Soil organic carbon (SOC) and soil aggregate stability as effected by returned farmland to forestland or grassland in the Loess Plateau Centre Gansu region of China

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Article

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Abstract

Land use change can significantly alter the proportion of soil aggregates, thereby influencing aggregate stability and distribution of soil organic carbon (SOC). However, there needed to be more research on the variations in the distribution of soil aggregates, aggregate stability, and SOC in soil aggregates following land use change from farmland (FL) to forest and grassland in the Loess Plateau region of central Gansu, China. The current research aimed to explore the dynamics of soil aggregates, aggregate stability, and SOC distribution in the Anjiagou watershed in the hilly and gully areas of the Loess Plateau in central Gansu, China. Six land use types (farmland (FL), abandoned cropland (ACL), *Medicago sativa* (MS), natural grassland (NG), *Picea asperata* Mast. (PA), *Platycladus orientalis* (L.) Franco (PO)) were selected as the research objects. By measuring the water-stable aggregates and SOC content of soil aggregates at 0–10 cm, 10–30 cm, and 30–50 cm soil depths, the composition, stability, and SOC characteristics of soil aggregates were analyzed. The results showed that the conversion of FL to forestland and grasslands significantly increased the content of aggregates > 5 mm, mean weight diameter (MWD), and geometric mean diameter (GMD) but decreased the content of aggregates < 0.25 mm. Compared with FL, the increases of MWD and GMD in the soil depth of 0–50 cm under PA, NG, MS, PO and ACL were 473.71% ~ 732.55%, 283.98% ~ 724.60%, 179.06% ~ 634.12%, 142.31% ~ 413.50%, 110.25% ~ 213.34% and 244.04% ~ 607.77%, 141.68% ~ 666.67%, 52.39% ~ 483.33%, 50.49% ~ 214.43%, 35.23% ~ 64.29% respectively. Compared with FL, after FL was returned to forestland and grasslands, SOC content in soil and aggregates decreased under ACL. In other forestland and grasslands, SOC contents in bulk soil, > 5 mm, 2–5 mm, 1–2 mm, 0.5-1 mm, 0.25–0.5 mm, and < 0.25 mm aggregates at the 0–50 cm soil depth increased by 20.75–125.87%, 14.50–163.64%, -11.86–118.18%, 9.65–150.95%, 38.28–126.49%, 51.26–165.87% and − 15.59–163.37%, respectively. After returning FL to forestland and grasslands, the contributions of aggregates with sizes of > 5 mm, 2–5 mm, 1–2 mm, 0.5-1 mm, 0.25–0.5 mm, and < 0.25 mm to the increase in SOC content in bulk soil were 104.74%, 7.86%, 4.76%, 6.23%, 5.37%, and − 21.97%, respectively. MWD and GMD were positively correlated with SOC content in aggregates of > 5 mm, 2–5 mm, and 1–2 mm, as well as in bulk soil and aggregates. Although SOC content in bulk soil and different particle size aggregates was significantly higher under NG and PA conditions than under MS and PO conditions, soil macroaggregate content, MWD, and GMD were higher under PO and NG treatments than under PA and MS treatments, indicating that soil structure was more reasonable. The ability to resist soil erosion was strongest under PO and NG treatments. Therefore, to improve soil and water conservation capacity and increase soil C sequestration in the Loess Plateau, converting FL to PO and NG may be the best choice for improving the ecological environment.

1. Introduction

Land use change is a crucial factor contributing to global climate perturbations, holding significant relevance for biogeochemical cycles on regional and global levels[1−3]. Reasonable land use change management can promote the accumulation of SOC and play a key role in mitigating global climate change[4,5]. SOC stock and soil structure are often used as key indicators of the extent of soil degradation or improvement resulting from land use change[6–8]. The change in land use directly affects SOC's content and distribution and indirectly affects SOC by influencing factors related to its formation and transformation[9]. The direction and quantity of SOC change during the process of land use change not only on the vegetation type before and after the change but also on the history, present situation, and land use management measures[10,11]. In addition, the amount of change in SOC also depends on climate conditions and the initial SOC before land use change[10]. Among them, the most important reason for global SOC loss was changes in land use patterns and management practices, followed by changes in environmental factors such as rising temperatures and precipitation[12,13].

The Loess Plateau region suffers from severe soil erosion[14] and a fragile ecological environment[15]. Severe soil erosion destroys the ecological environment and reduces soil quality[16], decreases soil C sequestration[17], and reduces the efficiency of limited precipitation utilization[18,19]. The Loess Plateau region has recently adopted land use adjustments to restore the ecology and protect against soil erosion. The main way was to restore vegetation[20,21]. In vegetation restoration, the accumulation and diffusion of SOC in aggregates have attracted much attention from scholars[22,23]. Since implementing the Green for Grain Project (GGP) on the Loess Plateau in 1999, By 2019, more than 330,000 km^2 of farmland had been converted to forest or grassland, with vegetation coverage from 31.6% in 1999 to 65% in 2017[14].

