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Soil aggregation and intra-aggregate carbon fractions in relation to vegetation succession on the Loess Plateau, China

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ABSTRACT

Revegetation has been reported to be one of the most effective measures for reducing soil erosion on the Loess Plateau in China. The Yunwu observatory, located in the northwestern Loess Plateau of China, was selected to study the effect of vegetation succession on total carbon (C), aggregate C, and intra-aggregate particulate organic matter-carbon (iPOM-C) concentrations. The vegetation types studied, listed from the shortest to the longest enclosure duration order, were abandoned grazed grassland (Ab.G3), *Hierochloe odorata* Beauv. (Hi.O7), *Thymus mongolicus* Ronnm (Th.M15), *Artemisia sacrorum* Ledeb (At.S25), *Stipa bungeana* Trin Ledeb (St.B36), and *Stipa grandis* P. Smirn (St.G56) communities. Five sizes of aggregates were separated using the modified Yoder method (<0.25 mm, 0.25–1 mm, 1–2 mm, 2–5 mm and 5–8 mm). Fine and coarse iPOM-C concentrations were isolated from the soil aggregates. The results showed that revegetation led to an increase in the percentage of aggregates in small macroaggregates (0.25–2 mm) and thereby improved the uniformity of the soil aggregate size distribution. The concentration of bulk soil carbon ranged from 10.1 g kg^{-1} to 29.7 g kg^{-1} during vegetation succession. During the vegetation succession, with the exception of At.S25, the bulk soil carbon and aggregate carbon concentrations increased with recovery time. The fine iPOM-C concentrations were between 0.7 and 14.0 g kg^{-1}, which was significantly greater than the coarse iPOM-C concentrations. The coarse and fine iPOM-C concentrations exhibited different trends with vegetation restoration. In conclusion, vegetation restoration caused an increase in small macroaggregates, enhancing the uniformity of the soil aggregate size distribution and inducing greater soil organic carbon sequestration.

1. Introduction

Soil aggregates and their stability influence a wide range of soil properties, including carbon stabilization, soil porosity, water infiltration, aeration, compactability, water retention, hydraulic conductivity, and the ability to resist water erosion. Aggregate stability was described as one of the soil properties that can serve as an indicator of soil quality by Arshad and Cohen (1992). Soil microorganisms, organic matter and certain inorganic matter may contribute to soil aggregation. The organic matter influences soil structure and stability by binding soil mineral particles, reducing aggregate wettability, and influencing the mechanical strength of soil aggregates, which is a measure of the coherence of inter-particle bonds (Onweremadu et al., 2007). Meanwhile, the formation and stabilization of soil aggregates always facilitate soil carbon sequestration and provide physical protection for soil carbon.

Soil organic carbon (SOC) has a large influence on physical, chemical, and biological soil properties (Carter, 2001). SOC can be divided into several C fractions. Physical fractionation, according to the size and density of soil particles, emphasizes the importance of interactions between organic and inorganic soil components in the turnover of organic matter (Christensen, 2001). Based on this approach, Six et al. (1998) provided a conceptual explanation for aggregate formation. Soil carbon associated with aggregates (i.e., intra-aggregate particulate organic matter-carbon, iPOM-C) has been studied by many researchers (Conant et al., 2004; Zotarelli et al., 2007). This carbon fraction is also identified as a potential indicator of increasing C sequestration under zero tillage (Denef et al., 2007; Six et al., 2000).

Natural vegetation succession is an important measure of improving ecological and environmental quality. The response of SOC and aggregate stability associated with revegetation succession has been well studied (An et al., 2010; Barua and Haque, 2013; Fattet et al., 2011; Jia et al., 2012; Lenka et al., 2012; Peng et al., 2003; Tang et al., 2010;

Abbreviations: SOC, Soil organic carbon; Ab.G3, Abandoned grazed grassland (3 years); Hi.O7, *Hierochloe odorata* Beauv. (7 years); Th.M15, *Thymus mongolicus* Ronnm (15 years); At.S25, *Artemisia sacrorum* Ledeb (25 years); St.B36, *Stipa bungeana* Trin Ledeb (36 years); St.G56, *Stipa grandis* P. Smirn (56 years); MWD, Mean weighted diameter; iPOM-C, Intra-aggregate particulate organic matter-carbon.

