



# Vegetation Restoration Alleviated the Soil Surface Organic Carbon Redistribution in the Hillslope Scale on the Loess Plateau, China

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The redistribution of soil organic carbon (SOC) in response to soil erosion along the loess slope, China, plays an important role in understanding the mechanisms that underlie SOC's spatial distribution and turnover. Consequently, SOC redistribution is key to understanding the global carbon cycle. Vegetation restoration has been identified as an effective method to alleviate soil erosion on the Loess Plateau; however, little research has addressed vegetation restoration's effect on the SOC redistribution processes, particularly SOC's spatial distribution and stability. This study quantified the SOC stock and pool distribution on slopes along geomorphic gradients in naturally regenerating forests (NF) and an artificial black locust plantation (BP) and used a corn field as a control (CK). The following results were obtained: 1) vegetation restoration, particularly NF, slowed the migration of SOC and reduced the heterogeneity of its distribution effectively. The topsoil SOC ratios of the sedimentary area to the stable area were 109%, 143%, and 210% for NF, BP, and CK, respectively; 2) during migration, vegetation restoration decreased the loss of labile organic carbon by alleviating the loss of dissolved organic carbon (DOC) and easily oxidized organic carbon (EOC). The DOC/SOC in the BP and NF increased significantly and was 13.14 and 17.57 times higher, respectively, than that in the CK ( $p < 0.05$ ), while the EOC/SOC in the BP and NF was slightly higher than that in the CK. A relevant schematic diagram of SOC cycle patterns and redistribution along the loess slope was drawn under vegetation restoration. The results suggest that vegetation restoration in the loess slope, NF in particular, is an effective means to alleviate the redistribution and spatial heterogeneity of SOC and reduce soil erosion.

**Keywords:** vegetation restoration, soil organic carbon stability, hillslope, soil erosion, Loess Plateau (China)

## INTRODUCTION

Soil is considered the most significant terrestrial carbon sink. It is a critical factor in the regulation of the global carbon cycle, as well as in the supply of pivotal ecosystem services (Muñoz-Rojas et al., 2016; Pereira et al., 2018; Brevik et al., 2020). Soil organic carbon (SOC) is the amount of organic carbon contained in the soil fraction and contributes to a variety of important biological, physical, and chemical functions (Muñoz-Rojas et al., 2016; Willaarts et al., 2016; Wiesmeier et al., 2019;

Pereira et al., 2020). SOC's depletion has a negative influence on water storage capacity, soil fertility, and the supply of other significant ecosystem services, such as climate regulation, and is therefore a major factor that leads to soil degradation (Kiani-Harchegani and Sadeghi, 2020). In water-limited ecosystems, vegetation restoration is one of the options to prevent land degradation and soil erosion (Yu et al., 2016; Shi et al., 2019a). Ongoing vegetation restoration and climate change processes are having a far-reaching effect on soil carbon stocks, which creates an imbalance in carbon input/output ratios and results frequently in net releases back into the atmosphere (Haigh et al., 2019; Petrakis et al., 2020; van der Bank and Karsten, 2020). SOC is the most susceptible to changes in site conditions and is therefore the target of most evaluations (García-Díaz et al., 2016; Yeasmin et al., 2020).

In past years, numerous estimates of SOC stocks have been conducted at multiple scales (from slope to watershed, regional and global), using different approaches (Abdalla et al., 2018; Álvaro-Fuentes et al., 2014; Grebliunas et al., 2016; García-Díaz et al., 2018; Shi et al., 2019b; Rodrigo-Comino et al., 2020). Quantitative assessments of the redistribution of SOC along geomorphic gradients and the processes involved have become increasingly important in a changing climate (Bloom et al., 2016; Yu et al., 2019a; Olson and Gennadiev, 2020). At the same time, the storage of SOC showed significant differences within ecological units because of the effect of such local factors as soil properties, topographic conditions, soil depth, and land use and management (Novara et al., 2019). Among these, topography is one of the five major soil surface formation factors (Jenny, 1994). Topography affects soil erosion and thus affects SOC's spatial distribution either directly or indirectly (Sun et al., 2010; Rodrigo-Comino et al., 2016, 2017; Cagnarini et al., 2019; Cerdà and Rodrigo-Comino, 2020). Several studies have demonstrated the effects of topography and soil erosion on SOC's distribution (Beguería et al., 2015). For example, a previous study reported a close relationship between soil erosion and SOC content and indicated further that the SOC content is generally higher in a slope's middle and lower reach than in the upper reach (Sanderman and Chappell, 2013; Hancock et al., 2019). A typical hill slope can be divided into a stable area, eroding area, and sedimentary area according to its position and gradient on the slope (Wang et al., 2014a; Wang et al., 2017). Topography affects the stable area less, but the SOC in the eroding area will continue to migrate toward the sedimentary area, where it will accumulate (Doetterl et al., 2016). At the same time, the slope system also affects the composition and stability of SOC (Wang et al., 2014b; Wiaux et al., 2014). In some simulations in hillslope plots, the distribution of labile organic carbon varied markedly along slopes (Berhe and Torn, 2017), and most followed the trend: sedimentary area > stable area > eroded area (Doetterl et al., 2012; Patton et al., 2019; Wang et al., 2019). However, current research on the distribution of the SOC in the extension of slopes focuses primarily on agricultural land or grassland (Kirkels et al., 2014; Doetterl et al., 2016; Li et al., 2019). Vegetation restoration is recognized widely as an effective way to enhance SOC content and control soil erosion (Kim and Kirschbaum, 2015; Xin et al., 2016; Hancock et al., 2019). Therefore, it seems likely that vegetation restoration may also affect the SOC redistribution process in areas with complex terrain.