The SOC content in the soil exceeds the sum of global vegetation and atmosphere. Forest SOC pool, the world's largest soil C pool[24], accounts for about 73% of the global soil C pool. Its slight changes may cause significant changes in atmospheric CO_2 concentration, directly affecting the C cycle of terrestrial ecosystems and global C balance[5,15,25]. The sequestration of SOC can help alleviate the increase in atmospheric CO_2 content[26,27], as most agricultural soils were in a state of organic matter consumption under traditional cultivation. It can also improve soil fertility and ensure sustainable land use[28,29]. Climate change, soil type, land management measures, vegetation types, and their interactions all affect the turnover and stability of SOC[30,31]. Compared to total SOC, soil physical, chemical, and biological components with different stabilization mechanisms can better and faster reflect changes in soil quality when external conditions change[32]. Soil aggregates were the key to all C sequestration mechanisms[33], and SOC benefited the formation and stability of soil aggregates[34,35]. In turn, soil aggregates affect the decomposition of SOC and are an important mechanism for SOC sequestration[36]. The aggregation process of soil determines the degree of protection of SOC, and due to different protection mechanisms, the stability and retention time of SOC in macroaggregates and microaggregates were also different[37,38]. Researchers found that SOC rapidly decomposed as macroaggregates broke, suggesting that SOC's stability was highly dependent on physical protection by macroaggregates[39]. Macroaggregate promotes the formation of internal microaggregates, which is the primary mechanism for SOC accumulation and stabilization[40], microaggregates are important for the long-term stability of SOC[41]. Therefore, researching the relationship between the two will help reveal the physical protection mechanism of SOC[42,43].

While considerable research has delved into the stability of SOC and its interplay with soil aggregates[23,44,45]. However, there remains a notable gap in understanding the variations in soil aggregates' distribution, aggregate stability, and SOC following land use transitions from farmland to forest and grassland, especially in the Loess Plateau region of central Gansu, China. Thus, the current study was undertaken to investigate these dynamics comprehensively. Our research focused on a typical area of the Loess Plateau, aiming to provide robust theoretical foundations for land use type adjustments, soil C sequestration strategies, and soil fertility enhancements in the region. This study aimed to contribute insights into evaluating the ecological benefits of land use changes. The objectives were twofold: firstly, to elucidate the relationship between SOC storage and soil aggregates' stability in the study area, and secondly, to unveil the correlation between SOC and vegetation type and restoration time in the Loess Plateau region. It was hypothesized that land use change from farmland (FL) to forest and grassland in the Loess Plateau region of central Gansu, China, will lead to significant variations in the distribution of soil aggregates, aggregate stability, and SOC content. Specifically, transitioning to forest and grassland was expected to enhance SOC storage and promote the stability of soil aggregates due to increased vegetation cover and restoration efforts. The findings of this study will underscore the importance of vegetation restoration efforts in enhancing soil quality and C sequestration potential, thus contributing to sustainable land management practices and ecological benefits in the region.

2. Materials and methods

2.1. Study area

The study was carried out in the Anjiagou watershed of Dingxi City (35°33′–35°35′ N, 104°38′–104°40′ E, 1,900–2,250 m elevation), which was a small tributary of the Guanchuan River in the Zuli River system of the Yellow River Basin and a part of typical hilly-and-gully region of Loess Plateau, China (Fig. 1). The study area has a temperate semiarid zone climate, with a mean annual temperature of 6.3℃, an annual sunshine duration of 2,408.6 hours, a frost-free period of 141 days, and an average annual precipitation (more than 60% concentrated in July to September) of 427 mm[46]. The main soil types were loess and river saline soils[47], categorized as Calcaric Cambisol[48]. It features weak cohesion, high infiltrability, low water retention, and is prone to erosion[45]. Before the 1990s, to meet the increasing demand for food from the rapidly growing population, the native vegetation in the region was destroyed, resulting in severe soil erosion and land degradation. In the 1990s, "the Conversion of Farmland to Forests and Grasses Project" was officially launched to protect against soil erosion, and many farmlands were abandoned and replaced by artificial forests and grasslands[49]. *Picea asperata Mast.* (PA), *Platycladus orientalis (L.) Franco* (PO) and *Pinus tabuliformis Carrière* are common afforestation tree species in the local area. *Medicago sativa* (MS) was a perennial herbaceous plant with strong drought resistance and adaptation to poor soils, which was widely planted in the region[50]. Moreover, the dominant species in natural grasslands (NG) include *Leontopodium leontopodioides(Willd.)Beauv., Artemisia annua L., Picris hieracioides L..* The dominant species in abandoned cropland (ACL) include *Leymus secalinus (Georgi) Tzvelev., Stipa bungeana Trin., Plantago asiatica L., Setaria viridis (L.) P. Beauv.*

2.2. Experimental design and sampling

Sampling was conducted in July 2023 during peak vegetative growth and species richness. Six typical land use types were selected based on a thorough investigation of land use changes in the study area: farmland (FL), *Medicago sativa* (MS), *Picea asperata* Mast. (PA), *Platycladus orientalis* (L.) Franco (PO), abandoned cropland (ACL), and natural grassland (NG). These sites were chosen to represent diverse land use scenarios while ensuring similar geographical characteristics such as elevation, slope gradient, and parent soil material. The restoration times for *Medicago sativa*, *Picea asperata* Mast., *Platycladus orientalis* (L.) Franco, and abandoned cropland were 10 years, 28 years, 10 years, and 10 years, respectively. Maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) were the main crops before the evolution from farmland to forestland or grassland, with no subsequent destruction or human disturbance noted at the sampling sites. Each land use pattern was replicated three times, with sampling sites on sloping land (< 5∘) and uniform areas of 20 m × 20 m. Soil samples were collected at depths of 0–10 cm, 10–30 cm, and 30–50 cm, with chemical samples stored in self-sealing bags and aggregate samples in plastic lunch boxes to prevent extrusion and shock during transportation to the laboratory. Upon arrival, roots, stones, and visible plant debris were meticulously removed by hand from the samples. The air-dried chemical and aggregate samples underwent bulk soil physicochemical and aggregate analysis.