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Wang et al., 2011; Young et al., 2005). However, the soil aggregation and carbon sequestration during revegetation succession are still not well documented. The isolation of iPOM-C has been mainly conducted in agroecosystems. The iPOM-C can be used as a general diagnostic of management-induced changes in SOC levels in agroecosystems across a wide range of soil types and under drastically different climate conditions (Six and Paustian, 2014). Quantifying the iPOM-C can help us in better understanding the mechanisms of carbon sequestration and soil aggregation during vegetation restoration.

Although a number of studies have been conducted on the effect of vegetation succession on soil carbon sequestration and aggregation, the dynamics and mechanisms of soil carbon sequestration during revegetation succession are not well documented. The objective of this study was to assess the effect of vegetation succession on soil carbon by quantifying bulk soil carbon, aggregate carbon and iPOM-C during natural revegetation restoration on the Loess Plateau of China. The following hypotheses were tested in this study: (1) vegetation recovery would alter soil aggregate size distribution; (2) vegetation succession would increase bulk soil carbon and aggregate carbon; (3) iPOM-C would also be identified as a potential indicator of increasing C sequestration during vegetation restoration.

2. Materials and methods

2.1. The study sites and approach

The studied area was the Yunwu Observatory for Vegetation Protection and Eco-environment, located on the Loess Plateau in China. The observatory is under permanent grassland in Guyuan, Ningxia autonomous region, between 106°24′E and 106°28′E longitude and between 36°13′N and 36°19′N latitude (Fig. 1). It has been a protected grassland area for more than 100 years. The study area has a sub-arid climate. The mean annual temperature is 7 °C. The average annual rainfall is 400 mm (1941–2000; C.V. 18%) with distinct wet and dry seasons. The rainy season starts in July and ends in September. The rainfall in July accounts for 24% of the total annual rainfall. The studied pedons were classified as Entisols, according to soil taxonomy (Soil Survey Staff, 2010).

The method of space-for-time substitution, an effective way to study changes over time (Sparling et al., 2003), was used to monitor plant and soil changes occurring along a vegetative chronosequence that have developed with similar soils and climatic conditions. Sites stabilized by revegetation at different times offer an ideal opportunity to understand the vegetation succession process because soil conditions before revegetation are largely driven by geomorphologic processes and vegetation succession occurs over time.

In this study, an existing succession series, i.e., a series of stages of a particular plant succession, was selected. According to the process of plant succession in this area (Zou and Guan, 1997), we studied six successional stages that represent 3, 7, 15, 25, 36 and 56 years (Table 1). Depending on the age of the natural succession, the plant communities were as follows: (a) Ab.G3 (3-year-old abandoned overgrazing grassland), (b) Hi.O7: *Hierochloe odorata* Beauv. (7 years), (c) Th.M15: *Thymus mongolicus* Ronnm (15 years), (d) At.S25: *Artemisia sacrorum* Ledeb (25 years), (e) St.B36: *Stipa bungeana* Trin Ledeb (36 years), and (f) St.G56: *Stipa grandis* P. Smirn (56 years).

2.2. Soil sampling and preparation

Soil samples were collected in July 2011. For each site, three areas of 60 m × 60 m were delineated on an upper slope, a middle slope, and a lower slope. From each area, three undisturbed soil samples from the depths of 0–20 cm and 20–40 cm were collected separately and stored in aluminum containers. A total of 108 undisturbed soil samples were obtained for all vegetation types. The samples were air dried at room temperature. Then, each sample was passed through an 8-mm sieve to remove large roots, stones, and macrofauna.

