Catena 185 (2020) 104294

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of different vegetation restoration measures on soil aggregate stability and erodibility on the Loess Plateau, China

Yanxing Dou[a,c], Yang Yang[b], Shaoshan An[a,b,*], Zhaolong Zhu[a]

[a] State Key Laboratory of Soil Erosion and Dry Land Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, PR China

[b] College of Resource and Environment, Northwest Agriculture & Forest University, Yangling, Shaanxi 712100, PR China

[c] University of Chinese Academy of Sciences, Beijing 100049, PR China

ARTICLE INFO

Keywords:
Soil aggregate stability
Soil erodibility
Vegetation restoration measures
Loess Plateau

ABSTRACT

Vegetation restoration may affect soil aggregate stability and the ability of soil to resist erosion. To evaluate the influence of vegetation restoration measures on the stability of soil aggregate and soil erodibility, we chose 7 types of vegetation restoration measures, which included artificial forest (AF), artificial mixed forest (AMF), economic forest (EF), artificial shrub (AS), natural shrub (NS), artificial grass (AG) and natural grass (NG). Then, we analyzed the distribution of water-stable aggregate fractions, mean weight diameter (MWD), geometric mean diameter (GMD), soil erodibility (K value) and other soil properties in the 0–20 cm and 20–40 cm soil layers, as well as aboveground and underground biomass (AGB and UGB). The results showed that under 7 kinds of vegetation restoration measures, the aggregate fraction < 0.25 mm was the main component (40.40–77.86%) and the proportion of the > 5 mm aggregates fluctuated greatly and ranged from 1.87% to 32.50%. And for 7 different vegetation restoration measures, the percentage of aggregate < 0.25 mm was lower than that of CK (abandoned land), however, the proportion of aggregate > 5 mm was higher than the CK. Overall, compared with CK, the MWD (2.22 and 1.93 mm) and GMD (2.86 and 2.66 mm) were both highest in two soil layers under the NS but lowest under the EF (MWD 0.68 and 0.49 mm, GMD 1.08 and 0.93 mm). The trend of the K value was opposite to these values. These results indicated that the stability of soil aggregate and the ability of soil to resist erosion under NS were strongest. The soil organic carbon (SOC), total nitrogen (TN) and UGB had significantly positive correlations with the proportion of > 1 mm aggregates and MWD but had negative correlations with the percentage of < 0.25 mm aggregates ($p < 0.05$), which indicated that SOC, TN and UGB were involved in the formation of macroaggregates and increased the stability of soil aggregates. These results suggested that natural shrub restoration measures could improve the soil aggregate stability and ability to resist erosion better than forest and grass restoration measures, which can provide a reference for the assessment of vegetation restoration measures.

1. Introduction

Soil aggregation is mediated by soil organic carbon (SOC), biota, ionic bridging, clay, and carbonates. SOC, as a binding agent, is important in the composition and the formation of aggregates (Cambardella and Elliott, 1993; Elliott, 1986; Six et al., 2000a, b; An et al., 2008). Soil aggregates, as the important aspects of soil structure, is the key indicator to evaluate soil quality and fertility. (Singh and Singh, 1996). They consist of different fractions and mainly include macroaggregates (> 0.25 mm) and microaggregates (< 0.25 mm) (Cambardella and Elliott, 1993; Six et al., 1998). Macroaggregates, with a higher carbon concentration, play a key role during the formation of new microaggregates (Six et al., 2000a; Tisdall and Oades, 1982). They are the independent and smallest structural units, which can make a large difference in aspects of fertility and environmental function (Fonte et al., 2010). Furthermore, the soil organic carbon within microaggregates decomposes slowly and contributes to long-term storage (Besnard et al., 1996; Cambardella and Elliott, 1993; Minreal et al., 1997; Puget et al., 2000; Tisdall and Oades, 1982). Aggregate stability, as one of the physical soil properties, is an important indicator to evaluate soil quality (Arshad and Cohen, 1992; Hortensius and Welling, 1996). The stability of soil aggregates is closely linked to soil structure and can affect some soil physical and biogeochemical processes, such as the movement and storage of water, biological activity and the growth

* Corresponding author at: State Key Laboratory of Soil Erosion and Dry Land Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, PR China.
E-mail address: shan@ms.iswc.ac.cn (S. An).

https://doi.org/10.1016/j.catena.2019.104294
Received 14 July 2018; Received in revised form 21 September 2019; Accepted 25 September 2019
Available online 19 November 2019
0341-8162/

of plant, as well as the ability of soil to resist erosion (Zhang and Miller, 1996; An et al., 2008; Six et al., 2000a). Maintaining high soil aggregates stability is essential for preserving soil productivity and minimizing soil erosion and environment pollution resulting from soil degradation (Cammeraat and Imeson, 1998; Six et al., 2000b; Six and Paustian, 2014; Zeng et al., 2018).

Vegetation restoration is vital for terrestrial ecosystem carbon cycling and global climate change because it can promote soil development, effectively control soil erosion and prevent soil degradation (Ren et al., 2007; Zhou et al., 2012; Wang et al., 2012). During the vegetation restoration process, the soil structure and properties may change with the vegetation restoration period (Tsunekawa et al., 2014). The Loess Plateau in China is strongly affected by soil erosion. With the implementation of the National Returning Farmland to Forest Project, soil erosion has been effectively alleviated. Moreover, vegetation restoration has changed the land use types and vegetation coverage, which could have a profound effect on the physical and chemical properties of soil (Anger et al., 1993). Soil aggregation is a dynamic soil property, which tends to react to environmental changes (Taboada et al., 2004). Many studies have focused on the effects of land use, tillage type, and biochar on soil aggregates and have yielded results (Liu et al., 2014; Majid and Bahareh, 2013; Singh and Singh, 1996; Spaccini et al., 2001; Rajeev et al., 2016; Zhang et al., 2015, 2017). There have also been some studies about the response of soil aggregates to vegetation restoration. For example, An et al. (2008) found that the stability of soil aggregates in the topsoil layer was higher than that in the subsoil layer during the natural revegetation of grass. This was different from some common results. Wang et al. (2012) showed that compared with planting species, natural grass recovery could better improve the physical properties of soil and the stability of water-stable aggregates. Erktan et al. (2016) examined the effects of Mediterranean successional gradients in severely eroded gully bed ecosystems and found that the plant community could stabilize the soil structure and increase the stability of soil aggregates. This suggested that natural vegetation restoration can improve soil properties. Tang et al. (2010) indicated that vegetation recovery could promote SOC accumulation by biomass input, which contributes to the stability of soil aggregates. Zhou et al. (2002) also revealed that after vegetation restoration, the content of SOC and the water stability of soil aggregates were improved significantly. Hence, the content of SOC was an important factor to soil aggregation. However, these studies did not combine forest (artificial pure forest, artificial mixed forest and economic forest), shrub (artificial and natural) and grass (artificial and natural) comprehensively to evaluate the stability of soil aggregates and erodibility. Therefore, the research in the current study is imperative.

Hence, the question remains as to how the soil aggregate stability and erodibility changed after the different kinds of vegetation restoration measures. Furthermore, it is not known which is most conducive to improvement of the stability of soil aggregates and the ability to resist soil erosion. Therefore, it is necessary to study the characteristics of soil aggregates and erodibility after vegetation restoration.

In this study, we investigated the effects of 7 different vegetation restoration measures on the soil aggregate stability and the ability of soil to resist erosion, aiming to (1) analyze the impacts of different vegetation restoration measures on the distribution of soil aggregate fractions and the water stability of soil aggregates; (2) explore the response of soil erodibility to different vegetation restoration measures and then evaluate which type of vegetation restoration measure is best for improving the ability of soil to resist erosion. Finally, these results can provide a basis for further assessment of vegetation restoration measures on the Loess Plateau or other similar regions.