2.3. Soil laboratory analysis

A 500 g aggregate sample was weighed and subjected to dry sieving to obtain fractions < 0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–5 mm, and > 5 mm. Subsequently, 50 g of a mixed soil sample containing various aggregate sizes was matched based on the proportion of each size and subjected to wet sieving to obtain water-stable aggregates of different sizes, following methods described by[51,52]. The processed samples underwent oven drying at 50°C for 48 hours until reaching constant weight to determine the content of each aggregate in the bulk soil. Soil aggregate and air-dried soil samples were ground to pass through a 0.25 mm sieve and stored in plastic bags for SOC and pH analysis. SOC content was measured using the $K_2Cr_2O_7$-H_2SO_4 oxidation method described. Soil pH was determined in a 1:2.5 soil/water solution using a PHS-3C instrument[44].

2.4. Soil mean weight diameter (MWD) and geometric mean diameter (GMD)

The mean weight diameter (MWD) and geometric mean diameter (GMD) were used to evaluate soil aggregate stability under different land use patterns. The two parameters were calculated using the following two formulas[44,45].

$$MWD=\sum_{i=1}^{n} xiwi$$

$$GMD = \exp\left[\frac{\sum_{i=1}^{n}(wi\ln xi)}{\sum_{i=1}^{n} wi}\right]$$

Where x_i was the mean diameter (mm) of different soil aggregate-size, w_i was the content (%) of soil aggregates in the ith size class to the total mass of the samples, and n was the number of different size soil aggregates, and lnx_i was the base-e natural logarithm of the mean diameter for different aggregate-size class.

The contribution of soil different aggregates with particle sizes to the total carbon contents of soil after changes in land use patterns as following equations[44].

$$\Delta C_i = (C_{Di} \times w_{Di}) - (C_{Fi} \times w_{Fi})$$

$$G_i = \left(\frac{\Delta C_i}{C_D - C_F}\right) \times 100$$

Where ΔC_i was the difference in SOC content in soil aggregate i between the resumed forests or grasslands from farmlands and the FL; C_{Di} was the SOC content in soil aggregate i under resumed forests or grasslands from farmlands, and w_{Di} was the content (%) of soil aggregate i in bulk soil under resumed forests or grasslands from farmlands. C_{Fi} was the SOC content in soil aggregate i under FL, and w_{Fi} was the content (%) of soil aggregate i in bulk soil under FL. G_i was the contribution (%) of soil aggregate i to SOC contents in bulk soil when FL was converted to the forests or grasslands, C_D was the SOC content in bulk soil under forests or grasslands, and C_F was the SOC content in bulk soil under FL.

2.5. Statistical analysis

All data were collected and organized using Microsoft Excel and subsequently analyzed utilizing SPSS 19.0 software (SPSS Inc., Chicago, IL, USA). Before analysis, all data underwent assessments for normality and homogeneity of variance. The distribution of soil aggregates of different sizes, MWD, GMD, and soil physicochemical properties across various land uses was compared through a one-way variance analysis (ANOVA). In cases where ANOVA indicated a significant effect, post hoc least significant difference (LSD, $P < 0.05$) tests were employed for pairwise comparisons. Correlation matrices between soil aggregate stability indices (MWD and GMD) and various soil physical-chemical properties were generated based on Pearson correlation coefficients, with significance levels set at $P < 0.05$, $P < 0.01$, and $P < 0.001$. Graphs were created using OriginPro 2021 software.

3. Results

3.1. Distribution characteristics of soil aggregates

The results of this study showed that different land use types significantly affected the distribution of soil aggregates (Table 1). Microaggregates (< 0.25 mm) dominate in aggregate size of different soil depths of FL. However, after FL transforms into grassland (MS, NG, and ACL) and forestland (PA, PO), microaggregates were significantly decreased by 16.66%~70.82%, 39.12%~83.17%, 0.48%~18.20%, 45.74%~72.22%, and 7.60%~41.49%, respectively. With the extension of transition time, soil macroaggregates (> 2 mm) significantly increased and soil microaggregates significantly decreased ($P < 0.05$), the distribution of soil aggregates no obvious rules between soil depths. During the same period of restoration, the proportion of macroaggregates in 0–10 cm and 10–30 cm soil depths was MS > PO > ACL, and the proportion of microaggregates were MS < PO < ACL, and there was no obvious rules of mesoaggregates (0.25-2.0 mm) ($P < 0.05$). At three soil depths, the proportion of macroaggregates in forestland and grassland (PA, NG, MS, PO, and ACL) was significantly higher than those in FL, while the proportion of microaggregates were significantly lower than those in FL. Among them, the macroaggregates in PA and NG treatments were significantly higher than those in other treatments, and the proportion of microaggregates was significantly lower than those in other treatments ($P < 0.05$).

