**0.39**	**0.87**	**0.77**	**0.79**	**0.81**
	AP	**0.40**	**0.75**	**0.68**	**0.71**	**0.72**
	C/N		**0.62**	**0.73**	**0.68**	**0.69**
Enzyme activity	Sucrase	**0.50**	**0.36**	**0.36**	**0.43**	**0.41**
	Catalase	**0.58**	**0.62**	**0.53**	**0.53**	**0.57**
	Cellulase	**0.47**	**0.62**	**0.52**	**0.53**	**0.57**
	β-glucosidase	**0.56**	**0.77**	**0.71**	**0.69**	**0.75**
Microbial characteristics	Chao1 index					
	Shannon index	**−0.63**		**−0.57**	**−0.63**	**−0.66**

LW, LC, and LT denote biomass, cover, and thickness of leaf litter, respectively. Correlation coefficients from −1 to 0 and red grid indicate negative correlation, The smaller the correlation coefficients and color saturation, the greater the negative correlation between SOC, its fractions, and environmental factors; 0 correlation coefficient and

white grid indicate no correlation; Correlation coefficients from 0 to 1 and blue grid indicate positive correlation, and the greater the correlation coefficient and color saturation, the greater the positive correlation between SOC, its fractions, and environmental factors. Only the significant correlation coefficients are shown. The bold letter indicates $p < 0.01$, and the letter without bold suggests $p < 0.05$.

3.4. Structural Equation Model Relating Environmental Factors to SOC and Its Fractions

A structural equation model was constructed to simulate and determine the direct and indirect effects of four potential driving forces (characteristics of leaf litter, soil physicochemical properties, microbial characteristics, and enzyme activities) on SOC and its fractions. SEM showed the rationale of the fitting with the assumed cause ($\chi^2/df = 2.550$, $p = 0.836$, RMSEA = 0.072; Figure 3). SEM results showed that the input of leaf litter indirectly affected the content of SOC and its fractions by affecting soil properties, microbial characteristics, and enzyme activities. Enzyme activity determined by microbial metabolism was a direct driving force of SOC and its fractions (Figure 3).

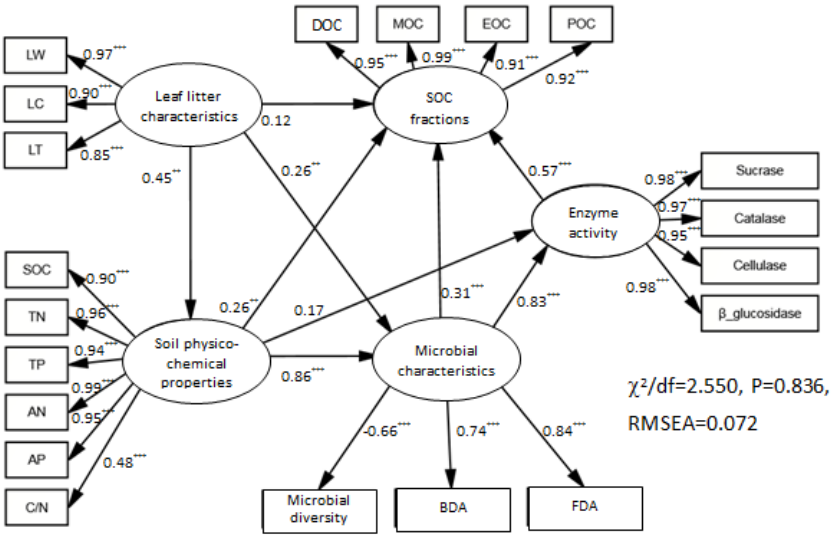

Figure 3. The structural equation model (SEM) describes the multivariate effects of environmental factors on SOC fractions. BDA, Bacterial decomposer abundance; FDA, fungal decomposer abundance. $^{++}$ Significant correlation at 0.05 level; $^{+++}$ Significant correlation at 0.01 level.