The Chinese Loess Plateau covers approximately  $64 \times 10^4 \text{ km}^2$ , lies in the semiarid zone of China, and is characterized by thick (50–300 m), yet highly erodible soil (Feng et al., 2013). Hundreds of years of intensive cultivation and severe erosion have incised the plateau and thus fragmented the vast flat area into tableland and slopes, with notable depositions in valley bottoms (Wang et al., 2017; Yu et al., 2019b). To alleviate soil erosion, large-scale ecological restoration efforts have been implemented in the Loess Plateau, the most notable example of which is the Grain for Green Project (GGP) that was initiated in the 1980s (Feng et al., 2013; Yu et al., 2020a). These projects have improved vegetation restoration greatly and affected SOC sequences and the carbon cycle on the Loess Plateau (Chang et al., 2011; Ran et al., 2013; Wang et al., 2017). However, systematic investigations of the results of vegetation restoration on SOC redistribution and its stability have not been reported to date. Particularly, the topographic positions of SOC in the hilly-gully region on the fragmented Loess Plateau remain unknown.

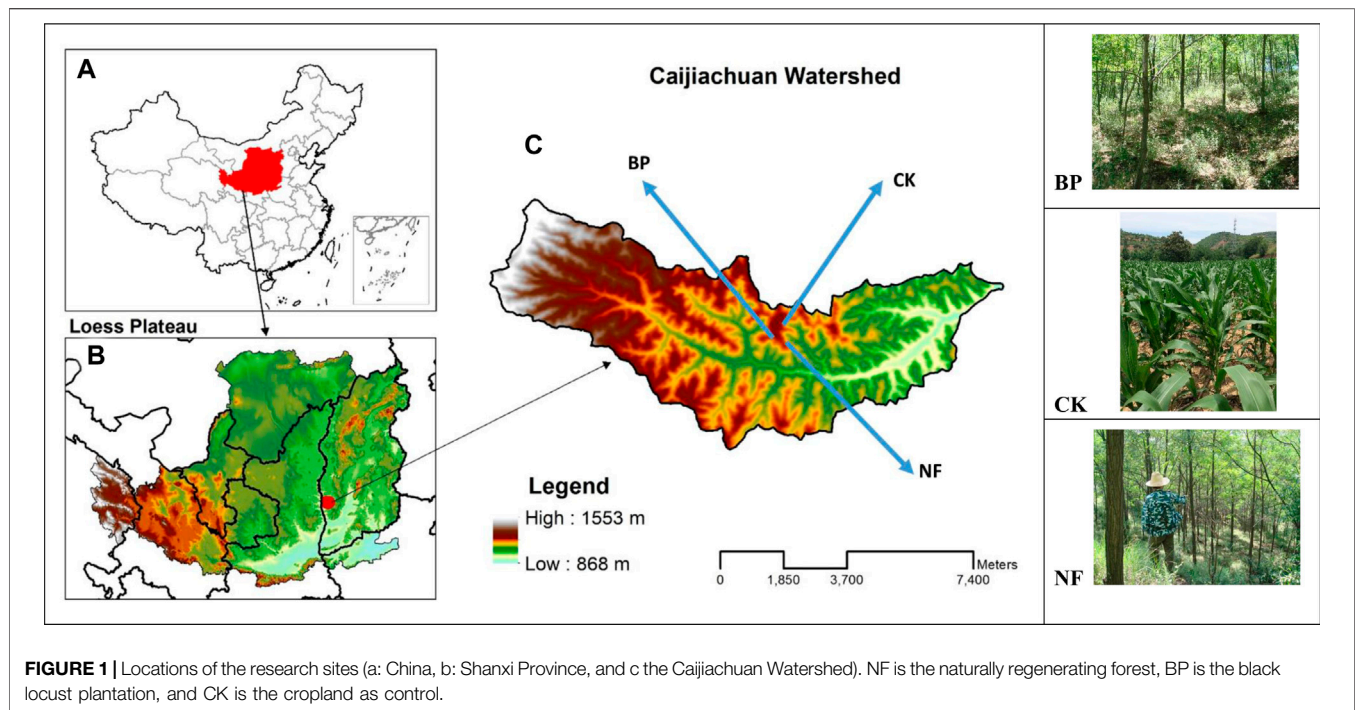
To offer new insights to fill this gap, hillslope positions and vegetation-induced changes in SOC in the first 0–30 cm were investigated on three different hillslopes of the loess hilly watershed where farmland has been transformed into forestland. Accordingly, this study's primary goals were to 1) detect changes in SOC at different soil depths (0–10, 10–20, and 20–30 cm) and different vegetation types at the hillslope scale and 2) assess the effects of vegetation species and topography on soil carbon stability during ecological restoration. Our study hypothesized that vegetation restoration alleviates the spatial heterogeneity of SOC by increasing organic input and decreasing soil erosion and the slow SOC mineralization or loss of unstable carbon.

## MATERIALS AND METHODS

### Study Area

As a typical loess gully area, the Caijiachuan Watershed ( $110^{\circ}27' - 111^{\circ}07'E$ ,  $35^{\circ}53' - 36^{\circ}21' N$ , elevation 868–1553 m) is located on the Loess Plateau in Ji County, Shanxi province, China (Figure 1). This area has a warm, temperate continental climate with an average mean temperature of  $10^{\circ}C$ , a mean duration of 2,563 h of sunshine, a frost-free period of 172 days, and a mean annual precipitation of 575.9 mm. The precipitation varies greatly between years and seasons and is concentrated largely between June and September of each year (Zhou et al., 2013). The study area is characterized by a deeply incised hilly-gully loess landscape. The soils are the result of a high wind-deposited loess process and can be classified as Haplic Luvisols (IUSS Working Group, 2006).