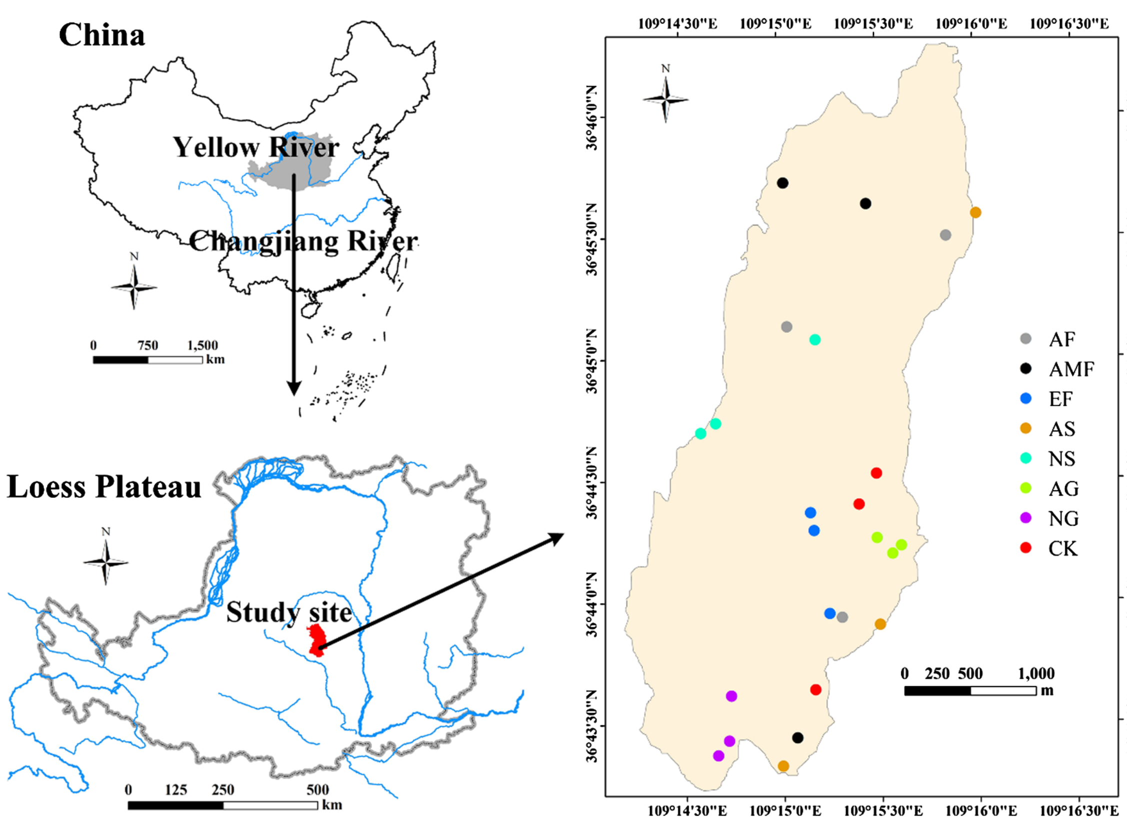

Fig. 1. The location of the study area and the distribution of sample sites in Zhifanggou watershed. The different colors of circular symbols represent the soils under different vegetation restoration measures.

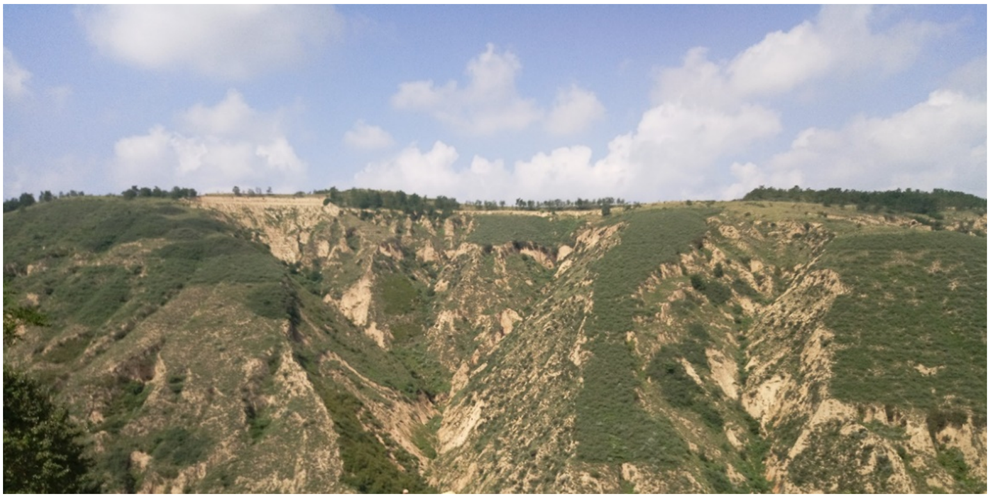

Fig. 2. Part of landform in Zhifanggou watershed.

Table 1
Basic information on Zhifanggou watershed.

Restoration measures	Vegetation types	Mean altitude/m	Mean slope/°	Soil temperature/°C	
				0–10 cm	10–20 cm
AF	*Robinia pseudoacacia*	1325	20.80	22.73	21.49
AMF	*Robinia pseudoacacia* and *Armeniaca sibirica*	1318	20.56	29.90	25.56
EF	*Malusdomestica*	1336	5.11	31.44	28.56
AS	*Korshinsk Peashrub*	1320	20.28	21.41	20.87
NS	*Sophora viciifolia*	1283	24.22	26.76	25.50
AG	*Medicago Linn.*	1315	3.44	27.56	25.22
NG	*Artemisia gmelinii*	1353	18.67	30.77	27.89
CK	Abandoned land	1137	7.00	28.00	26.57

Notes: AF is artificial forest; AMF is artificial mixed forest; EF is economic forest; AS is artificial shrub; NS is natural shrub; AG is artificial grassland; NG is natural grassland; FL is farmland; CK is the control.

2. Materials and methods

2.1. Study area

We chose Zhifanggou watershed, which is located in the middle of the Yellow river, northern of Shaanxi province, China, as the experimental area. It is the tributary of the Yanhe River Valley (108°45′-110°28′E, 36°23′- 37°17′N), which is distributed in northern Shaanxi Loess Plateau hilly areas (Fig. 1).

The Zhifanggou valley has a warm temperate semiarid climate. The annual sunshine hours range from 2300 h to 2400 h and the frost-free period is approximately 160 d. The annual average rainfall is 549.1 mm and during July to September, the rainfall accounted for 61.1% of annual rainfall, most of which was torrential rain. Zhifanggou watershed with the terrain fragmentation, belongs to the typical loess hilly and gully region and the scope of slope is 0–65° (Zhao et al., 2016), where due to the loose soil, it was prone to form many gullies after the erosion of torrential rain and these gullies was difficult to recover in a short period of time (Fig. 2). The area is 8.27 km^2. Since the beginning of the "7th Five-Year Plan" (it was the work plan formulated by the state council for national economic and social development in March 1986. During the implementation of this plan, there were some national key scientific research project about the comprehensive treatment of loess plateau and the special plan for soil and water conservation in the loess plateau was implemented from1990. And the engineering of returning farmland to forest and grassland in 1999 was the project with largest scale and investment. What's more, the Zhifanggou watershed was selected as the small watershed test area from then on), the Zhifanggou River Basin has become the demonstration area of comprehensive management of the Loess Plateau. After 20 years of comprehensive management, especially the implementation of the "Returning Farmland to Forest Project", the regional ecosystem has been gradually restored and has entered the orbit of a virtuous circle, which means the regional ecosystem gradually enter into a stage of virtuous cycle with the implementation of vegetation restoration. It refers to that the ecological environment in Zhifanggou watershed get better than ever with the results of significant ecological benefits. Taken the stage of 2000 to 2008 as an example: from 2000 to 2008, the soil carbon storage increased from 2.639 Pg C to 2.682 Pg C as well as the NPP increasing from 0.170 Pg C to 0.217 Pg C; the trend of soil loss also decreased, etc. (Lü et al., 2012; Feng et al., 2013). The main dominant species are *Robinia pseudoacacia*, *Korshinsk Peashrub*, *Rosa xanthina Lindl*, *Artemisia sacrorum*, *Artemisia giraldii* and others.