Table 1
Distribution of soil aggregates under different land uses

Land uses	Aggregate-size distribution (g)					
	> 5 mm	2–5 mm	1–2 mm	0.5-1.0 mm	0.25–0.5 mm	< 0.25 mm
Soil depth 0–10 cm						
FL	0.48 ± 0.05Cd	0.89 ± 0.05Cc	1.72 ± 0.09Bc	1.79 ± 0.22Bb	2.38 ± 0.23Aab	42.73 ± 0.33Aa
MS	26.29 ± 1.50Ab	3.84 ± 0.29Aa	2.32 ± 0.12Bb	2.64 ± 0.17Aa	2.44 ± 0.20Aab	12.47 ± 0.94Cd
PA	32.06 ± 1.57Aa	2.22 ± 0.18Bb	1.72 ± 0.16Bc	1.10 ± 0.10Bc	1.04 ± 0.16Cd	11.87 ± 1.45Cd
PO	18.06 ± 2.75Bc	1.85 ± 0.14Bb	2.19 ± 0.11Bb	1.37 ± 0.10Bbc	1.54 ± 0.11BCcd	25.00 ± 2.76Bc
ACL	4.98 ± 0.13Cd	1.82 ± 0.17Bb	1.96 ± 0.2Bbc	1.76 ± 0.06Bb	2.86 ± 0.10Aa	36.61 ± 0.21Ab
NG	29.82 ± 0.47Aab	3.52 ± 0.15Aa	4.71 ± 0.31Aa	2.66 ± 0.31Aa	2.10 ± 0.18ABbc	7.19 ± 0.88Ce
Soil depth 10–30 cm						
FL	0.78 ± 0.04De	1.29 ± 0.10Cc	2.26 ± 0.25BCbc	4.00 ± 0.19Aa	6.02 ± 0.26Aa	35.65 ± 0.38Aa
MS	11.57 ± 1.18BCbc	2.36 ± 0.22Bb	2.23 ± 0.17BCc	2.69 ± 0.22Cc	4.49 ± 0.25Bb	26.66 ± 1.96Bb
PA	27.21 ± 2.48Aa	1.64 ± 0.08Cc	1.00 ± 0.08Dd	1.46 ± 0.22Dd	1.35 ± 0.22De	17.34 ± 2.02Cc
PO	8.98 ± 0.47BCcd	1.29 ± 0.14Cc	1.67 ± 0.22CDc	2.62 ± 0.06Cc	2.50 ± 0.26Cd	32.94 ± 1.09Aa
ACL	6.93 ± 0.32Cd	1.49 ± 0.20Cc	2.88 ± 0.21Bb	1.29 ± 0.15Dd	1.58 ± 0.10De	35.82 ± 0.33Aa
NG	13.66 ± 1.56Bb	4.53 ± 0.14Aa	4.51 ± 0.31Aa	3.47 ± 0.17Bb	3.65 ± 0.14BCc	20.18 ± 1.58Cc
Soil depth 30–50 cm						
FL	0.09 ± 0.01Cd	0.95 ± 0.06Bb	0.70 ± 0.03Cd	1.16 ± 0.11Dd	2.27 ± 0.17Bbc	44.84 ± 0.30Aa

Note: Values are mean ± standard error. Values with the same uppercase letters within land uses and lowercase letters within soil aggregates are not significant different at $P < 0.05$. <0.25 mm, 0.25–0.5 mm, 0.5-1.0 mm, 1–2 mm, 2–5 mm and > 5 mm represent the particle size distribution of aggregates; ACL, FL, MS, NG, PA and PO represent abandoned cropland, farmland, *Medicago sativa*, natural grassland, *Picea asperata* Mast., *Platycladus orientalis* (L.) Franco.

Land uses	Aggregate-size distribution (g)					
	> 5 mm	2–5 mm	1–2 mm	0.5-1.0 mm	0.25–0.5 mm	< 0.25 mm
MS	6.11 ± 1.02Bc	1.50 ± 0.19Bb	1.02 ± 0.06BCc	1.49 ± 0.18CDcd	2.51 ± 0.13Bb	37.37 ± 1.29Bb
PA	19.87 ± 1.18Aa	1.22 ± 0.10Bb	0.91 ± 0.07BCcd	1.85 ± 0.20Cc	1.82 ± 0.14Bc	24.33 ± 1.36De
PO	6.56 ± 0.37Bbc	1.06 ± 0.10Bb	1.36 ± 0.14ABb	2.87 ± 0.09Bb	4.71 ± 0.25Aa	33.44 ± 0.77Cc
ACL	7.71 ± 0.32Bbc	1.03 ± 0.05Bb	1.12 ± 0.08BCbc	1.56 ± 0.12CDcd	1.90 ± 0.21Bc	36.68 ± 0.30BCb
NG	8.16 ± 0.80Bb	6.24 ± 0.59Aa	1.76 ± 0.18Aa	4.00 ± 0.09Aa	2.55 ± 0.14Bb	27.30 ± 1.36Dd

Note: Values are mean ± standard error. Values with the same uppercase letters within land uses and lowercase letters within soil aggregates are not significant different at $P < 0.05$. <0.25 mm, 0.25–0.5 mm, 0.5-1.0 mm, 1–2 mm, 2–5 mm and > 5 mm represent the particle size distribution of aggregates; ACL, FL, MS, NG, PA and PO represent abandoned cropland, farmland, *Medicago sativa*, natural grassland, *Picea asperata* Mast., *Platycladus orientalis* (L.) Franco.