In general, soils are characterized by a high content of sand (45–60%) and silt (36–55%) material with certain variations depending on the hillslope position and previous land uses (Zhang et al., 2013b). The soil bulk density is approximately  $1.15 - 1.30 \text{ g cm}^{-3}$ , with a low organic matter content ( $5 - 15 \text{ g kg}^{-1}$ ). The principal forest types are naturally regenerating forests (NF) dominated by aspens (*Populus davidiana*) and oaks (*Quercus liaotungensis*) and reforested areas of black locust (*Robinia pseudoacacia*), Chinese pine (*Pinus*



**TABLE 1** | Basic information on the research site (Caijiachuan catchment, Shanxi Province, North China). DBH = diameter at breast height; canopy density is provided for the forested sites and coverage is provided for the corn farmland; “–” = not measured. The values presented are the means and SD in brackets.

Vegetation type	Slope length (m)	Slope angle (°)	Slope aspect	Altitude (m)	DBH (cm)	Tree height (m)	Tree density (hm <sup>-2</sup> )	Canopy density/coverage (%)
Black locust plantation	281	19	South	1 120	11.48 (0.26)	8.39 (0.40)	1864 (12)	84.6 (2.3)
Natural recovery forest	302	20	Southeast	1 040	10.96 (0.35)	6.68 (0.22)	1942 (15)	87.3 (5.1)
Corn farmland	278	18	South	1 120	—	—	—	84.5 (1.6)

*tabulaeformis*), and cypresses (*Platyclusus orientalis*). All forests were planted in 1990 as part of the GGP.

## Experimental Design

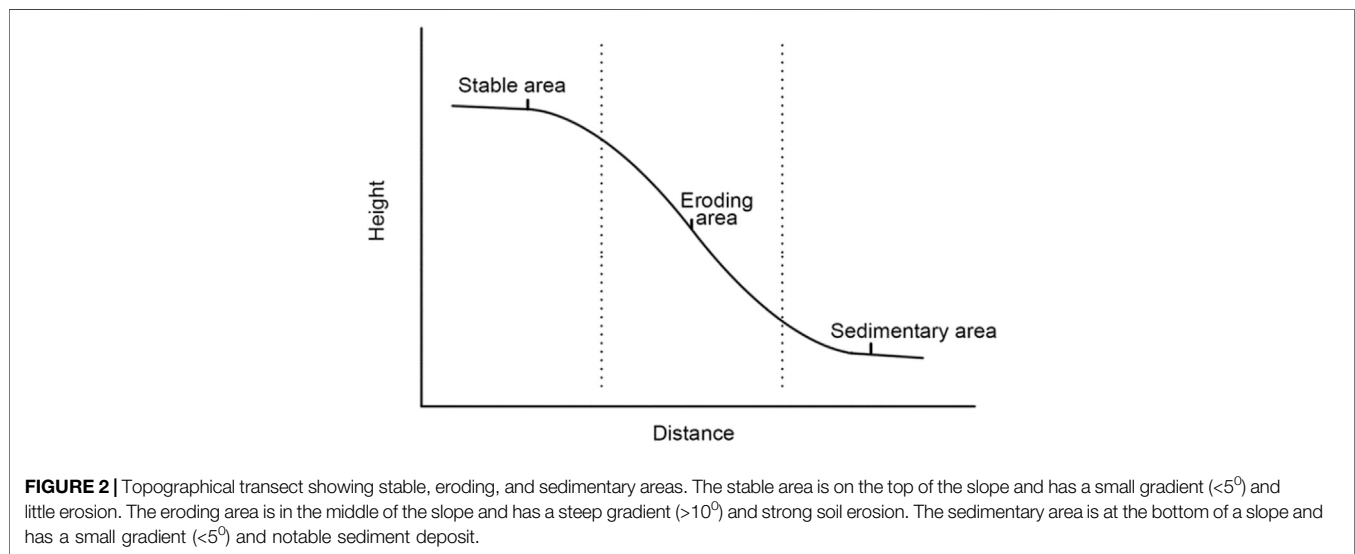
Three typical hillslopes characterized by similar landforms (considering the gradient, aspect, and length fully) and different vegetation types (Table 1) were selected, representing 1) a black locust plantation (BP), 2) NF, and 3) a corn field as a control (CK). Both the BP and NF were converted from corn field in 1990, and the main tree species in the NF was secondary *Quercus aliena* Bl. Both the BP and CK are located in the same gully at similar elevations (1120 m a.s.l.). The NF is located in an area affected by a gully of approximately 4 km southeast and an elevation of approximately 1040 m a.s.l. Corn fields in this area adopt the traditional cultivation model with few management measures, such as ploughing and fertilization.

In this study, the hillslopes were divided into three erosional areas based on the slope gradient and soil erosion conditions (Figure 2). Specifically, the stable area was defined as the area at the shoulder of a slope with a low gradient (<50) and light soil

erosion marks. The eroding area was defined as the area in the backslope with a steeper gradient (>100) and clearer soil erosion signs. Finally, the sedimentary area was defined as the area at the footslope with a lower gradient (<50). Because the eroded material from the eroding areas is used to accumulate in the sedimentary parts, the soils therein consist largely of a mixture of sediment setting on loess parent materials in deeper layers (Doetterl et al., 2012; Doetterl et al., 2016; Wang et al., 2017).

## Field Sampling

In mid-August, 2017, three plots of 10 × 10 m (separated by at least 10 m) were established representing the typical erosional area of each typical hillslope. Detailed site conditions (including elevation, slope length, angle, and aspect), as well as a vegetation inventory, were conducted in each plot. Five sampling points were set randomly and soil samples were collected at 10 cm intervals from a depth of 0–30 cm using a cylindrical soil driller (4 cm diameter and 20 cm long). Soil from corresponding layers was mixed to form one soil composite



sample. Five replicate soil samples were collected in each plot, and 135 soil samples were collected in total. Each soil sample was divided evenly into two parts after visible roots and other impurities were removed, and one was naturally air-dried, while the other was refrigerated at  $4^\circ\text{C}$  until further use.