2.2. Experimental design and field sampling

The experimental region has been restored by different types of vegetation restoration measures since 1999, that are shown in Table 1. We chose different treatments, mainly including artificial forest (AF), artificial mixed forest (AMF), economic forest (EF), artificial shrub (AS), natural shrub (NS), artificial grass (AG), and natural grass (NG), as well as abandoned farm land (the control check, CK), and randomly selected three different slopes for each vegetation type so that samples taken were typical and representative. Then, we completed soil sampling from July to August 2016.

During the process of sampling, each slope was divided into three parts, namely, uphill, downhill and mid-slope. Aluminum boxes (19 × 11 × 4.5 cm) were used to collect undisturbed soil at depths of 0–20 cm and 20–40 cm to investigate the related characteristics of water-stable aggregates. Meanwhile, small aluminum cans (31.4 cm^3) and cutting ring were used to collect undisturbed soil for determining the soil relative water content (RWC) and bulk density (BD). In total, there were 9 samples for every treatment from the field sampling. Then, we obtained soil samples at depths of 0–20 cm and 20–40 cm by soil drilling that were used to determine soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP). In addition, we chose 3 plots for each part of slope and determined the vegetation cover as the forest (5 m × 5 m), shrub (2 m × 2 m) and grass (1 m × 1 m). Then, the aboveground and underground biomass (AGB and UGB) were collected and brought to the lab to determine dry matter quantity.

2.3. Sample analysis

Water-stable aggregates:The undisturbed soil in the aluminum boxes was brought back to the lab and was gently divided into small pieces (near 1 cm), and roots, stones and other debris were removed and naturally kept dry. Then, we weighed a 300 g sample and used a dry sieve method to obtain the aggregates of < 0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–5 mm and > 5 mm. According to the proportion of each aggregate size, 50 g of mixed soil sample, including different aggregate fractions, were matched, and a wet sieve method was used to obtain water-stable aggregates of different sizes (Liu et al., 2014). Combining the different fractions of soil water-stable aggregates, the mean weight diameter (MWD), the geometric mean diameter (GMD) and the soil erodibility (K value) were calculated by the following equation (Shirazi and Boerama, 1984; Vanbavel, 1950):

$$\mathrm{MWD} = \sum_{i}^{n} x_i w_i / \sum_{i}^{n} w_i \tag{1}$$

$$\mathrm{GMD} = \exp\left(\sum_{i}^{n} w_i \ln x_i / \sum_{i}^{n} w_i\right) \tag{2}$$

$$K = 7.954 \times \left\{0.0017 + 0.0494 \times \exp\left[-0.5 \times \left(\frac{\log \mathrm{GMD} + 1.675}{0.6989}\right)^2\right]\right\} \tag{3}$$

where x_i and w_i are the mean diameter (mm) and proportion (%) of each size fraction of the aggregate, respectively.

Soil RWC was measured by a drying method. Soil pH was determined by a pH electrode, with a soil-to-water ratio of 1:2.5 (Sumner and Miller, 1996). Soil BD was determined by the cutting ring method (Huang et al., 2015). SOC was measured by the $K_2Cr_2O_7$ wet oxidation method (Nelson and Sommers, 1996). Soil TN was determined using the Kjeldhal digestion procedure (Bremner, 1996). Soil TP was extracted by perchloric acid digestion, followed by the molybdenum stibium-ascorbic acid colorimetry method (Jackson, 1979).

2.4. Statistical analysis

SPSS 16.0 was used to analyze the difference of soil properties, the MWD, GMD and K value of water-stable aggregates under different vegetation restoration measures by ANOVA; the correlations between the percentage of soil aggregate fractions, MWD, GMD, K value and soil properties were obtained using the Pearson correlation test and the comprehensive scores of soil aggregate stability and erodibility were obtained by Factor Analysis method. We chose the related indicators including soil properties (RWC, BD, pH, SOC, TN, TP), aboveground and underground biomass, MWD and GMD as the initial variables. Then we selected out the common factors, F_1 and F_2 by Factor Analysis method in the SPSS based on these related indicators. After that, we used the weight of F_1 and F_2 on all related factors to calculate the total score (F) by the Eq. (4).

$$F = F_1 \frac{0.3798}{0.6298} + F_2 \frac{0.2320}{0.6298} \tag{4}$$

where 0.3978 is the contribution rate of eight factors selected on the common factor F_1; 0.2320 is the contribution rate of eight factors selected on the common factor F_2; 0.6298 is the contribution rate summation of eight factors selected on the common factor F_1 and F_2.

Finally, using this method, we could calculate the total score of soil aggregates stability and the ability of soil to resist erosion under each type of vegetation restoration measure. According to these scores, we drew the Fig. 7 in our manuscript.

The graphs of the proportion of different aggregate fractions, the MWD of soil water-stable aggregates and K value under different vegetation restoration measures were drawn by SigmaPlot 10.0. The radar charts were conducted by Origin 9.0.

3. Results

3.1. Basic physical and chemical properties of soil for different vegetation restoration measures

The RWC of EF (11.57% and 11.88%) were higher than that of CK (11.42% and 11.32%) in the 0–20 cm and 20–40 cm soil layers. This was due to that the EF was irrigated by farmer during the different growth stages. However, the RWC of other 6 kinds of restoration measures were lower than that of CK, which may be caused by the use of soil water by plants and the vegetation transpiration. Among the 7 types of vegetation restoration measures, the RWC of EF was highest and the RWC of the AF (5.56% and 5.42%) was lowest in two soil layers. The BD of 7 kinds of restoration measures were lower than that of CK (1.34 g/cm^3) at the topsoil layer. Furthermore, the BD of EF was the highest, the AG (1.27 g/cm^3) was the second, and the AF (1.04 g/cm^3) was the lowest. But in the subsoil layer, the trend was not the case. Among the different measures, the BD of AG (1.38 g/cm^3) was highest, the EF (1.26 g/cm^3) and CK (1.26 g/cm^3) were the second, and the AMF (1.16 g/cm^3) was the lowest. As a whole, the BD in topsoil layer was lower than that of subsoil layer. This was because the well-developed roots at the 0–20 cm soil layer could improve soil porosity and increase air permeability better than at the 20–40 cm layer. In the two soil layers, the soil pH in the different measures was significantly higher than the CK ($p < 0.05$). The SOC content of 7 types of measures in the 0–20 cm and 20–40 cm soil layers were significantly higher than the CK ($p < 0.05$), especially the SOC content of NS which was nearly two times of CK. In addition, among the different restoration measures, the SOC content under NS was highest, the AS was the second, the AG was the lowest in the two soil layers. As for the TN content of the 7 types of measures, they were also higher than that of CK. Among them, the TN content of NS was highest that was two times of the CK ($p < 0.05$), the AS was the second and the AG was lowest. In terms of the content of TP, there was no significant difference among the 7 kinds of vegetation restoration measures ($p > 0.05$). (Table 2).

3.2. The distribution of soil water-stable aggregate fractions

The results of soil water-stable aggregate fractions in the 0–20 cm soil layer under different vegetation restoration measures are presented in Fig. 3. The fraction of < 0.25 mm (microaggregates) occupied the largest proportion as a whole, and among the different vegetation restoration measures, the percentage of microaggregates under the CK was the highest and accounted for 76.65%. Among the different sizes of macroaggregates (> 0.25 mm soil aggregates), the proportion of the > 5 mm aggregates fluctuated greatly under types of vegetation restoration measures and the maximum value (32.50%) appeared in the NS. The order of the proportion of the > 5 mm aggregates among the forest restoration measures was AMF > AF > EF. The proportion of the > 5 mm aggregates under the NS and NG were both higher than that of AS and AG. However, the percentage variations of the 2–5 mm, 1–2 mm, 0.5–1 mm and 0.25–0.5 mm aggregates were relatively stable. The total percentages of the 2–5 mm, 1–2 mm, 0.5–1 mm and 0.25–0.5 mm aggregates under the NG were lowest among 7 kinds of vegetation restoration measures, while the NS were highest.