4. Discussion

4.1. SOC and Its Fractions in Different Vegetation Types

SOC is mainly derived from the input of litter and roots [43], and the quantity and quality of litter and root exudates are different in different vegetation types [44]. SOC in RE was significantly higher than that in RNE. This was mainly because Eucalyptus, with fast-growing and aridity-resistant characteristics, grew fast in the degraded red soil area, formed a canopy (Table 1), prevented the original seeds from losing water and soil (better protecting the soil seed bank), and simultaneously created a suitable microclimate habitat for seed germination and seedling growth under the forest canopy, making the understory vegetation recover and grow well, with a high vegetation cover rate of over 90% (Table 1). The communities with high vegetation cover had more organic carbon sources such as leaf litter and roots, more microbial decomposers, higher microbial metabolic activities, and faster litter decomposition, and therefore, more SOC was accumulated [45,46]. In contrast, the study area is located in the tropical area of southern China, with heavy rainfall, if without vegetation, such as Eucalyptus plantations, to accelerate vegetation restoration, the little and thin surface soil and seed bank left in the degraded red soil area were lost with leaching and surface runoff [47], which could hinder plant growth and vegetation restoration, and the vegetation cover rate was low, mostly below 30%. The input of leaf litter and roots and SOC accumulation were correspondingly reduced. Therefore, SOC was higher in RE than in RNE. Soil LOC (MBC, DOC, EOC, and POC) mainly comes from

humic organic matter, plant litter, root exudates, and microbial exudates [48]. Organic carbon is the main factor affecting LOC, and the higher the SOC content, the higher the LOC content [9,49]. Correlation analysis also showed that organic carbon was positively correlated with its labile fractions such as EOC, MBC, DOC, and POC [2,48,50]. LOC in RE with high SOC was consistently higher than that in RNE with low SOC. In addition, RE with high vegetation and litter cover could effectively prevent rainfall leaching and surface runoff [28,51], thus reducing the loss of soil LOC, especially DOC, and largely retaining LOC. Therefore, the soil LOC (EOC, MBC, DOC, and POC) content was higher in RE than in RNE, which was consistent with the results found by Ahmad [52] et al. that organic carbon storage of forests with higher vegetation cover was higher than that of forests with low vegetation cover.

Aboveground plant litter inputs are important sources of soil carbon (C), and it determines carbon storage across soil profiles [53]. DOC, MBC, EOC, and POC were significantly higher in ES than in EG and ED. Thus, the input of organic carbon sources, such as leaf litter was higher in ES than in the other vegetation types and more nutrients were returned to the soil, providing the soil with higher SOC and its fractions. This was consistent with the results found by Zhao et al. whereby, the litter accumulation in the *Pinus*-shrub vegetation type was higher than that in the *Pinus*-*Dicranopteris* and *Pinus*-grass vegetation types [54]. However, leaf litter in the ES community was low (Table 1), probably because shrub leaf litter had a high decomposition rate and had rapidly decomposed to provide more organic carbon and other nutrients to the soil. The C/N ratio of shrub leaf litter is low [55,56], thus, the C/N ratio of soil was correspondingly low. Soil with a lower C/N ratio had a higher organic matter decomposition rate [12,57], and therefore, the decomposition of leaf litter was faster. In addition, the synergistic non-additive effects of litter mixing [58,59] produced after various litter types were mixed could accelerate litter decomposition. Therefore, the accumulation of SOC and its fractions with the rapid decomposition of leaf litter was more in ES than in EG and ED.

Soil DOC, MBC, EOC, and POC were significantly higher in EG than in ED, suggesting that the input of organic carbon sources, such as leaf litter and roots, was higher in EG than in ED. However, litter in the EG community was low, which might be related to the lower C/N ratio and higher decomposition rate of grass leaf litter [60]. In addition, soil pH in the vegetation type of *Dicranopteris pedata* was low and permeability of the habitat was poor, which was not conducive to maintaining the abundance and diversity of microbes as well as their metabolic activities. Therefore, leaf litter decomposed slowly and accumulated more in ED communities.