### Laboratory Analysis

The air-dried soil was passed through a 0.2 mm sieve to ensure complete removal of gravel. The SOC content was determined by the potassium dichromate external heating method (Bao, 2000). The dissolved organic carbon (DOC) content was analyzed as follows: 10 g of a soil sample was added to a triangular flask with 40 ml of distilled water. The sample was shocked and leached for approximately 30 min at room temperature after 10 min of high-velocity centrifugation (6000 r/min at  $4^\circ\text{C}$ ). The supernatant obtained was filtered through a  $0.45\ \mu\text{m}$  filter into separate vials and the extracts were analyzed for DOC using a total organic carbon analyzer (Multi N/C 3100, Analytik Jena AG, Thuringia, Germany). The level of easily oxidized organic carbon (EOC) in the organic phases was measured using 333 mmol/L of  $\text{KMnO}_4$  by shaking for 1 h, centrifugation for 5 min at 4000 g, diluting 10 times with deionized water, and using a spectrophotometer (AQ8100, Thermo Scientific™, MA) to measure the absorbance at 565 nm (Von Lützwow et al., 2007). The  $\text{KMnO}_4$  standard curve and calculation method were based on Blaire et al. (1995) report.

### Statistical Analysis

An analysis of variance (ANOVA) was used to analyze vegetation restoration's effects on SOC content, DOC/SOC, and EOC/SOC between forest types, slope areas, and soil depth ( $p < 0.05$ ). The means for each vegetation type in Table 1 were calculated by averaging the values of nine plots within the same slope, and the means in the figures for each area were calculated by averaging the values from three replicated plots in the corresponding soil layers. All data analyses were performed using SPSS v. 23.0 (SPSS Inc. 2016; NC) and R software v. 3.6 (R Development Core Team, 2012; R Project for Statistical Computing, Vienna, Austria).

## RESULTS

### Effect of Vegetation Restoration on SOC Content

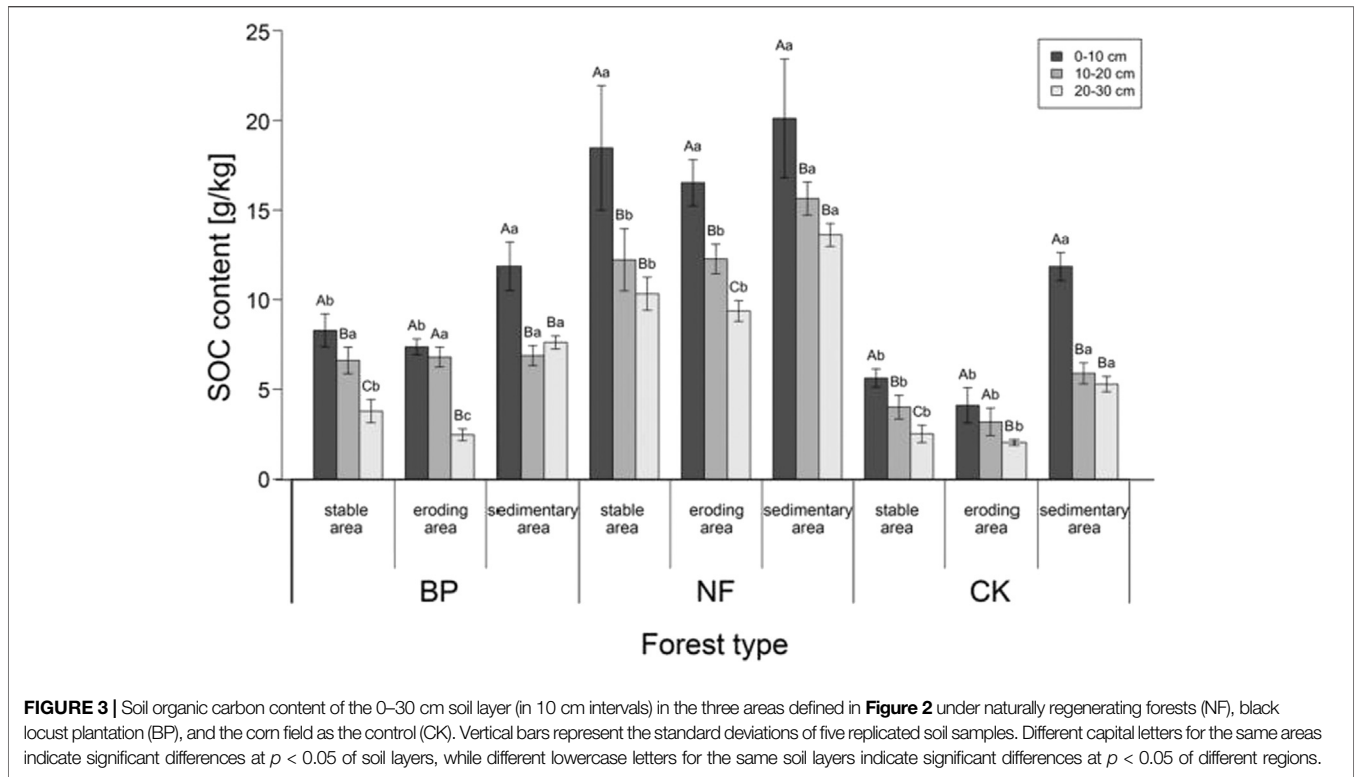
Figure 3 shows that the SOC content increased significantly in response to vegetation restoration ( $p < 0.05$ ). For the BP, the average SOC content was 6.85 g/kg, 1.38 times higher than that of the CK. For NF, the average SOC content was 14.28 g/kg, 2.88 times higher than that of the CK. The SOC content in the same area decreased significantly with increasing soil depth ( $p < 0.05$ ).