3.2. Stability of soil aggregates

The mean weight diameter (MWD) and geometric mean diameter (GMD) of soil aggregates considerably varied among the six land uses (Fig. 2). Similar changing trends for the MWD and GMD were observed among the three soil depths, and the highest values of these two indices were both at their maximum for the PA. At the three depths, the average values of MWD under FL were significantly ($P < 0.01$) lower than those under MS, PA, PO, ACL, and NG, and the average values of GMD under FL were significantly ($P < 0.05$) lower than those under MS, PA, PO, and NG. Among the 5 vegetation restoration measures, the MWD values were significantly ($P < 0.01$) higher than PO and ACL under the PA and NG at the three different soil depths. The GMD values were significantly ($P < 0.01$) higher than PO and ACL under the NG at the 0–10 cm soil depths. However, the GMD values were significantly ($P < 0.05$) higher than MS, PO, ACL, and NG under the PA at 10–30 cm and 30–50 cm. In the 0–10 cm, 10–30 cm, and 30–50 cm soil depths, the variation range of MWD were 0.42 mm to 3.50 mm, 0.52 mm to 2.98 mm, and 0.35 mm to 2.26 mm, respectively, and the value of the GMD ranged from 0.30 mm to 2.30 mm, 0.35 mm to 1.54 mm, and 0.28 mm to 0.96 mm in the 0–10 cm, 10–30 cm and 30–50 cm soil depths, which indicated that the soil water-stable aggregates in topsoil were more stable than those of the subsoil. The order of MWD and GWD under different land use types was PA > NG > MS > PO > ACL > FL (Fig. 2).

3.3. SOC content in bulk soil and in different soil aggregates

Soil depth and aggregate size influenced soil SOC content (Fig. 3). Among the three soil depths, the SOC content in bulk soil and soil aggregates was the highest under NG and lowest under ACL. At the soil depth of 0–10 cm, the SOC content in bulk soil and soil aggregates was significantly higher ($P < 0.05$)

than FL, MS, PA, and ACL under NG and significantly higher ($P < 0.05$) than FL and ACL under PO and NG. In addition, MS and PA treatments were significantly higher ($P < 0.05$) than FL and ACL treatments in soil aggregates > 5 mm, 0.5-1.0 mm, and 0.25-0.5mm, and soil aggregates > 2 mm and < 0.25 mm, MS treatment was significantly higher ($P < 0.05$) than FL and ACL (Fig. 3(a)). At the soil depths of 10–30 cm and 30–50 cm, the SOC content in bulk soil and soil aggregates was significantly higher ($P < 0.05$) than FL, MS, PA, and ACL under NG and significantly higher ($P < 0.05$) than FL and ACL under MS. However, MS treatment was significantly higher than PA treatment in soil aggregates > 5 mm and 1–2 mm in 10–30 cm soil depth (Fig. 3(b)(c)). In soil depths 0–10 cm, 10–30 cm, and 30–50 cm, the average SOC content in the bulk soil and soil aggregates of > 5 mm, 2–5 mm,1–2 mm, 0.5-1 mm, 0.25–0.5 mm and < 0.25 mm was 17.49, 15.43, 15.84, 16.90, 16.99, 15.82 and 14.63 g kg^{-1}, 13.28, 12.34, 12.22, 13.28, 12.64, 13.29 and 11.24g kg^{-1} and 10.98, 9.29, 10.88, 10.64, 10.39, 10.84 and 9.64 g kg^{-1}, respectively. Compared with the SOC content under FL in three different soil depths, the average SOC content in the bulk soil and soil aggregates of > 5 mm, 2–5 mm, 1–2 mm, 0.5-1 mm, 0.25–0.5 mm and < 0.25 mm under the forestland and grassland increased by 4.83, 7.62, 2.02, 4.98, 6.16, 7.21 and 1.25 g kg^{-1}, 5.16, 5.21, 4.01, 6.01, 4.83, 6.39 and 4.62 g kg^{-1} and 3.62, 4.68, 3.81, 4.53, 4.04, 4.78 and 4.71 g kg^{-1}, respectively.

3.4. Contributions of different soil aggregates to SOC sequestration in bulk soil after afforestation

Compared with FL, the SOC content in bulk soil under MS, PA, PO, and NG treatments increased by 24.57%, 20.73%, 76.25%, and 81.05%, respectively, at the 0–10 cm depth, by 43.10%, 24.39%, 109.91%, and 125.91%, at the 10–30 cm depth and by 33.92%, 26.14%, 102.93% and 90.59%, respectively, at the 30–50 cm depth. However, ACL treatment decreased by 23.06%, 16.04%, and 26.73% in 0–10 cm, 10–30 cm, and 30–50 cm soil depths, respectively (Table 2). Significant differences were in the contribution rates of different particle size aggregates to soil SOC content after changes in land use patterns (Table 2). When FL was transformed into MS, PA, PO, and NG, the soil aggregates of > 5 mm and 2–5 mm in the three soil depths all had a positive contribution to the increase of soil SOC content, while the soil aggregate of < 0.25 mm had the opposite effect in 0–10 cm depth. However, when FL was transformed into ACL, the contributions of the soil aggregates of > 5 mm and 2–5 mm in 0–10 cm soil depth and 2–5 mm in 10–30 cm to soil SOC content were negative, but the soil aggregate of < 0.25 mm had the positive effect (Table 2). After FL was transformed into forestland and grasslands, in the 0–10 cm soil depth, the contributions of > 5 mm to soil SOC content were 211.29%, 419.49%, 71.16%, -25.39%, and 121.51%, respectively, and the contributions of < 0.25 mm to soil SOC were – 229.97%, -318.56%, -24.20%, 141.20%, and – 81.97%, respectively. In the 10–30 cm soil depth, the contributions of > 5 mm to soil SOC content were 66.60%, 125.56%, 79.21%, 23.89%, and 136.86%, respectively, and the contributions of < 0.25 mm were 8.62%, -102.77%, 47.39%, 52.79%, and 22.91%, respectively. However, in the 30–50 cm soil depth, the contributions of > 5 mm were 42.66%, 120.15%, 67.36%, 25.28%, and 85.41, respectively, while the contributions of < 0.25 mm were 46.92%, -31.89%, 51.22%, 47.62%, and 41.08%, respectively (Table 2).