SOC, MBC, EOC, and POC in each vegetation type mostly gathered in the topsoil, and all decreased with soil depth. This might be because plant litter and roots were mostly distributed in the topsoil. Other studies have reached similar conclusions [9,61].

4.2. Ratio of SOC Fractions to SOC in Different Vegetation Types

LOC is an unstable organic carbon fraction in soil which is easily lost with soil erosion [14,62]. In the topsoil of the 0–10 cm layer, DOC/SOC, EOC/SOC, and POC/SOC were significantly higher in RE than in RNE. This might be related to the lower vegetation cover and litter in RNE. On the one hand, in RNE with low vegetation cover the input of carbon sources such as litter was low and soil erosion was serious, resulting that LOC (DOC, EOC, POC) content was low and also easily lost with water and soil runoff. On the other hand, non-labile organic carbon not easily lost with water and soil runoff remained in soil and made the SOC content gradually increase. On the contrary, LOC (DOC, EOC, POC) in RE with high vegetation and litter cover input more and lost less with the protection by vegetation and litter [51]. Therefore, LOC/SOC (DOC/SOC, EOC/SOC, and POC/SOC) in RNE were lower than that in RE.

In the 10–20 cm soil layer, DOC/SOC, MBC/SOC, EOC/SOC, and POC/SOC were higher in RNE than in RE. This might be because soil LOC (DOC, MBC, EOC, POC) protected by vegetation cover was lost less [63], and thus had a relatively high content,

which led to correspondingly higher LOC/SOC. In addition, with the continuous increase of carbon sources in leaf litter and roots and the accumulation of non-labile organic carbon, the SOC content increased more and more, leading to the lower LOC/SOC. Therefore, compared with RNE, LOC/SOC (DOC/SOC, MBC/SOC, EOC/SOC, and POC/SOC) in RE was lower in 10–20 cm soil layer.

In addition, soil DOC/SOC and EOC/SOC increased with soil depth, which might also be related to the protection of soil LOC fractions such as DOC and EOC by the soil layer. which was in agreement with Pang et al. [9].

4.3. Relationship between SOC, Its Fractions, and Environmental Factors

Litter is an important source of SOC [1]. In this study, litter input was positively correlated with SOC and its fractions, and the content of SOC and its fractions increased with leaf litter input, which was in agreement with Wang and Feng et al. [14,46].

A significant negative correlation usually exists between SOC and soil BD; the higher the SOC content, the lower the soil BD [44]. This is because under the condition of high SOM, soil microbial activity is vigorous and the root system is developed, which leads to the increase in soil porosity and the corresponding decrease in soil BD [64]. However, no significant relationship was found between SOC, its fractions, and soil BD, suggesting that the time of vegetation restoration was limited and the influence of vegetation restoration on soil BD changed little.

SOC and its fractions were significantly positively correlated with SOM, TN, AN, TP, and AP in soil, which might be because those plants grew better, biomass accumulated more, and carbon sources such as litter and roots input more, in environments with higher SOM, nitrogen and phosphorus nutrients, and thus SOC and its fractions increased more correspondingly. In addition, the increase of SOC and its fractions could promote microbial metabolic activities and enzyme activities, further decomposed more organic matter and produced more carbon, nitrogen and phosphorus nutrients. Therefore, SOC and its fractions had positive correlations with SOM, TN, AN, TP, and AP, which was in agreement with Pang et al. [9].

Soil C/N ratio affects microbial organic matter decomposition. When the soil C/N ratio > 25:1, microbial organic matter decomposition is limited. In contrast, a soil C/N ratio < 25:1 is beneficial for microbial organic matter decomposition [65,66]. Xia et al. [67] believe that it is beneficial for the microbial decomposition of SOC when the soil C/N ratio is lower than 25:1. By comparing the ratio of soil carbon to nitrogen and the decomposition rate of organic matter in four land use types, they found that soil C/N in wetland (10.9–13.9) was the lowest, and the decomposition rate of lignin was the fastest. In this study, the soil C/N ratio (<15:1) in different vegetation types was small, which indicated that organic matter decomposition was not restricted. With the input of more carbon sources from leaf litter, SOC and its fractions obtained by microbial decomposition correspondingly increased, thereby rapidly releasing nitrogen, which was used during the growth of plants and microorganisms, resulting in more input of carbon sources from leaf litter and a corresponding increase in the C/N ratio. This might be the reason why SOC and its fractions were significantly positively correlated with the C/N ratio.