The SOC content followed the same distributions throughout the three vegetation types: sedimentary area  $>$  stable area  $>$  eroding area. However, the range of the changes observed was smaller after vegetation restoration. The ratio of the SOC content in the sedimentary to eroding areas in the CK was 247.0%, which decreased to 158.4% and 129.3% in response to the BP and NF, respectively. The change in the SOC distribution along the slope was most obvious in the 0–10 cm soil layer following vegetation recovery. In BP and CK, the SOC content in the deposition area was significantly higher than that in both the stable and eroding areas ( $p < 0.05$ ). However, in NF, no significant difference was found in the surface soil between the three areas tested ( $p < 0.05$ ). In the 20–30 cm soil layer, the SOC contents of NF, BP, and CK were all significantly higher in the deposition area than in the stable area and the content in the stable area was significantly higher than that in the eroding area ( $p < 0.05$ ).

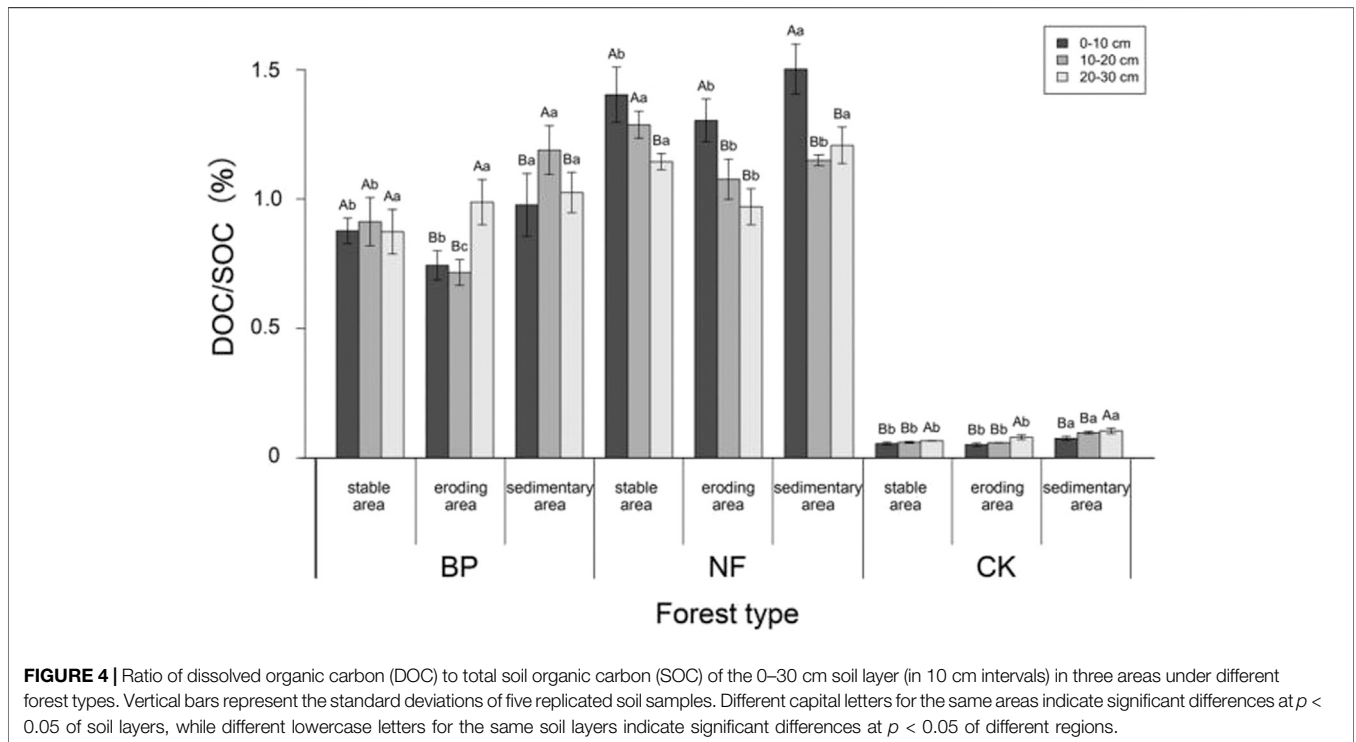
### Effects of Vegetation Restoration on SOC Stability

#### Effects on Dissolved Organic Carbon

The proportion of DOC in SOC increased significantly ( $p < 0.05$ ) after vegetation restoration (Figure 4). The DOC/SOC of the BP and NF was 0.92% and 1.23%, respectively, 13.14 times and 17.57 times higher, respectively, compared to the CK



**FIGURE 3 |** Soil organic carbon content of the 0–30 cm soil layer (in 10 cm intervals) in the three areas defined in **Figure 2** under naturally regenerating forests (NF), black locust plantation (BP), and the corn field as the control (CK). Vertical bars represent the standard deviations of five replicated soil samples. Different capital letters for the same areas indicate significant differences at  $p < 0.05$  of soil layers, while different lowercase letters for the same soil layers indicate significant differences at  $p < 0.05$  of different regions.