Table 2
Influence of returned farmland to forestland or grassland on SOC content in bulk soil and the contributions of different soil aggregates to SOC sequestration in bulk soil.

land use change from FL to-	SOC changes in bulk soil	G_i(%)					
	(g kg^{-1})	> 5 mm	2–5 mm	1–2 mm	0.5-1 mm	0.25–0.5 mm	< 0.25 mm
soil depth 0–10 cm							
MS-FL	3.31	211.29	25.03	13.92	16.05	12.59	-229.97
PA-FL	2.79	419.49	10.83	1.48	-1.53	-5.07	-318.56
PO-FL	10.26	71.16	4.82	5.28	1.84	1.52	-24.20
ACL-FL	-3.10	-25.39	-4.62	2.84	3.20	-2.65	141.20
NG-FL	10.91	121.51	12.70	16.71	7.29	3.95	-81.97
soil depth 10–30 cm							
MS-FL	3.87	66.60	9.37	5.51	0.53	5.80	8.62
PA-FL	2.19	125.56	5.75	-6.82	-15.66	-28.51	-102.77
PO-FL	9.87	79.21	1.50	2.86	1.62	-0.56	47.39
ACL-FL	-1.44	23.89	-1.26	-0.67	36.59	51.12	52.79
NG-FL	11.31	136.86	12.62	13.24	5.87	5.20	22.91
soil depth 30–50 cm							
MS-FL	2.70	42.66	5.14	4.76	5.04	9.56	46.92
PA-FL	2.08	120.15	4.47	3.53	10.32	3.17	-31.89
PO-FL	8.20	67.36	2.46	3.96	7.99	13.16	51.22
ACL-FL	-2.13	25.28	2.01	-1.47	-0.47	4.38	47.62
NG-FL	7.22	85.41	27.02	6.24	14.71	6.92	41.08

Note: G_i: contributions of different soil aggregates to SOC sequestration in bulk soil after returned farmland to forestland or grassland; <0.25 mm, 0.25–0.5 mm, 0.5-1.0 mm, 1–2 mm, 2–5 mm and > 5 mm represent the particle size distribution of aggregates; ACL, FL, MS, NG, PA and PO represent abandoned cropland, farmland, *Medicago sativa*, natural grassland, *Picea asperata* Mast., *Platycladus orientalis* (L.) Franco.

3.5. Principal component analysis (PCA) and correlation analysis

Analyze the dynamic patterns within different land use patterns and use principal component analysis (PCA) to discern the complex relationship between soil characteristics and land use patterns. After conducting PCA on soil characteristics, it was observed that three principal components (PCs) exhibited eigenvalues greater than 1, indicating their substantive contribution to the variance explained in the dataset. On the contrary, PCs with eigenvalues below 1 were considered inconsequential for further elucidation. The cumulative values of PCs account for approximately 83.29% of the disparities discernible among the various land use patterns, primarily encapsulated in the first two principal components, with the third principal component accounting for 7.65% (Fig. 4). However, it is not allowed to add other principal component axes in the figure, so it has not plotted. PC1 constituting approximately 60.2% of the total variability, was predominantly delineated by bulk soil SOC and SOC content across different particle sizes (> 5 mm, 2–5 mm, 1-2mm, 0.5-1.0 mm, 0.25–0.5 mm, and < 0.25 mm), as well as MWD, GMD, pH and < 0.25 mm, >1mm soil aggregate content (Fig. 4). Conversely, PC2 representing approximately 15.4% of the total variation, was chiefly influenced by 0.25-1mm soil aggregate. The PCA biplot highlights the stark differences between L1, L2 and L3, but L2 and L3 exhibited a relatively analogous profile (Fig. 4(a)). PCA biplot between different land use patterns highlights the significant differences between FL and ACL compared to MS, NG, PA and PO, however, there are similar changes between FL and ACL, as well as between MS, NG, PA, and PO (Fig. 4(b)).

Figure 5 presents the correlations between the percentage of water-stable soil aggregate fractions, MWD, GMD, SOC, and soil pH. The MWD and GMD were positively correlated with the soil aggregates of > 5 mm, 2–5 mm, and 1–2 mm and SOC contents in bulk soil and aggregates soil ($P < 0.05$). However, The MWD and GMD were negatively correlated with the soil aggregates of < 0.25 mm. Among them, GMD was also negatively correlated with soil aggregates of 0.25–0.5 mm and soil pH ($P < 0.05$) (Fig. 5). The content of SOC in aggregates of different particle sizes, as well as the soil aggregates of > 5 mm, 2–5 mm, 1–2 mm, and 0.5-1 mm, was positively correlated with the content of SOC in bulk soil, and negatively correlated with soil aggregates of < 0.25 mm. However, there was a negative correlation between soil pH and GMD, soil aggregates of > 5 mm, 2–5 mm, 1–2 mm, 0.5-1 mm, and 0.25–0.5 mm, SOC content in different aggregates and bulk soil, only a positive correlation with aggregates of < 0.25 mm.