The correlation coefficient between SOC, its fractions, and soil moisture was small, but still positively correlated, indicating that soil moisture might affect organic matter decomposition by affecting the biological activity of microbial decomposers. Appropriate soil moisture could promote the biological activity of microbial decomposers, while too low or too high soil moisture content would change the community structure of soil microorganisms, inhibit the activities of soil microorganisms and enzymes, and reduced the decomposition rate of soil organic matter [68]. SOC generally has a negative correlation with soil pH [69]. However, the results were inconsistent as SOC and its fractions were positively correlated with soil pH. The reason might be that organic matter decomposition in the vegetation restoration area produced more substances with low acidity, such as weakly acidic phenols [70], and the highly acidic soil from the degraded red soil area in

Leizhou Peninsula was diluted to increase the pH. Substances produced by organic matter decomposition and their pH need further study.

Soil enzymes produced by microbes play a key role in biochemical functions of organic matter decomposition and nutrient cycling [71]. The enzymes cellulase, sucrase, CAT, and β-glucosidase in the soil carbon cycle play important roles in organic matter decomposition reactions [72,73]. SOC and its fractions had a significant positive correlation with soil enzyme activities. This might be because the input of organic carbon nutrients promoted the reproduction and biological activity of microbial decomposers, thus further improving enzyme activities, decomposing more organic matter, and producing more SOC and its fractions [74]. Therefore, SOC and its fractions had a positive correlation with the activities of cellulase, sucrase, CAT, and β-glucosidase.

No significant correlation was found between SOC, its fractions, and microbial richness, indicating that the total number of microbial species was not mainly affected by carbon nutrient resources and remained relatively stable when carbon nutrient resources were either abundant or insufficient [75]. However, SOC and its fractions were negatively correlated with microbial diversity, which was inconsistent with the results obtained by Constancias and Dequiedt et al. [76,77], indicating that SOC had a positive correlation with microbial species diversity. The distribution of microbial richness might have been uneven because of the influence of carbon nutrient resources. This was when carbon resources were abundant. For example, in ES, environment-adaptive microorganisms such as organic decomposers multiplied rapidly and even inhibited reproduction in other species [78], leading to an uneven distribution of species, large difference in relative abundance, and low diversity. However, when the nutrient resources were insufficient, each microbial species still maintained a certain number under resource stress, with a small difference in relative abundance, high uniformity, and great diversity, which was in agreement with Wu and Naveed et al. [79,80].

5. Conclusions

Planting Eucalyptus could effectively promote the accumulation of organic carbon nutrients in severely degraded soil in Leizhou Peninsula. In combination with shrubs (ES), the Eucalyptus plantation had higher SOC, EOC, DOC, MBC, and POC than the other vegetation restoration types. By correlation and SEM analyses, enzyme activity associated with microbial metabolism was a direct driving force of SOC and its fractions, and the activity of each studied soil enzyme had a significant positive correlation with SOC and its fractions. By affecting microbial characteristics and enzyme activities, the leaf litter carbon source input and soil properties were indirect driving forces affecting SOC and its fractions. Leaf litter cover and biomass and soil properties, such as SOM, SOC, TN, AN, TP, and AP, were positively correlated with SOC and its fractions. SOC and its fractions had no significant relationship with microbial richness but a significant negative correlation with microbial diversity. Therefore, soil microorganisms enhancing enzyme activities is a direct driver of carbon cycling. The vegetation restoration strategy focusing on the restoration of soil microbial community may promote soil carbon cycling, improve the quality of degraded soil, and should be advocated. Eucalyptus plantations could effectively improve the soil microorganism's activity and speed up SOC sequestration in areas where soil is seriously degraded, and natural vegetation recovery is difficult.

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