Fig. 4 presents the distribution of different sizes of aggregates in the 20–40 cm layer for different vegetation restoration measures. The percentage of soil microaggregates under CK were higher than that of the others. Among the 7 types of vegetation restoration measures, the proportion of soil microaggregates for NG was highest, the EF was second and the NS was lowest compared to CK. In terms of macroaggregates, the tendency of the > 5 mm aggregates was similar to that of the 0–20 cm soil layer. The minimum value of the total percentage of the 2–5 mm, 1–2 mm, 0.5–1 mm and 0.25–0.5 mm aggregates also appeared in the NG.

Table 2
Soil properties of different vegetation types.

Restoration measures	Soil layer (cm)	RWC (%)	BD (g/cm^3)	pH	SOC (g/kg)	TN (g/kg)	TP (g/kg)
AF	0–20	5.56 ± 0.01B	1.04 ± 0.07 E	8.24 ± 0.05B	6.09 ± 0.54D	0.27 ± 0.13AB	0.66 ± 0.24A
AMF	0–20	8.93 ± 0.37AB	1.11 ± 0.06 E	8.31 ± 0.02B	5.82 ± 0.49D	0.20 ± 0.02B	0.62 ± 0.18A
EF	0–20	11.57 ± 0.03A	1.30 ± 0.12 AE	8.17 ± 0.01BC	6.81 ± 0.78C	0.22 ± 0.02B	0.65 ± 0.14A
AS	0–20	9.17 ± 0.09B	1.14 ± 0.04 CE	8.29 ± 0.03B	8.43 ± 0.87A	0.26 ± 0.01AB	0.56 ± 0.11A
NS	0–20	6.08 ± 0.15B	1.14 ± 0.01 BCD	8.34 ± 0.04AB	8.70 ± 0.39A	0.32 ± 0.12A	0.60 ± 0.13A
AG	0–20	9.16 ± 0.65B	1.27 ± 0.14 BCDE	8.26 ± 0.03B	5.04 ± 0.57E	0.19 ± 0.01B	0.62 ± 0.17A
NG	0–20	7.45 ± 1.01B	1.08 ± 0.07 D	8.43 ± 0.02A	7.52 ± 0.77B	0.25 ± 0.01AB	0.59 ± 0.21A
CK	0–20	11.42 ± 0.03B	1.34 ± 0.04 BD	8.10 ± 0.05C	4.20 ± 0.65F	0.15 ± 0.01B	0.55 ± 0.12A
AF	20–40	5.42 ± 0.01b	1.21 ± 0.01 d	8.23 ± 0.05c	4.41 ± 0.57b	0.16 ± 0.03b	0.48 ± 0.17a
AMF	20–40	9.41 ± 0.14ab	1.16 ± 0.06 d	8.28 ± 0.03bc	3.84 ± 0.41b	0.16 ± 0.02b	0.49 ± 0.15a
EF	20–40	11.88 ± 0.17a	1.26 ± 0.05 abd	8.12 ± 0.01d	4.36 ± 0.74b	0.19 ± 0.03ab	0.51 ± 0.22a
AS	20–40	6.70 ± 0.03b	1.20 ± 0.04 bd	8.32 ± 0.04b	4.98 ± 0.59ab	0.20 ± 0.05ab	0.32 ± 0.20a
NS	20–40	6.34 ± 0.01c	1.17 ± 0.09 e	8.29 ± 0.02bc	5.74 ± 0.82a	0.22 ± 0.04a	0.51 ± 0.24a
AG	20–40	10.44 ± 0.02b	1.38 ± 0.12 ac	8.28 ± 0.03c	3.30 ± 0.62c	0.16 ± 0.02b	0.39 ± 0.11a
NG	20–40	9.67 ± .029ab	1.19 ± 0.14c	8.35 ± 0.02ab	4.56 ± 0.43b	0.20 ± 0.02ab	0.48 ± 0.10a
CK	20–40	11.32 ± 0.05b	1.26 ± 0.01 ac	7.95 ± 0.02e	2.02 ± 1.79c	0.13 ± 0.01b	0.42 ± 0.09a

Note: Means with different uppercase letters represent the difference in the 0–20 cm soil layer under different vegetation restoration measures ($p < 0.05$); means with lowercase letters represent the difference in the 20–40 cm soil layer under different vegetation restoration measures ($p < 0.05$). RWC mean soil relative water content; BD mean soil bulk density; SOC mean soil organic carbon; TN mean soil total nitrogen; TP mean soil total phosphorus.

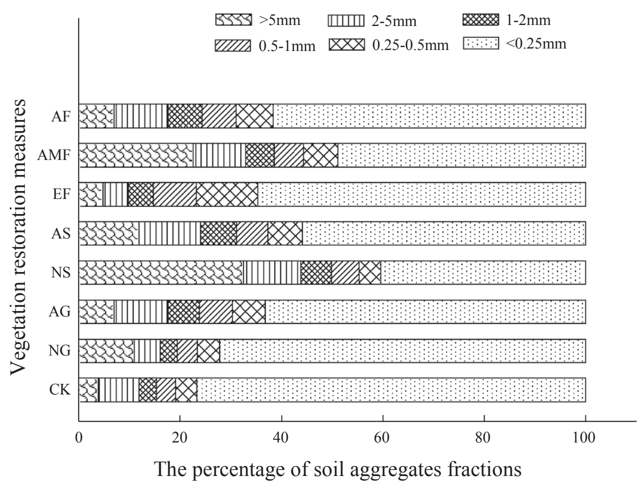

Fig. 3. The percentage of soil water-stable aggregate fractions in the 0–20 cm layer under different vegetation restoration measures.

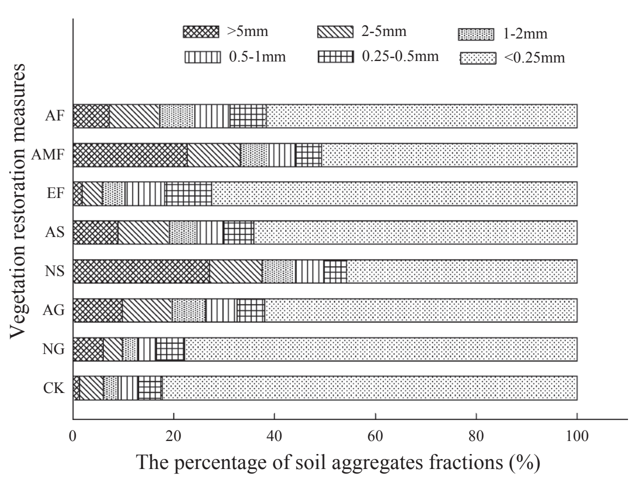

Fig. 4. The percentage of soil water-stable aggregate fractions in the 20–40 cm layer under different vegetation restoration measures.

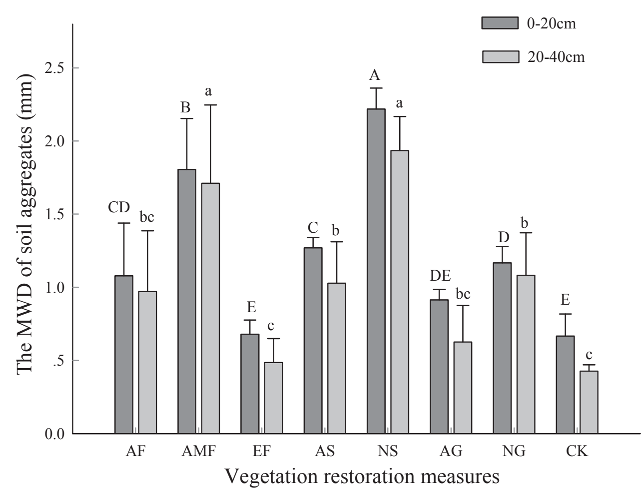

Fig. 5. The MWD of soil water-stable aggregates under different vegetation measures. Error bars represent the standard error of the mean (n = 3). Means with different uppercase (0–20 cm) and lowercase (20–40 cm) letters within the different soil layers are significantly different ($p < 0.05$).