2.3. Soil aggregate stability by the modified Yoder method

The aggregate separation was performed using a modified Yoder method (Zhu, 1982) with a set of sieves with openings of 0.25, 0.5, 1, 2, and 5 mm. The sieve set was rapidly immersed in distilled water and oscillated with a displacement of approximately 4 cm at 37 cycles per minute for 3 min. All fractions were dried at 70 °C overnight and

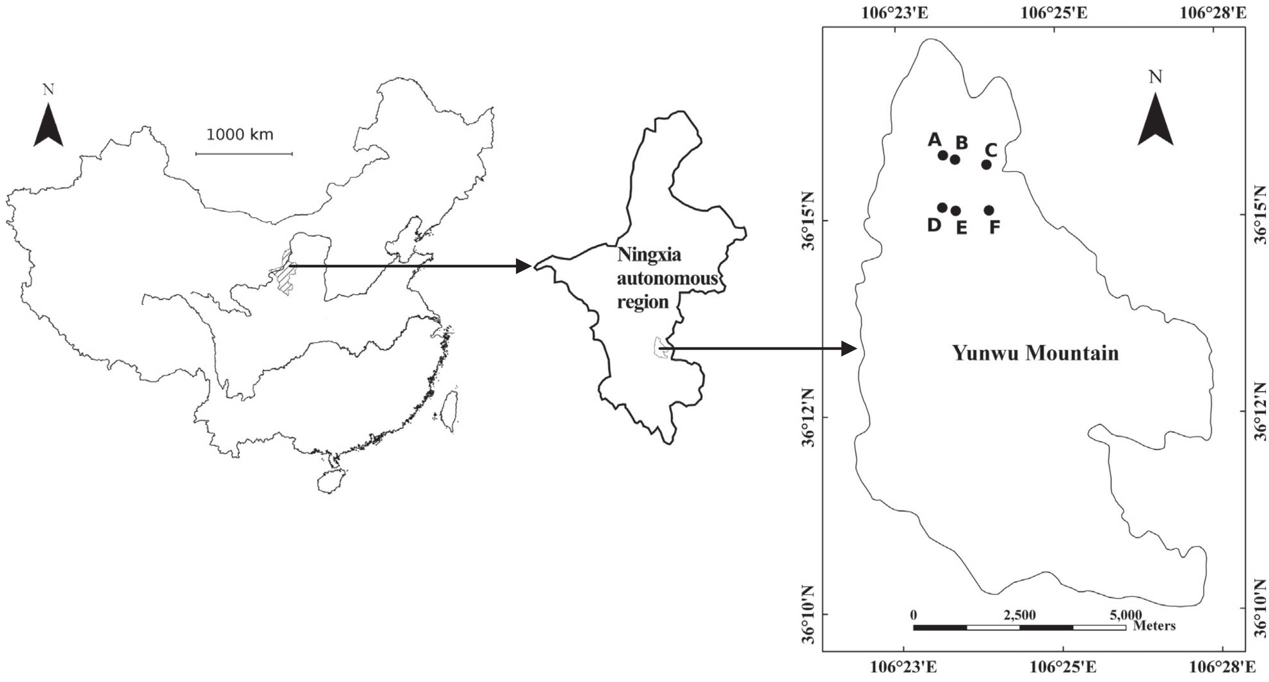


Fig. 1. Location of the study sites. A: recently abandoned grazing on grassland (3 years, Ab.G3); B: *Artemisia sacrorum* Ledeb (25 years, At.S25); C: *Hierochloe ordorata* Beauv (7 years, Hi.O7); D: *Stipa grandis* P. Smirn (56 years, StG56); E: *Thymus mongolicus* Ronnm (15 years, Th.M15); F: *Stipa bungeana* Trin Ledeb (36 years, St.B36).

Table 1
Characteristics of the study area and vegetation.