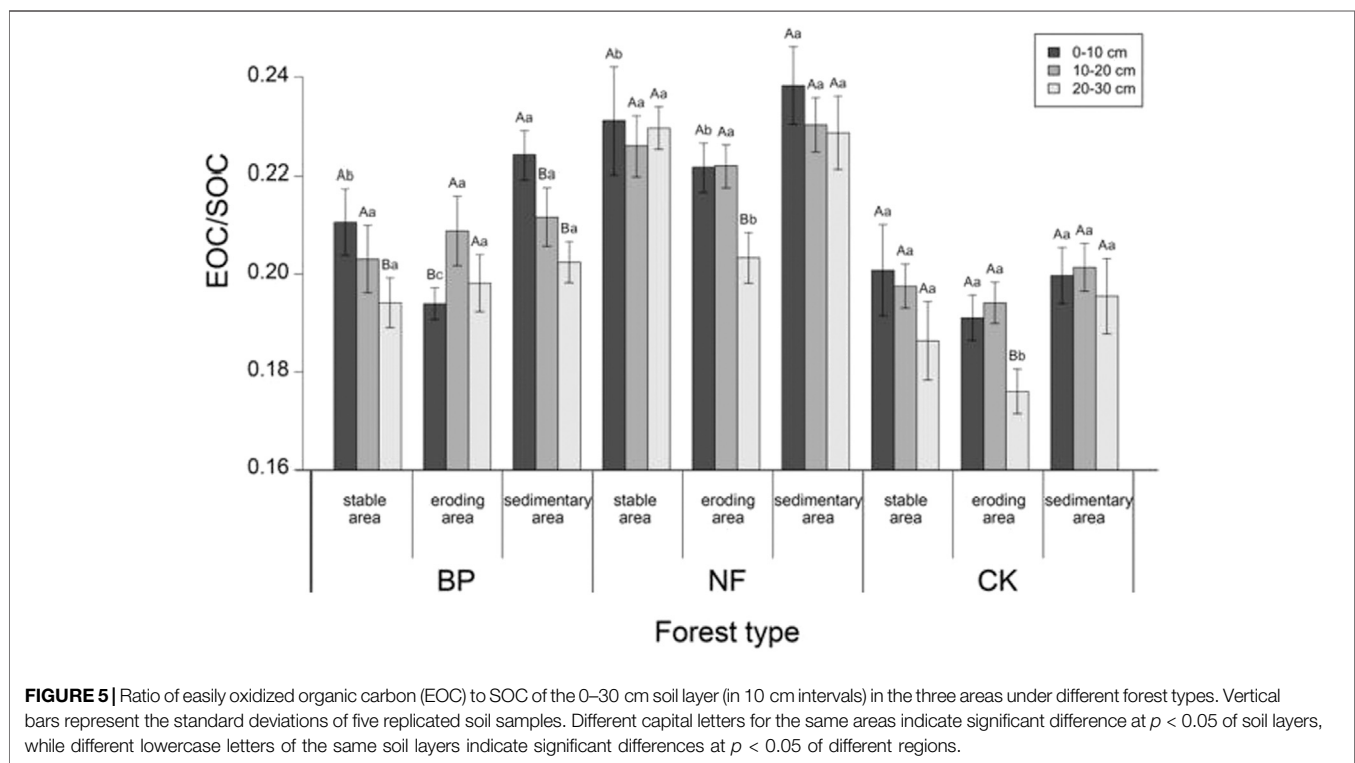


**FIGURE 4 |** Ratio of dissolved organic carbon (DOC) to total soil organic carbon (SOC) of the 0–30 cm soil layer (in 10 cm intervals) in three areas under different forest types. Vertical bars represent the standard deviations of five replicated soil samples. Different capital letters for the same areas indicate significant differences at  $p < 0.05$  of soil layers, while different lowercase letters for the same soil layers indicate significant differences at  $p < 0.05$  of different regions.

(0.07%). The DOC/SOC differed significantly in different soil layers; however, no consistent pattern of change was identified ( $p < 0.05$ ). In the BP, the DOC fluctuated with the soil layer,

but without apparent regularity; in the same area of NF, DOC/SOC decreased with increasing soil depth but increased in the CK.





**FIGURE 5 |** Ratio of easily oxidized organic carbon (EOC) to SOC of the 0–30 cm soil layer (in 10 cm intervals) in the three areas under different forest types. Vertical bars represent the standard deviations of five replicated soil samples. Different capital letters for the same areas indicate significant difference at  $p < 0.05$  of soil layers, while different lowercase letters of the same soil layers indicate significant differences at  $p < 0.05$  of different regions.

Compared to the CK, the increasing extent of DOC/SOC in the sedimentary area decreased significantly after vegetation restoration ( $p < 0.05$ ). In the BP, NF, and CK, the ratios of DOC/SOC in the deposition areas were 1.29, 1.15, and 1.50 times that in the eroding area. For the BP, the DOC/SOC in the sedimentary area in the 0–10 cm and 10–20 cm soil layers was significantly higher than that in the stable and eroding areas ( $p < 0.05$ ). However, in the 20–30 cm soil layer, no significant difference was found between the deposition and eroding areas ( $p < 0.05$ ), and in NF, no significant erosion or accumulation of DOC in a specific area was observed ( $p < 0.05$ ). In the CK, the DOC/SOC of each soil layer in the deposition area was significantly higher than that in both the stable and eroding areas ( $p < 0.05$ ).

### Effects on the Easily Oxidized Organic Carbon

Figure 5 shows that the increase in EOC/SOC following vegetation restoration was not significant ( $p < 0.05$ ). The average EOC/SOC values of the BP and NF were 20.52% and 22.56%, respectively, approximately 1.06 and 1.16 times higher than that of the CK (19.38%). The EOC/SOC in both the stable and sedimentary areas decreased with increasing soil depth; however, no regular change was identified in the eroding area. No significant difference was found between different soil layers in any of the three regions ( $p < 0.05$ ).