3.3. The water stability of soil aggregates under different vegetation restoration measures

The variation in MWD for soil water-stable aggregates is shown in Fig. 5. As a whole, the MWD of revegetation measures were higher than that of CK except the EF. Among the 7 kinds of vegetation restoration measures, the MWD of NS was the highest, the MWD of AMF was the second and the MWD of EF was the lowest at the two different soil layers. The difference of MWD in topsoil was more obvious than for the subsoil ($p < 0.05$). The value of the MWD ranged from 0.67 mm to 2.22 mm in the 0–20 cm layer, but it varied from 0.43 mm to 1.93 mm in the 20–40 cm layer, which indicated that the soil water-stable aggregates in topsoil were more stable than those of the subsoil. In terms of forest restoration measures, the order of MWD was AFM > AF > EF. For the shrub restoration measures, the MWD of NS was significantly higher than that of AS ($p < 0.05$).

The variations in soil aggregate GMD are listed in the Table 3. In the

Table 3
GMD of soil aggregates under different vegetation restoration measures.

Restoration measures	Soil layer (cm)	GMD (mm)
AF	0–20	1.61 ± 0.18 BC
AMF	0–20	2.39 ± 0.71 AB
EF	0–20	1.08 ± 0.25 C
AS	0–20	1.93 ± 0.12 B
NS	0–20	2.86 ± 0.11 A
AG	0–20	2.05 ± 0.19 B
NG	0–20	1.67 ± 0.18 BC
CK	0–20	2.09 ± 0.76 B
AF	20–40	1.58 ± 0.38 bc
AMF	20–40	2.57 ± 0.69 ab
EF	20–40	0.93 ± 0.10 c
AS	20–40	1.86 ± 0.45 b
NS	20–40	2.66 ± 0.15 a
AG	20–40	1.49 ± 0.44 bc
NG	20–40	1.88 ± 0.43 b
CK	20–40	1.40 ± 0.15 c

Note: Means with different uppercase (0–20 cm) and lowercase (20–40 cm) letters within the different soil layers are significantly different under different vegetation restoration measures ($p < 0.05$).

topsoil layer, the GMD of NS was significantly higher than that of CK, however, the GMD of EF was significantly lower than that of CK ($p < 0.05$). In the subsoil layer, except the GMD of AF, EF and AG, the GMD under other vegetation restoration measures were significantly higher than that of CK, especially the GMD of NS and AS ($p < 0.05$). Overall, the maximum value of GMD under different restoration measures in the two soil layers was achieved in the NS; the AMF was the second and the minimum was observed for the EF, which was consistent with the changes of MWD. At the two different soil layers, the GMD of AS and NS exhibited a significant difference ($p < 0.05$).

3.4. The comparison of soil erodibility

The variation in soil erodibility (K value) is shown in Fig. 6. The K value of EF was significantly higher than that of CK; but the K value of NS was significantly lower than that of CK ($p < 0.05$). The K value of EF was the highest, but the K value of NS was lowest among different vegetation restoration measures, which indicated that the ability of soil to resist erosion in EF was weakest, but the ability of soil to resist erosion in the NS was the strongest. The K values in the 0–20 cm soil layer were lower than that in the 20–40 cm soil layer, which showed that the soil erosion resistance ability of topsoil was stronger than that of subsoil. Among the forest restoration measures, the order of soil ability to resist erosion was AMF > AF > EF in two soil layers; as for the shrub restoration measure, the K values of AS was not significantly higher than that of NS ($p > 0.05$); in terms of grass measure, the soil erodibility resistance of AG was higher than that of NG at the 0–20 cm soil layer, whereas in the 20–40 cm soil layer, the results were the opposite.

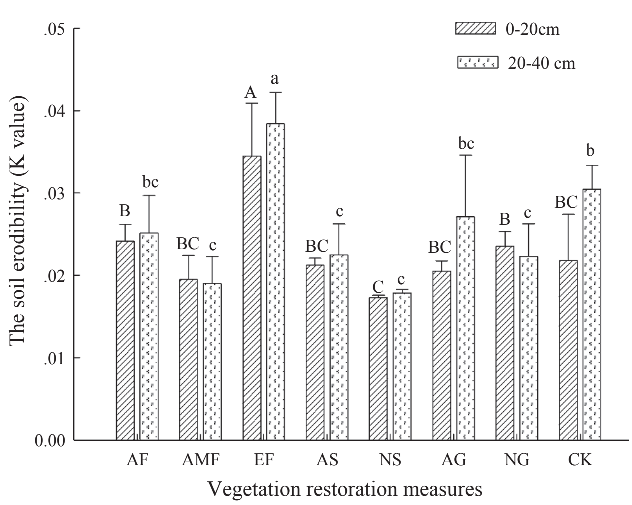

Fig. 6. The soil erodibility (K value) under different vegetation restoration. Uppercase and lowercase letters represent the difference of K values between the 0–20 cm and 20–40 cm soil layer ($p < 0.05$).

3.5. The correlations between the percentage of soil aggregate fractions, MWD, GMD, K value and basic physical and chemical properties of soil

Table 4 presents the correlations between the percentage of water stable soil aggregate fractions, MWD, GMD, K value and soil properties. The TN, SOC and UGB had positive significant correlations with the proportion of the > 5 mm, 2–5 mm and 1–2 mm soil aggregates ($p < 0.05$) but had a significant negative correlation with the percentage of the < 0.25 mm soil aggregates ($p < 0.01$). This may be closely related to that there was a higher carbon concentration in macroaggregates. Hence, if the proportion of macroaggregates increased, the content of SOC would increase considerably. This could be demonstrated by the SOC and the percentage of macroaggregates under NS in our research. The RWC had significant negative effects on the percentage of the > 5 mm and 2–5 mm soil aggregates ($p < 0.05$) but had significant positive effects on the proportion of the 0.5–1 mm and 0.25–0.5 mm soil aggregates ($p < 0.05$). The impacts of UGB on the percentage of > 1 mm was that the roots as the temporary binding agents improve the water-stability of macroaggregates by physical protection. This could be explained by (1) the structure of soil present study area was not stable and was prone to induce the disintegration of macroaggregates when the soil was infiltrated quickly; (2) The RWC was closely related to the soil water environment and soil porosity. When the RWC changed, it will make a difference to the environment around aggregates and soil porosity, which may lead aggregates to be shrunken and swelled easily. During the process of shrinking and swelling, the structure of macroaggregates may be destroyed and disintegrate to be some smaller aggregates. The MWD had a significant positive correlation with SOC, TN and UGB, but a significant negative correlation with RWC ($p < 0.05$). The RWC had a significant negative correlation with GMD but had a significantly positive correlation with the K value ($p < 0.05$). These results demonstrated that SOC, TN and UGB could promote the stability of soil aggregates, but RWC could reduce the stability of soil aggregates and weaken the ability of soil to resist erosion.

3.6. Comprehensive evaluation of the stability of soil aggregates and the ability of soil to resist erosion

The comprehensive scores of the stability of soil aggregates and the ability of soil to resist erosion are shown in Fig. 7. The stability of soil aggregates and the ability of soil to resist erosion were better with the increase of higher comprehensive scores (F). The results showed that the score of soil aggregate stability and ability of soil to resist erosion were strongest under the NS and lowest under the EF, which were the same as the trends observed for MWD and GMD. Among the forest restoration measures, the score of AMF was higher than that of AF and EF. The score of NS was higher than that of AS. The trends of AG and NG were the same as the AS and NS.