Sample site name	Revegetation years (a)	Geographical coordinates Ψ(N), λ(E)	Elevation (m)	Slope gradient (°)	Dominant species	Accompanying species	Fresh mass of aerial biomass (g/m^2)
Ab.G3	3	36°15.807′ 106°23.226′	2078	5	*Leymus secalinus* (Georgi) Tzvel.	*Artemisia scoparia* *Thymus mongolicus* *Potentilla bifurca*	86
Hi.O7	7	36°15.683′ 106°23.906′	2080	6	*Hierochloe ordorata* *Leymus secalinus*	*Artemisia scoparia* *Thymus mongolicus*	180
Th.M15	15	36°15.101′ 106°23.415′	1903	10	*Thymus mongolicus* Ronnm	*Stipa gradiss*; *Artemisia sacrorum*; *Potentilla bifurca* Linn.	539
At.S25	25	36°15.751′ 106°23.415′	2082	12	*Artemisia sacrorum* Ledeb	*Stipa bungana* *Heteropappus altaicus* *Thymus mongolicus*	546
St.B36	36	36°15.101′ 106°23.935′	2097	14	*Stipa bungeana* Trin Ledeb	*Artemisia sacrorum* *Thymus mongolicu* *Leymus secalinu* *Potentilla bifurca*	618
St.G56	56	36°15.143′ 106°23.204′	2058	10	*Stipa grandis* P. Smirn	*Artemisia frigida* Willd. *Potentilla acaulis* L. *Medicago ruthenica* *Potentilla angustiloba*	806

Note: Ab.G3: recently abandoned grazing on grassland (3 years); Hi.O7: *Hierochloe ordorata* Beauv (7 years); Th.M15: *Thymus mongolicus* Ronnm (15 years); At.S25: *Artemisia sacrorum* Ledeb (25 years); St.B36: *Stipa bungeana* Trin Ledeb (36 years); St.G56: *Stipa grandis* P. Smirn (56 years).

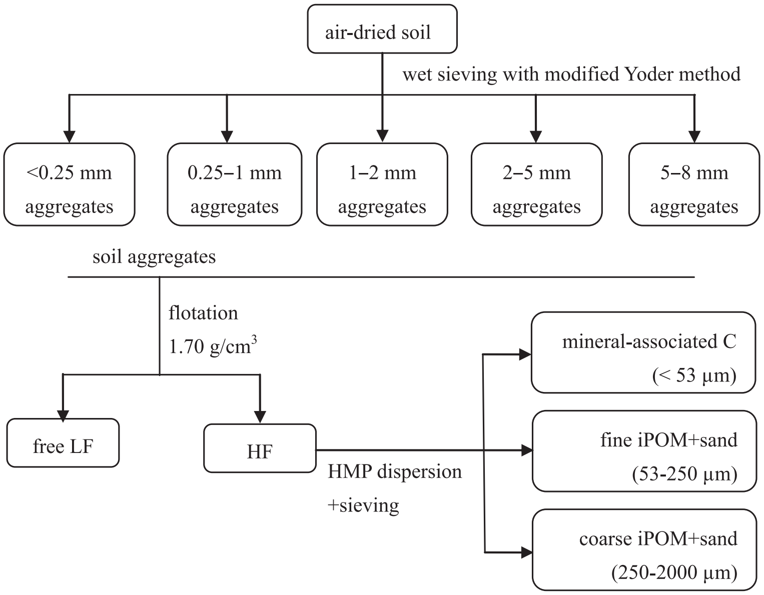
then weighed. The mean weighted diameter (MWD) of water-stable aggregates was calculated as follows:

$$MWD = \sum_{i=1}^{n} \overline{x_i} \times w_i \qquad (1)$$

where $\overline{x_i}$ is the mean diameter of each size fraction and w_i is the proportional weight of the corresponding size fraction (Kemper and Rosenau, 1986).

2.4. Soil aggregate carbon and fine and coarse intra-aggregate particulate organic carbon

To measure C concentrations, bulk soil samples and aggregate fractions were ground fine enough to pass through a 0.15 mm sieve. The bulk soil C (g kg^{-1}) and aggregate C concentrations were analyzed by potassium dichromate volumetry. The procedure of Six et al. (1998) was used to obtain intra-aggregate particulate organic carbon (iPOM-C) and is summarized in Fig. 2. Approximately 25.0 g of dried aggregates was transferred to a 100-ml graduated centrifuge tube and dispersed in 50 ml of sodium iodide (with a density of 1.7 g cm^{-3}). The suspension was shaken thoroughly for 60 min by a horizontal shaker. The suspension was then centrifuged at 3000 r/min for 30 min. The supernatant, including floating particles, was filtered (using polyamide membrane filters with a pore size of 0.45 μm) under vacuum and washed with distilled water to obtain the free light fraction (LF). The floating material was transferred to a small aluminum pan and dried at 50 °C. To achieve a complete extraction, the above steps were then repeated with the heavy fraction, which was dispersed, shaken, centrifuged, and filtered to obtain the free light fraction a second time. The content of free light



Note: LF = light fraction; HF = heavy fraction; iPOM = intra-aggregate particulate organic matter; HMP = hexametaphosphate.