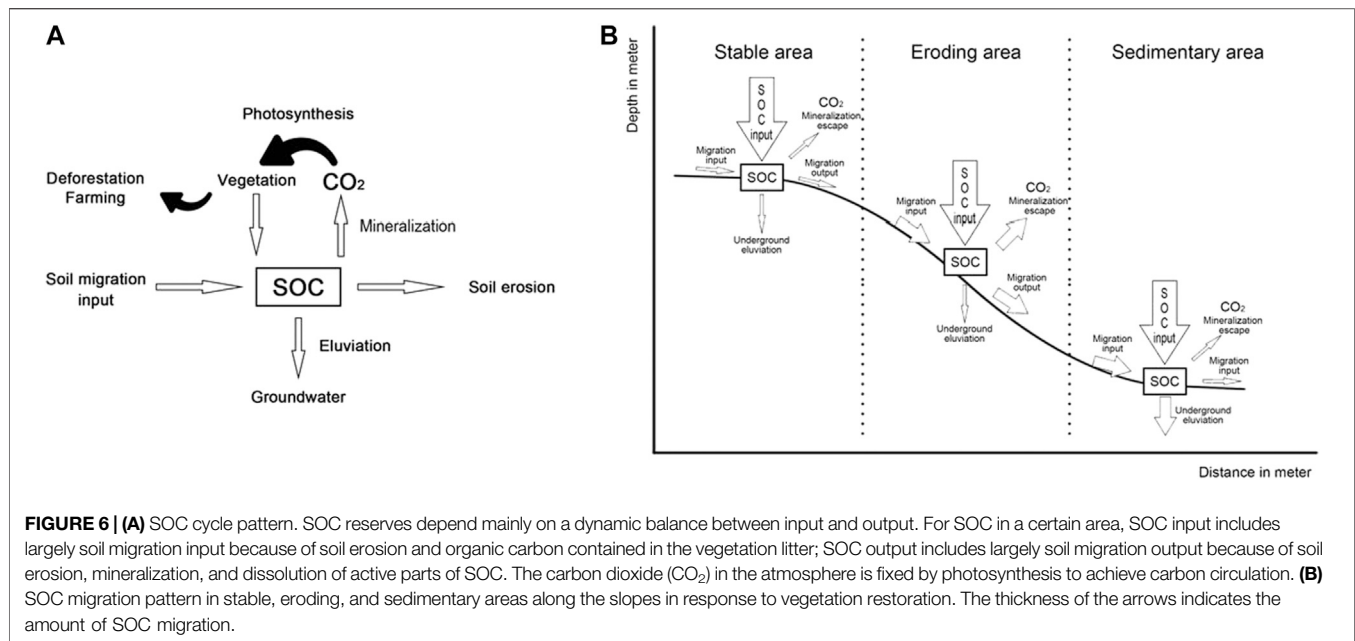
Among the three vegetation types, the EOC/SOC ratio was slightly, but not significantly, lower in the eroding area than the stable area, and the EOC/SOC in the deposition area was identical to that in the stable area ( $p < 0.05$ ). Vegetation restoration did not affect this result significantly ( $p < 0.05$ ). The ratios of EOC/SOC in the sedimentary areas of the BP, NF, and CK were 1.06, 1.08, and 1.06 times higher, respectively, than that in the eroding area. The

EOC/SOC of the 0–10 cm layer in the BP and NF was significantly higher than that in the eroding area ( $p < 0.05$ ); however, in the 10–20 cm and the 20–30 cm soil layers, there were no significant ( $p < 0.05$ ) differences among the three areas. The CK showed no significant difference between soil layers ( $p < 0.05$ ).

## DISCUSSION

### Effect of Vegetation Restoration on SOC Migration at the Soil Surface (0–30 cm)

Soil erosion and SOC deposition along hillslopes can lead to spatial redistribution of SOC, i.e., the removal of soils that are rich in organic carbon from source hillslopes (shoulder and backslope) and their accumulation at the footslope (Wang et al., 2017). It has been confirmed that the SOC content in the cultivated areas of the Loess Plateau had the following distribution pattern: sedimentary area > stable area > eroded area (Wang et al., 2014a; Li et al., 2019). In our study, considering the first 30 cm, the SOC distribution along the hillslope after vegetation restoration followed a similar trend. However, the ratio of SOC content in the sedimentary area to the eroded area decreased significantly ( $p < 0.05$ ). This could indicate that vegetation restoration reduced the migration of SOC effectively in some areas. Further, while vegetation recovery increased the SOC input, it decreased soil erosion effectively (Wang et al., 2011; Qin et al., 2014). This could also explain the fact that the SOC among these three areas of the 0–10 cm soil layer after vegetation recovery decreased significantly; at the same time, the change was not significant in the 20–30 cm soil layer ( $p < 0.05$ ). Further, in NF, the surface SOC did not differ



significantly between different areas, and thus, NF could be considered to perform better in reducing SOC heterogeneity. This could be the case because the BP vegetation types were relatively simple over time and their diversity recovery was slower than that of NF (Zhang et al., 2017). This led indirectly to a low root density in the surface soil and a small cumulative amount of litter on the surface (Ceccon et al., 2011; Vos et al., 2019). Therefore, the resulting soil erosion-inhibiting effects were weaker in the BP than in NF.

With respect to the sampling depth, we cannot assume that the SOC concentration below 30 cm was unimportant. Therefore, future research should be devoted to assessing the effects that the tree roots, root secretions, and the microorganisms associated with them may affect, which, subsequently, enrich the SOC pool themselves. Secondly, it would be possible to observe whether dissolved SOC migrates deep into the soil. Finally, soil organisms have a very large effect (direct and indirect) on the distribution of SOM in soil (also at a depth of over 30 cm). This is particularly common in soils developed on loess and is associated particularly with earthworms (anecic earthworms) (Lavelle, 1988).

## Effect of Vegetation Restoration on the Stability of SOC on Hillslopes

It is accepted generally that DOC, microbial biomass carbon, EOC, and particulate organic carbon are the most active parts of SOC (Von Lützow et al., 2007; Wang et al., 2014b). These indices reflect small changes in the soil before it experiences changes in the total organic carbon (Bloom et al., 2016; Yu et al., 2020b). EOC and DOC were considered the most sensitive indicators of labile organic carbon in response to changes in vegetation areas (Haynes, 2005; Zhang et al., 2013a). Hence, EOC/SOC and DOC/SOC were chosen to evaluate vegetation restoration's effects on SOC stability.