4. Discussion

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

In this study, the abandoned farmland soil (CK) was more degraded than the other restored soils because of the higher proportion of microaggregates in CK compared to macroaggregates. Liu et al. (2014)

Table 4
The correlations between the percentage of soil aggregate fractions, MWD, GMD, K value and physical and chemical properties of soil.

	RWC	BD	pH	SOC	TN	TP	AGB	UGB
$W_{>5mm}$	−0.416*	−0.129	0.213	0.409*	0.433*	−0.105	−0.163	0.433*
$W_{2\text{-}5mm}$	−0.597**	−0.398*	0.257	0.480*	0.496**	−0.331	−0.076	0.695**
$W_{1\text{-}2mm}$	−0.190	−0.255	0.353	0.633**	0.549**	−0.176	0.147	0.431**
$W_{0.5\text{-}1mm}$	0.384*	0.027	0.202	0.387*	0.327	0.056	0.363	−0.045
$W_{0.25\text{-}0.5mm}$	0.596**	0.117	−0.068	0.206	0.112	0.207	0.258	−0.257
$W_{<0.25mm}$	0.296	0.207	−0.309	−0.664**	−0.642**	0.133	−0.001	−0.516**
MWD	−0.425*	−0.284	0.220	0.457*	0.480*	−0.071	−0.172	0.503**
GMD	−0.419*	−0.098	0.033	0.086	0.162	−0.269	−0.213	0.371
K value	0.505**	0.348	−0.101	−0.010	−0.133	0.259	0.183	−0.349

Note: *, ** mean correlation coefficients are significant at the level of 0.05 and 0.01, respectively. $W_{>5mm}$: % of water stable aggregates higher than 5 mm; $W_{2\text{-}5mm}$: % of water stable aggregates between 2 and 5 mm; $W_{1\text{-}2mm}$: % of water stable aggregates between 1 and 2 mm; $W_{0.5\text{-}1mm}$: % of water stable aggregates between 0.5 and 1 mm; $W_{0.25\text{-}0.5mm}$: % of water stable aggregates between 0.25 and 0.5 mm; $W_{<0.25mm}$: % of water stable aggregates lower than 0.25 mm. MWD: the mean weight diameter of soil aggregates; GMD: the geometric mean diameter of soil aggregates; K value: soil erodibility; AGB indicates aboveground biomass; UGB: underground biomass.

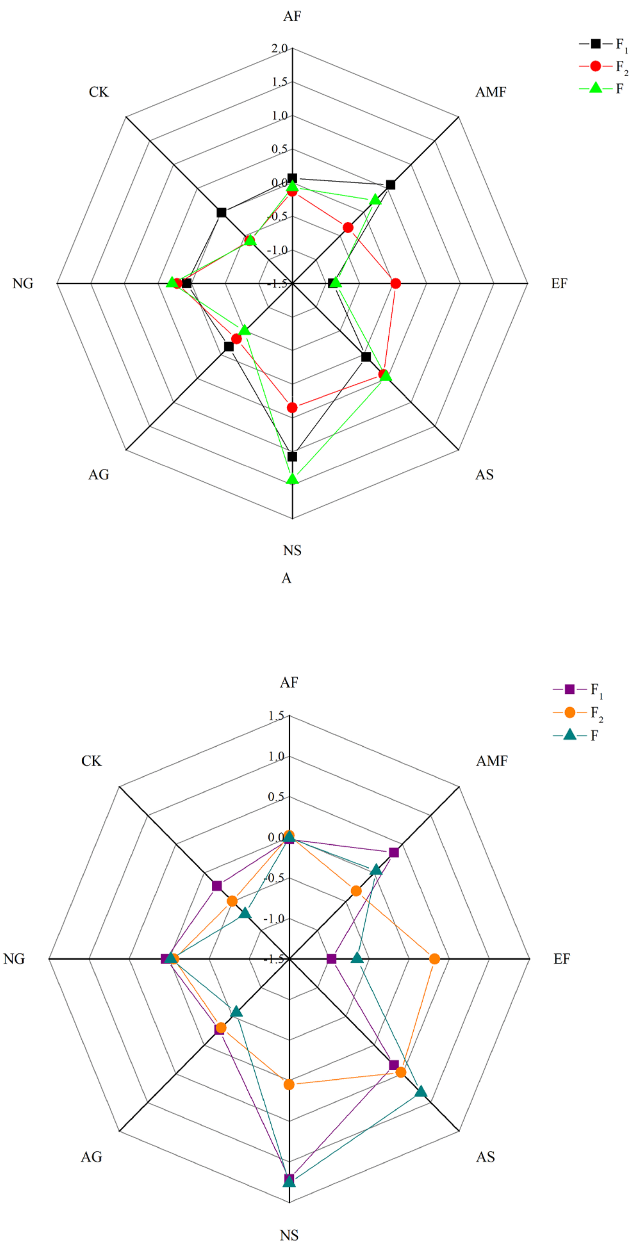

Fig. 7. The comprehensive score of soil aggregate stability (A) and erosion resistance ability (B).

found that the dominant aggregate size fractions were < 0.5 mm for farmland and > 0.5 mm for grass land and forestland. Similar results were demonstrated by these researches (Spaccini et al., 2001; Dong et al., 2016). They showed that due to long-term cultivation, the proportion of macroaggregates at the farmland were reduced. In addition, the findings that there were higher proportions of macroaggregates for the native grasslands compared with farmland, which agreed with the result of previous study (Cambardella and Elliot, 1993).

The changes of 0.25–5 mm macroaggregates were relatively stable compared with the > 5 mm aggregates. The reason is that the > 5 mm aggregates can be more susceptible to degradation by rain or wind erosion when soil was faced with rain erosion or wind erosion, since the erosion can physically disrupt the formation of water-stable aggregates with larger sizes (Ayoubi et al., 2012). Wang et al. (2016) found that the percentage of water-stable aggregates increased with increasing organic matter content ($p < 0.001$). In this study, we also observed that due to the higher content of organic carbon in the natural shrub land compared with CK, even other restoration measures, the content of macroaggregates was the highest in NS. A similar result was present in the study of Huang et al. (2010). Therefore, the present research also demonstrated that the proportion of soil aggregates with sizes > 2 mm appeared to be a suitable indicator for evaluating the effect of vegetation restoration changes on soil aggregates (Huang et al., 2010).

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

The MWD and GMD of soil aggregates play a vital role in assessing the stability of aggregates, and if the values of MWD and GMD are larger, the stability of the aggregates is stronger because of the higher ability to agglomerate (Piccolo et al., 1997; Rajeev et al., 2016). In our results, the MWD and GMD of soil aggregates under different vegetation restoration measures were basically higher compared with CK, especially the NS restoration measure, which indicated that the soil structure became more stable with the greater stability of aggregates after vegetation restoration. The effects of natural shrub land on the stability of the soil physical structure were the greatest, the artificial mixed forest was second, and the economic forest was the worst compared to the CK. This could be caused by the fact that the influence of human disturbance activities such as weeding and loose soil on farmland was the most serious and led to the vulnerability of the physical structure under the EF soil. This outcome was consistent with the previous research (Chrenková et al., 2014). They found that aggregates stability in farmland (conventional tillage management) was significantly lower than in forest land. And the impacts of conventional ploughing on the macroaggregates of bigger size was higher than the smaller ones. What's more, after the orchard terraces were abandoned for years, the stability of soil aggregates increased considerably (Chrenková et al., 2014). Celik (2005) also showed that the cultivated soils were more susceptible to water erosion than the forest and pasture soils. Accordingly, the abandoned farmland could protect the integrity of soil macroaggregates from the ploughing activities and then may improve the soil aggregates stability compared with the cultivated land. However, after years of cultivation, the stability of aggregates in abandoned farmland was low, as it demonstrated in the present study. As a consequence, among the different vegetation restoration measures, the soil of the natural shrub, which exhibited the largest MWD and GMD, was the most stable and its physical structure was relatively good.