4. Discussion

The results of this study align with the initial hypothesis regarding the significant variations in soil aggregates' distribution, aggregate stability, and SOC content following land use transitions from farmland (FL) to forest and grassland in the Loess Plateau region of central Gansu, China. Moreover, the current research findings support the expectation that transitioning to forest and grassland would enhance SOC storage and promote the stability of soil aggregates. This was attributed to the increased vegetation cover and restoration efforts associated with such land use changes. The observed changes in soil aggregates' distribution and stability, coupled with the noticeable increase in SOC content, underscore the positive impact of vegetation restoration on soil quality and carbon sequestration potential. These outcomes validate the importance of sustainable land management practices, particularly in ecologically sensitive regions like the Loess Plateau, where soil erosion and degradation are prevalent concerns. These findings have significant implications for policymakers, land managers, and conservationists striving to balance agricultural productivity with environmental conservation goals.

4.1. Effects of vegetation restoration measures on the distribution of aggregate fractions

Significant increases were observed in the content of aggregates larger than 5 mm, accompanied by notable decreases in aggregates smaller than 0.25 mm, while changes in aggregates ranging from 0.25 to 5 mm showed no clear pattern during the transition from farmland to forests and grasslands, as detailed in Table 1. These observations suggest that afforestation and grass planting initiatives in former farmlands have facilitated the formation of macroaggregates, thereby enhancing soil structure in the Loess Plateau region of central Gansu, China. This finding aligns with similar outcomes reported by Yu *et al.*[44] study conducted in southwest China, and it is consistent with the findings of Dou *et al.*[51] study conducted in the central part of the Loess Plateau. These findings are consistent with previous literature highlighting that farmland soil typically exhibits a lower proportion of macroaggregates compared to forestland and grassland soils, with tillage operations and precipitation shocks being identified as dominant contributing factors[45,51,53]. Continuous tillage practices can disrupt macroaggregate structures[54] or impede the natural transformation of microaggregates into macroaggregates [55,56]. Furthermore, prolonged farming activities result in the constant mixing of soil layers, particularly under rain erosion, which is more likely to destroy macroaggregates and increase the proportion of smaller aggregates[57,58]. Upon transitioning farmland back to forests and grasslands, there was a notable increase in aggregates larger than 5 mm and a decrease in aggregates smaller than 0.25 mm. This phenomenon can be attributed to several factors related to vegetation type, root systems, and litter. Vegetation restoration enhances vegetation coverage and litter content, reduces soil water evaporation, and increases humus content[59]. Additionally, the increase in root biomass leads to the concretion and secretion release by roots, enhancing soil resistance to erosion and the cementation ability of microaggregates, thereby increasing the proportion of macroaggregates. Moreover, the content of soil organic carbon plays a crucial role in aggregate formation and stability[34,35]. Conversely, soil aggregates influence SOC decomposition and serve as an essential mechanism for SOC sequestration[36]. These findings were supported by the significant positive correlation between soil organic carbon and soil aggregates larger than 0.5 mm and a significant negative correlation with soil aggregates smaller than 0.25 mm in this study (Fig. 4) (Fig. 5).

4.2. The response of aggregate stability to different vegetation restoration measures

The MWD and GMD of soil aggregates are pivotal indicators for assessing their stability and aggregation capacity. Higher values of these indices signify stronger aggregate stability and enhanced aggregation capabilities[51,60]. Consequently, aggregate stability variations reflect their composition differences[61]. The findings of this study demonstrate that, compared to farmland (FL), the MWD and GMD of soil aggregates significantly improved ($P < 0.05$) with various vegetation restoration measures, indicating enhanced soil structure and stability through vegetation restoration. Specifically, the soil aggregate stability of forestland and natural grassland restored for 28 years showed the highest improvement, while abandoned cropland exhibited the lowest stability. This disparity can be attributed to the higher plant species diversity, root biomass associated with natural restoration measures, and increased years of artificial vegetation restoration, resulting in a greater amount of easily decomposable plant litter and root exudates[62]. Moreover, plant litter is a crucial source of soil organic matter, providing a conducive environment for soil microorganisms post-decomposition. Microbial activity produces substances favoring soil cementation, coupled with root exudates, which further promote the aggregation of small soil particles into larger aggregates[45], thereby effectively enhancing soil aggregate stability. Notably, the study observed the strongest stability of the soil surface layer under different vegetation restoration measures, possibly due to higher moisture levels, litter content, and optimal temperature in the soil surface layer, facilitating increased soil organic matter content and promoting the reproduction and metabolism of soil microorganisms[63]. The significant positive correlation ($P < 0.05$) between soil aggregate stability and soil organic carbon (SOC) in this study (Fig. 4) (Fig. 5) corroborates these findings. Additionally, the relatively low stability of soil aggregates in abandoned land aligns with prior research results of[51], emphasizing the critical role of vegetation restoration measures in enhancing soil structure and stability.