Fig. 2. Fractionation sequence of soil organic carbon. Note: LF = light fraction; HF = heavy fraction; iPOM = intra-aggregate particulate organic matter; HMP = hexametaphosphate.

fraction was taken as the sum of the free LF obtained from the first and second filtering processes. After the isolation of the free LF, aggregates were dispersed in a 5-g/L sodium hexametaphosphate solution by shaking for 18 h in a reciprocal shaker. The dispersed heavy fraction was passed through 2000-, 250-, and 53-μm sieves. The coarse intra-aggregate particulate organic matter (250–2000 μm) and the fine intra-aggregate particulate organic matter (53–250 μm) were isolated by sieving. The C concentrations of all fractions were analyzed.

2.5. Statistical analysis

A factorial experiment (Factor 1: vegetation types with six levels, Factor 2: soil depth with two levels, and nine replications) based on the completely randomized blocks was performed. Statistical analyses of the studied soil carbon were performed on the samples obtained from the two depths (0–20 cm and 20–40 cm). The data were analyzed using analysis of variance (ANOVA) in the SPSS statistical software (SPSS Institute, 2010). The Student–Newman–Keuls method ($P < 0.05$) was used to assess the differences among revegetation durations and soil depths. The soil property data are taken from An et al. (2013). The correlation between the soil carbon fractions and the soil properties was studied using the Spearman's correlation test.

3. Results

3.1. Fractions and stability of water-stable macroaggregates

The soil aggregate distribution and the mean weighted diameter (MWD) associated with each sampling depth are listed in Table 2. In the 0–20 cm depth range, the percentage of water-stable macroaggregates (>0.25 mm) decreased in the following order: Hi.O7 > Th.M15 > Ab.G3 > At.S25 > St.B36 > St.G56. The MWD of Hi.O7-dominated vegetation was significantly higher than the others, followed by Ab.G3, and in the later stages, the MWD decreased with vegetative recovery time.

For the 20–40 cm soil depth, with the exception of Hi.O7, the percentages of water-stable macroaggregates of all the plant communities were higher than those of Ab.G3. The MWD decreased in this order: Th.M15 > St.G56 > At.S25 > St.B36 > Ab.G3 > Hi.O7. The MWDs of St.G56 and Th.M15 were not significantly different, whereas they differed significantly from the MWDs of Ab.G3 and At.S25. The MWDs of Hi.O7 and St.B36 were statistically lower than those of Ab.G3 and At.S25. Additionally, at both soil depths, small macroaggregates (0.25–2 mm) increased with vegetation succession, whereas large macroaggregates (2–5 mm and 5–8 mm) increased following vegetation restoration only at 20–40 cm depth.

3.2. Concentrations of bulk soil carbon, aggregate carbon and intra-aggregate POM-C

The vegetation types were found to have a significant effect ($P < 0.05$) on the bulk soil carbon concentration. The bulk soil carbon concentrations were 15.1–26.8% higher at 0–20 cm depth than at 20–40 cm depth (Table 3). At both 0–20 and 0–40 cm depths, the SOC concentration tended to increase with recovery time, except under At.S25-dominated vegetation. The changes in aggregate C followed trends similar to those observed for the concentration of bulk soil carbon. Under the Ab.G3 vegetation type, the carbon concentrations were significantly lower in the 0–20 cm depth than in the 20–40 cm depth except for <0.25 mm and 5–8 mm size aggregates. For all the other vegetation types, the concentrations of aggregate C were significantly higher in the 0–20 cm layer than in the 20–40 cm layer for most of size aggregates. Also, the medium-sized aggregates (0.25–5 mm size class) generally had higher SOC concentrations than the smallest and largest aggregates.