4.3. Soil erodibility under different vegetation restoration measures

The soil erodibility factor, namely, the K value, can reflect the stability of soil physical structure, which is closely linked to soil aggregate stability (Barthès and Roose, 2002). Soils with large K values were vulnerable to erosion. In the present study, we observed the changes of the K value under different vegetation restoration measures and found that the K value of economic forests (EF) was highest but the K value for natural shrubs (NS) was the lowest in the 0–20 cm and 20–40 cm soil layers. Furthermore, the soil erodibility of EF was significantly higher than that of CK ($p < 0.05$) and the soil erodibility of NS was significantly lower than that of CK ($p < 0.05$). This indicated that the ability of soil to resist erosion under economic forests (EF) was weakest, but the ability of soil to resist erosion under natural shrubs (NS) was strongest contrast with abandoned farmland (CK) at two soil layers. Accordingly, vegetation restoration measures contributed to the improvement of the ability of soil to resist erosion, which was consistent with the previous results (Pinheiro et al., 2004; Sarah, 2005; Tang et al., 2010). Vegetation could reduce soil susceptibility to erosion by improving soil aggregate stability (Erktan et al., 2016). In our research, with the implementation of vegetation restoration measures, the coverage of plant aboveground has increased, which induced to the organic matter input by plant to increase and then may improve the physical and chemical properties of soil and promote the formation of new and more abundant aggregates. As a consequence, the stability of soil aggregates increased, which enhanced the ability of soil to resist erosion. This result was consistent with previous researches (Zhou et al., 2012; Pérès et al., 2013).

4.4. The correlations between the percentage of soil aggregate fractions, MWD, GMD, K value and basic physical and chemical properties of soil

In the present study, the content of RWC and SOC played a positive role on the proportion of 0.25–0.5 mm and 0.5–1 mm soil aggregates. This was due to that when the RWC was high, water would enter into the soil pore space and made the macroaggregates suffer extrusion and became inflation by absorbing water, which lead them to disintegration (Liu et al., 2018). Contrary to previous results (Huang et al., 2010), we found that the increase in the content of SOC, TN and UGB could produce a negative effect on the percentage of the < 0.25 mm soil aggregates (microaggregates) ($p < 0.01$). The reason is that microaggregates are generated firstly. After that, macroaggregates are formed on the base of microaggregates (Tisdall and Oades, 1982). Furthermore, macroaggregate was formed by the holding of the roots and hyphae, and then formed microaggregate in the center of the macroaggregate. However, the roots and hyphae can't insist on too long. With the decomposition of roots and hyphae, some fragments from that process coated with mucilages will get encrusted with clays and then form a microaggregate within a macroaggregate (Tisdall and Oades, 1982; Oades, 1984; Six et al., 2004). And the water-stability of macroaggregates depend on temporary binding agents (roots and hyphae) but the water-stability of microaggregates depends on the persistent organic binding agents (i.e. some multivalent cations and complexing organic acids) (Tisdall and Oades, 1982). The well-developed roots could increase the input of UGB, which lead to the increase of SOC and promote the formation of macroaggregates. Therefore, under the different vegetation restoration measures, the SOC and UGB had positive effects on the formation of macroaggregates.

In the present study, the effects of underground biomass (UGB) on MWD and GMD were positive, especially for MWD ($p < 0.01$). However, the effects of RWC on MWD and GMD were significantly negative ($p < 0.01$), which may be because the higher RWC is more prone to loosen the soil structure, leading to the reduction of soil aggregate stability. These results suggested that high UGB could increase the soil aggregates stability and the effect of the RWC on the soil aggregates was not to be ignored. Under the 7 types of vegetation restoration measured, the RWC has a significantly positive correlation with the K value, which indicates that soil RWC can make a substantial difference in soil erodibility. This could be because the resistance of soil to erosion will become weak when the RWC is relatively high, leading to the loss of the physical structure of the soil.

Hence, under the different vegetation restoration measures, maintaining high content of SOC and input of underground biomass were benefit to promote the formation of macroaggregates and increase the stability of soil aggregates and the ability of soil to resist erosion.

5. Conclusions

After the vegetation restoration measures were carried out, the distribution of aggregates, the stability of aggregates and the ability of soil to resist erosion have changed positively in the Zhifanggou watershed, Loess Plateau. The proportion of macroaggregates (> 0.25 mm) have increased, especially under natural shrub, which had positive correlation with SOC. Among the 7 types of restoration measures, the stability of soil aggregates under the natural shrub was highest; the artificial mixed forest was the second; the economic forest was the lowest. As a whole, the trend of the ability of soil to resist erosion was same to the stability of soil aggregates under different vegetation restoration measures. In addition, the increase of underground biomass and SOC could promote the formation of macroaggregates and improve the stability of soil aggregates and the ability of soil to resist erosion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was funded by Special-Funds of Scientific Research Programs of State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (A314021403-C6) and NSFC (41771317). The authors express their sincere thanks to the reviewers and issue editor of the journal for their valuable comments, suggestions, and revisions of this manuscript.

References

Anger, D.A., Samson, N., Légere, A., 1993. Early changes in water-stable aggregation induced by rotation and tillage in a soil under barely production. Can. J. Soil Sci. 73, 51–59.
An, S.S., Huang, Y.M., Zheng, F. Li., Yang, J.G., 2008. Aggregate characteristics during natural revegetation on the loess plateau. Pedosphere 18, 809–816.
Arshad, M.A., Cohen, G.M., 1992. Characterization of soil quality: physical and chemical criteria. Am. J. Altern. Agr. 7, 25–32.
Ayoubi, S., Karchegani, P.M., Mosaddeghi, M.R., Honarjoo, N., 2012. Soil aggregation and organic carbon as affected by topography and land use change in western Iran. Soil Tillage Res. 121, 18–26.
Barthès, B., Roose, E., 2002. Aggregates stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena. 47, 133–149.
Besnard, E., Chenu, C., Balesdent, J., 1996. Fate of particulate organic matter in soil aggregates during cultivation. Eur. J. Soil Sci. 47, 495–503.