Generally, DOC originates from plant litter, microbial decomposition, and root exudation (Franzuebbers, 2002). Although the DOC content is very low, it has strong mobility in the soil and therefore is considered one of the main forms of soil nutrient loss (Perakis and Hedin, 2002; Zhang et al., 2003). In this study, the increment in DOC/SOC in the sedimentary area was significantly lower in response to vegetation restoration, particularly for NF compared to the CK ( $p < 0.05$ ). This showed that vegetation restoration could slow the migration of DOC to some extent. This could be because of the higher litter inputs in NF and BP than that in the CK, and decomposed litter add DOC to the surface soil. Moreover, litter's runoff interception function can reduce the migration of DOC (Ma et al., 2016b). EOC refers to the part of SOC that can be oxidized by 330 mmol/L potassium permanganate (Neff and Asner, 2001; Von Lützow et al., 2007). In NF, BP, and CK, the distribution trends of EOC/SOC along the slopes were fundamentally identical: EOC/SOC was identical in the stable and sedimentary areas and slightly exceeded that in the eroded area. No significant ( $p < 0.05$ ) enrichment trend in EOC was found in the sedimentary area, which Doetterl et al. (2012) also reported for cropland in central Belgium. It has been suggested that most of the EOC may have been mineralized during the migration process (Zhou et al., 2005; Ma et al., 2016a). In the 0–10 cm layer in both NF and BP, the EOC/SOC ratios in the stable and the sedimentary areas were significantly higher ( $p < 0.05$ ) than that in the eroded area. However, there was no significant difference among the three areas in the CK ( $p < 0.05$ ). This indicated that vegetation restoration could reduce topsoil mineralization during erosion to some extent.

Several studies have concluded that the SOC is more active in the foothills than in other areas (Doetterl et al., 2012; Zhang et al., 2019), although naturally, anthropogenic effects can introduce some variability in this final result. However, this study did not find any significant enrichment of labile organic carbon in the sedimentary area. This may be because the active components in

organic carbon have been mineralized already during the migration process, or they may have migrated to deeper soil layers because of leaching (Wang et al., 2015; Kelleway et al., 2016).

This research concerns soil, and therefore in the future, more aspects related to the lack of clear information about the way soil properties affect (strongly in some cases) the process of soil organic matter (SOM) mineralization and its transformation should be included. For example, the potential presence of redox traces in soil (which is likely in soils at the bottom part of the slope) would indicate the contribution to the SOM mineralization of conditions other than simply erosion or vegetation. Another soil process could be related to soil oxygenation conditions and thus the conditions for SOM mineralization as well. In this research, we did not include information about the activity of soil fauna, but it could be an interesting line of future research because even earthworms can change the distribution of SOM (and also SOC) in soil significantly.

## Schematic Diagram of SOC Cycle Patterns on Hillslopes

Since Doetterl et al. (2012); Doetterl et al. (2016) proposed agricultural land slopes' effect on SOC content and its stability explicitly, several models and regional organic carbon estimates have introduced topographic factors (Bloom et al., 2016; Fissore et al., 2017; Patton et al., 2019). Therefore, a model for the process of SOC migration on the slope was proposed in this study. SOC reserves depend mainly on a dynamic balance between input and output (Bloom et al., 2016; Vos et al., 2019), as indicated in **Figure 6A**. According to the findings of this study, SOC also migrated and redistributed within the soil slope system, as shown in **Figure 6B**. In stable areas, topographic factors affected SOC less and the input and output along the slope were both very small. In the vertical direction, the litter vegetation produced increased the SOC input and improved the SOC activity to some extent. The activated SOC was mineralized and then either degassed in the form of carbon dioxide or continued to migrate to lower layers because of leaching. However, stable organic carbon is stored in the soil for a long period. In the eroded area, SOC will migrate downward together with the eroded soil because of the slope. Therefore, for a specific area, SOC input and output will increase simultaneously. In the vertical direction, the vegetation-induced organic carbon input remains largely the same as in the stable area; however, soil erosion will intensify the labile organic carbon's mineralization and leaching, thus causing organic carbon to decrease continuously during its downward migration. In the sedimentary area, the eroded soil is deposited and the SOC content increases in response. However, the primary component is stable organic carbon. The reason may be that most of the labile organic carbon either has been mineralized during the migration process or could not be enriched in the sedimentary area because of leaching. However, the CK's slope migration and conversion process differed notably from that of the BP and NF. On the one hand, the SOC input on arable land is relatively small and crop yield increases the SOC output, thus decreasing the total SOC on the slope (Von Lütow et al., 2006; Vos et al., 2019). On the other hand, because of the decreased coverage with surface litter and low content of labile organic carbon, a large

amount of SOC migrates downward from the eroded area because of soil erosion and finally deposits in the sedimentary area.

Finally, we agree strongly that erosion changes the soil and affects its morphology, properties, and taxonomic position. It cannot be assumed that the same soil will be everywhere, but we consider that although other soils occur in each of the transect sections studied, which is attributable to erosion and other processes in the past, as well as different water-air conditions in the soil, our results correspond to the most representative possible patterns according to the number of soil surface samples and low variability.

## CONCLUSION

To examine vegetation restoration's effects on SOC redistribution along a loessial hillslope, soil samples were collected from stable, eroding, and sedimentary areas of typical hillslopes with different vegetation types in the hilly-gully loess area of China. Our results demonstrated that, compared to croplands, the differences in SOC content among these three areas decreased in NF and the BP, and the proportion of labile carbon to total SOC increased significantly for DOC/COC, but not for EOC/DOC. We conclude that this could indicate that vegetation restoration in the typical Loess Plateau hillslopes (NF in particular) is an effective measure to alleviate SOC's redistribution and spatial heterogeneity and reduce soil erosion, which directly affects other ecosystem services. Therefore, the effect of vegetation recovery considering the vegetation type should be taken into account to better estimate the soil carbon storage and evaluate ecosystem services in the sloping areas of the Loess Plateau in China.

## 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

YL finished the data curation and formal analysis and wrote the original draft. TZ played a guiding role in conceptualizing the field experiment, review, and editing the manuscript. XL and XZ assisted in data analysis and sample collection.

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**Conflict of Interest:** Author XZ was employed by company The Third Construction Co., Ltd. of China Construction First Group.

The remaining 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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