4.3. Effects of vegetation restoration measures on the soil organic carbon content

SOC is pivotal in regulating the global carbon balance, influenced by various factors such as land use, climate change, and cultivation methods[25,30]. In the current study, SOC content in grassland and forest land was significantly higher than that under farmland (FL) and abandoned cropland (ACL) (Fig. 3). The SOC content under different vegetation restoration measures followed this order: NG > PO > MS > PA > FL > ACL. Continuous farmland cultivation disrupts soil aggregate structure, hindering SOC accumulation[64]. However, as farmland transformed into grasslands and forests, increased vegetation coverage, plant species, litter, root biomass, and root exudates increased SOC input and reduced SOC loss[23], resulting in higher SOC content. This aligns with research findings in the Loess Plateau[23] and southwest China region[44]. Different agroforestry systems can increase SOC storage globally, such as in the Indo-Gangetic Plains in Bihar, India[65]. Kim *et al.*[29] demonstrated in a global review that after farmland was restored to secondary forests, soil SOC increased by 193%. The potential for soil carbon sequestration is influenced by many factors, including the soil's background carbon content, which significantly impacts later carbon sequestration capacity. The average SOC content in FL soil at a depth of 0–50 cm in this study region was 9.47 g/kg, significantly lower than in karst regions of Southwest China[44,66] and the Loess Plateau hilly regions of North Shaanxi[51], indicating enormous SOC sequestration potential in the study region post-farmland conversion. However, the average SOC content in the 0–50 cm soil of ACL was 7.42 g/kg, slightly lower than FL. This may be due to the lack of exogenous nutrient input in the soil post-abandonment, hindering SOC accumulation. Additionally, the predominance of natural weeds in ACL soil, limited total litter and root biomass in the short term, and seasonal growth leading to soil nutrient consumption contribute to ACL's lower SOC content than FL.

The findings of this study revealed a significant positive correlation between soil SOC and aggregates > 0.5 mm, as well as SOC in aggregates, while a negative correlation was observed with aggregates < 0.5 mm and soil pH (Fig. 4) (Fig. 5). Vegetation restoration resulted in a notable increase in aggregates > 5 mm and a corresponding decrease in aggregates < 0.25 mm (Table 1), indicating the positive role of macroaggregates in SOC accumulation (Table 2). This underscores the potential of vegetation restoration to facilitate the conversion of soil microaggregates into larger macroaggregates, with aggregates > 0.5 mm playing a crucial role in soil organic carbon sequestration[44,51]. Researchers suggest that organic carbon sequestration is closely linked to aggregate size[25], with particulate SOC and mineral-associated soil organic carbon in macroaggregates serving as significant sources of SOC[67]. Studies also indicate that the influx of organic matter from vegetation into the soil primarily drives the increase in soil macroaggregate SOC[23,68]. Furthermore, during vegetation restoration, the combined effects of plant roots and root exudation transform microaggregates into macroaggregates through cementation, thereby safeguarding SOC[69].

In this study, the surface soil (0-10cm) exhibited higher SOC content compared to the subsoil (10-50cm) (Fig. 3), consistent with the consensus among researchers[45,64]. This disparity can be attributed to the substantial accumulation of fresh organic matter in the surface soil during vegetation restoration, primarily derived from plant biomass, litter, and roots[23]. Among the different vegetation restoration measures, soils and aggregates under NG, PO, and MS demonstrated significantly higher SOC content than FL and ACL. This phenomenon can be attributed primarily to the enhanced fine root system, with grasslands exhibiting higher fine root biomass than forestlands during the same restoration period. This increased fine root biomass contributes to carbon reserves through root decomposition and the release of root exudates[37,70].

Overall, although returning FL to forestland and grassland significantly increased the SOC content in bulk soil and different soil aggregates, the SOC in soil and soil aggregates under NG and PA were significantly higher than those under MS and PO (Fig. 3). These results indicated that conversion from FL to NG and PA was more beneficial for soil carbon sequestration than the MS and PO in China's Loess Plateau center Gansu region. However, the soil macroaggregate content, MWD, and GMD were higher under PO and NG than under PA and MS, showing that the soil structure was more reasonable and the ability to resist soil erosion was the strongest under PO and NG. Therefore, to improve soil and water conservation capacity and increase soil carbon sequestration in the Loess Plateau, converting FL to PO and NG may be the best choice for improving the ecological environment. However, the present study was only part of the Loess Plateau region, and future research should expand the research scope because the spatial heterogeneity in the Loess Plateau region may alter the effects of PO and NG on SOC sequestration and aggregate stability. This study also determined soil aggregate stability and SOC at 0–50 cm depths.

Future research should investigate changes in soil aggregate stability and SOC at deeper soil depths due to afforestation.

5. Conclusions

This study highlights the impact of vegetation restoration on soil quality in the Loess Plateau region of central Gansu, China. Transitioning from farmland to forest and grassland led to significant changes in soil aggregates, with larger aggregates increasing and smaller ones decreasing. This shift indicates the positive influence of afforestation and grass planting on soil structure. Moreover, different vegetation restoration measures improved aggregate stability, as shown by higher MWD and GMD values. Forestland and natural grassland, restored over 28 years, exhibited the highest stability, emphasizing the long-term benefits of natural restoration. Furthermore, increased SOC content in grassland and forest land compared to farmland and abandoned cropland was observed. This rise in SOC was linked to enhanced vegetation coverage, biodiversity, litter content, root biomass, and root exudates from vegetation restoration efforts. The study underscores the importance of these measures in enhancing soil quality, promoting carbon sequestration, and advocating for sustainable land management practices. While the study's focus was on a specific region within the Loess Plateau, future research should expand to capture spatial variations and assess long-term sustainability.

Declarations

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Authors contribution

L.Q.C. and Z.D.P. conceived and designed the experiments; Z.D.P. and C.S.G. performed the experiments; Z.D.P. and X.M.C. analysed the data and wrote the paper; L.Q.C. and F.U.H. revised the manuscript; Y.M.B., H.X.Y. and X.C.L. collected and processed samples.

Data availability

The datasets used during the current study available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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