Bremner, J.M., 1996. Nitrogen-total. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Parts 3. Chemical Methods. No 5. ASA and SSSA, Madison, Wi, pp. 1085–1121.
Cambardella, C.A., Elliott, E.T., 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57, 1071–1076.
Cammeraat, L.H., Imeson, A.C., 1998. Deriving indicators of soil degradation from soil aggregation studies in southeastern Spain and southern France. Geomorphology 23, 307–321.
Celik, I., 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. Soil Tillage Res. 2, 270–277.
Chrenková, K., Jorge, M.S., Dlapa, P., Arcenegui, V., 2014. Long-term changes in soil aggregation comparing forest and agricultural land use in different Mediterranean soil types. Geoderma 235–236, 290–299.
Dong, X.L., Guan, T.Y., Li, G.T., Lin, Q.M., Zhao, X.R., 2016. Long-term effects of biochar amount on the content and composition of organic matter in soil aggregates under field conditions. J. Soil Sediment. 16, 1481–1497.
Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633.
Erktan, A., Cécillon, L., Graf, F., Roumet, C., Legout, C., Rey, F., 2016. Increase in soil aggregates stability along a Mediterranean successional gradient in severely eroded gully bed ecosystems: combined effects of soil, root traits and plant community characteristics. Plant Soil. 398, 121–137.
Feng, X.M., Fu, B.J., Lu, N., Zeng, Y., Wu, B.F., 2013. How ecological restoration alters ecosystem services: an analysis of carbon sequestration in China's Loess Plateau. Sci. Rep. 3, 28–46.
Fonte, S.J., Barrios, E., Six, J., 2010. Earthworms, soil fertility and aggregate-associated soil organic matter dynamics in the Quesungual agroforestry system. Geoderma 155, 320–328.
Huang, L., Wang, C.Y., Tan, W.F., Hu, H.Q., Cai, C.F., Wang, M.K., 2010. Distribution of organic matter in aggregates of eroded Ultisols. Central China. Soil Tillage Res. 108, 59–67.
Huang, Y.M., Liu, D., An, S.S., 2015. Effects of slope aspect on soil nitrogen and microbial properties in the Chinese Loess region. Catena. 125, 135–145.
Hortensius, D., Welling, R., 1996. International standardization of soil quality measurements. J. Commun. Soil Sci. Plant Anal. 27, 387–402.
Jackson, M.L., 1979. Soil Chemical Analysis. Advanced Course, 2nd ed. University of Wisconsin, Madison, Wi, USA, pp. 33–35.
Liu, M.Y., Chang, Q.R., Qi, Y.B., Liu, J., Chen, T., 2014. Aggregation and soil organic carbon fractions under different land uses on the table land of the Loess Plateau of China. Catena 115, 19–28.
Liu, Y., Ma, M.H., Wu, S.J., Ran, Y.G., Wang, X.X., Huang, P., 2018. Progress and prospect of soil aggregates stability induced by wetting and drying cycles. Soils 50, 853–865.
Lü, Y.H., Fu, B.J., Feng, X.M., Zeng, Y., Liu, Y., Chang, R.Y., Sun, G., Wu, B.C., 2012. A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. PLoS ONE 7, e31782.
Majid, M., Bahareh, A., 2013. Dry and water-stable aggregates in different cultivation systems of arid region soils. Arab. J. Geosci. 6, 2997–3002.
Minreal, C.M., Scgulten, H.R., Kondana, H., 1997. Age, turnover and molecular diversity of soil organic matter in aggregates of a Gleysol. Can. J. Soil Sci. 77, 379–388.
Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Parts 3. Chemical Methods. No 5. ASA and SSSA, Madison, Wi, pp. 961–1010.
Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76, 319–337.
Pérès, G., Cluzeau, D., Menasseri, S., Soussana, J.F., Bessler, H., Engels, C., Habekost, M., Gleixner, G., Weigelt, A., Weisser, W.W., Scheu, S., Eisenhauer, N., 2013. Mechanisms linking plant community properties to soil aggregate stability in an experimental grassland plant diversity gradient. Plant Soil 373, 285–299.
Piccolo, A., Piettramellara, G., Mbagwu, J.S.C., 1997. Use of humic substances as soil conditioners to increase aggregate stability. Geodem. 75, 265–277.
Pinheiro, E.F.M., Pereira, M.G., Anjos, L.H.C., 2004. Aggregates distribution and soil organic matter under different tillage systems for vegetable crops in a Red Latosol from Brazil. Soil Tillage Res. 77, 79–84.
Puget, P., Chenu, C., Balesdent, J., 2000. Dynamics of soil organic matter associated with particle-size fractions of water-stable aggregates. Eur. J. Soil Sci. 51, 595–605.
Rajeev, P., Rajiv, R., Anupam, D., Sharama, R.P., 2016. Effects of various organic amendments on organic carbon pools and water stable aggregates under a scented rice–potato–onion cropping system. Paddy Water Environ. 14, 481–489.
Ren, H., Li, Z.A., Shen, W.J., Yu, Z.Y., Peng, S.L., Liao, C.H., Ding, M.M., Wu, J.G., 2007. Changes in biodiversity and ecosysterm function during the restoration of a tropical forest in South China. Sci. China, Ser. C Life Sci. 50, 277–284.
Sarah, P., 2005. Soil aggregates response to long- and short-term different in rainfall amount under arid and Mediterranean climate conditions. Geomorphology 70, 1–11.
Shirazi, M., Boerama, L., 1984. A unifying quantitative analysis of soil texture. Soil Sci. Soc. Am. J. 48, 142–147.
Singh, S., Singh, J.S., 1996. Water-stable aggregates and associated organic matter in forest, savanna, and cropland soils of a seasonally dry tropical region. India. Bioi Fertil Soils. 22, 76–82.
Six, J., Eilliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62, 1367–1377.
Six, J., Elliott, E.T., Paustian, K., 2000a. Soil macro-aggregate turnover and micro-aggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103.
Six, J., Elliott, E.T., Paustian, K., 2000b. Soil structure and organic matter II. A normalized stability index and the effect of mineralogy. Soil Sci. Soc. Am. J. 64, 1042–1049.
Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Till Res 79, 7–31.
Six, J., Paustian, K., 2014. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol. Biochem. 68, 4–9.
Spaccini, R., Zena, A., Igwe, C.A., Mbagwu, J.S.C., Piccolo, A., 2001. Carbohydrates in water-stable aggregates and particles size fractions of forested and cultivated soils in two contrasting tropical. Biogeochemistry 53, 1–22.
Sumner, M.E., Miller, W.P., 1996. Cation exchange capacity and exchange coefficients. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Parts 3. Chemical Methods. No 5. ASA and SSSA, Madison, Wi, pp. 1201–1229.
Taboada, M.A., Barbosa, O.A., Rodriguez, M.B., Cosentino, D.J., 2004. Mechanisms of aggregation in a silty loam under different simulated management regimes. Geoderma 3–4, 233–244.
Tang, X.Y., Liu, S.G., Liu, J.X., Zhou, G.Y., 2010. Effects of vegetation restoration and slope positions on soil aggregates and soil carbon accumulation on heavily eroded tropical land of Southern China. J. Soil Sediment. 10, 505–513.
Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. Eur. J. Soil Sci. 33, 141–163.
Tsunekawa, A., Liu, G., Yamanaka, N., Du, S., 2014. Restoration and Development of the Degraded Loess. Springer, Plateau, China, pp. 51–55.
Vanbavel, C.H.M., 1950. Mean weight-diameter of soil aggregates as a statistical index of aggregation. Soil Sci. Soc. Am. J. 14, 22–23.
Wang, J.Y., Xiong, Z.Q., Kuzyakov, Y., 2016. Biochar stability: meta-analysis of decomposition and priming effects. GCB Bioenergy 8, 512–523.
Wang, L., Mu, Y., Zhang, Q.F., Jia, Z.K., 2012. Effects of vegetation restoration on soil physical properties in the wind–water erosion region of the northern Loess Plateau of China. Clean-soil air water. 40, 7–15.
Zhang, L.Q., Wei, X.R., Hao, M.D., Zhang, M., 2015. Changes in aggregate-associated organic carbon and nitrogen after 27 years of fertilization in a dry land alfalfa grassland on the Loess Plateau of China. J. Arid Land. 7, 429–437.
Zhang, M., Cheng, G., Feng, H., Sun, B.H., Zhao, Y., Chen, J., Dyck, M., Wang, X.D., Zhang, J.G., Zhang, A.F., 2017. Effects of straw and bio-char amendments on aggregate stability, soil organic carbon, and enzyme activities in the Loess Plateau. China. Environ Sci and Pollut Res. 24, 10108–10120.
Zhang, X.C., Miller, W.P., 1996. Polyacrylamide effect on information and erosion in furrows. Soil Sci. Soc. Am. J. 60, 866–872.
Zhao, W., Zhang, R., Huang, C.Q., Wang, B.Q., Cao, H., Koopal, L.K., Tan, W.F., 2016. Effect of different vegetation cover on the vertical distribution of soil organic carbon and inorganic carbon in the Zhifanggou Watershed on the loess plateau. Catena 139, 191–198.
Zeng, Q.C., Frédéric, D., Cheng, M., Zhu, Z.L., An, S.S., 2018. Soil aggregate stability under different rain conditions for three vegetation types on the Loess Plateau (China). Catena 167, 276–283.
Zhou, G.Y., Morris, J.D., Yan, J.H., Yu, Z.Y., Peng, S.L., 2002. Hydrological impacts of reafforestation with aucalypts and indigenous species: a case study in southern China. Forest Ecol. Manage. 167, 209–222.
Zhou, H., Peng, X.H., Peth, S., Xiao, T.Q., 2012. Effects of vegetation restoration on soil aggregates microstructure quantified with synchrotron-based micro-computed tomography. Soil Tillage Res. 124, 17–23.