During vegetation succession, the concentration of coarse iPOM-C tended to increase with aggregate size in the 0–20 cm depth (Fig. 3A), whereas coarse iPOM-C was highest in 0.25–1 mm sized aggregates in the 20–40 cm depth (Fig. 3B). The coarse iPOM-C concentrations were the highest under At.S25- and St.B36-dominated vegetation. The fine iPOM-C concentrations were between 0.7 and 14.0 $g\ kg^{-1}$, obviously greater than the coarse iPOM-C concentrations (Figs. 3C and D). During vegetation succession, apart from St.G56 and St.B36, the fine iPOM-C concentrations in microaggregates (<0.25 mm) were clearly greater than those in macroaggregates (0.25–8 mm). During vegetation restoration, the fine iPOM-C concentrations tended to increase from Ab.G3 to Th.M15, decrease from Th.M15 to St.B36, then increase again from St.B36 to St.G56.

3.3. The correlation of soil carbon and soil properties

Soil carbon fractions were correlated to soil properties, such as pH and nutrients (Table 4). Significant correlations were found between all fractions of aggregate C and SOC content, total N, available P, and available K. Coarse and fine iPOM-C within medium-size aggregates (0.25–1 mm, 1–2 mm, 2–5 mm size aggregates) were significantly correlated with soil carbon, total N, available P, and available K.

4. Discussion

4.1. The influence of natural vegetation succession on soil aggregation

The distribution of soil aggregates is a determinant of the soil pore size distribution (Hillel, 1982). Stable aggregates can physically protect soil organic matter against rapid decomposition (Pulleman and

Table 2
Aggregate size distribution and mean weight diameter (MWD) under different vegetation types.

Vegetation type	Aggregate content (%)										MWD[a]	
	<0.25 mm		0.25–1 mm		1–2 mm		2–5 mm		5–8 mm			
Depth (cm)	0–20	20–40	0–20	20–40	0–20	20–40	0–20	20–40	0–20	20–40	0–20	20–40
Ab.G3	34.9	38.3	10.2	7.8	6.5	4.7	13.2	11.4	35.2	37.9	2.95(0.56)bA	3.03(0.17)abA
Hi.O7	26.5	41.3	9.1	10.3	5.9	5.3	12.3	10.9	46.2	32.3	3.61(0.21)aA	2.68(0.57)bB
Th.M15	32.7	20.8	20.2	13.1	11.9	8.6	15.6	20.5	19.6	37.1	2.17(0.32)cB	3.37(0.50)aA
At.S25	36.6	26.2	17.5	14.2	10.5	9.3	15.4	19.7	20.0	30.6	2.15(0.30)cB	2.94(0.39)abA
St.B36	38.5	34.1	17.8	14.5	10.2	7.7	15.3	16.1	18.2	27.7	2.03(0.29)cA	2.61(0.37)bA
St.G56	44.9	25.7	17.4	11.8	8.1	6.2	10.5	13.9	19.2	42.5	1.90(0.45)cB	3.45(0.30)aA

Note: (1) Ab.G3: recently abandoned grazing on grassland (3 years); Hi.O7: *Hierochloe ordorata* Beauv (7 years); Th.M15: *Thymus mongolicus* Ronnm (15 years); At.S25: *Artemisia sacrorum* Ledeb (25 years); St.B36: *Stipa bungeana* Trin Ledeb (36 years); St.G56: *Stipa grandis* P. Smirn (56 years). (2) Different lowercase letters indicate significant differences at $P < 0.05$ among different vegetation types, and different capital letters indicate significant differences at $P < 0.05$ among soil depths.

[a] Mean weight diameter. Mean value with standard error.

Table 3
Concentration of bulk soil carbon and aggregate carbon (g kg^{-1}, mean values with standard errors) under different vegetation types.

Vegetation types	Aggregate carbon concentration (g kg^{-1})										Bulk soil carbon (g kg^{-1})	
	< 0.25 mm		0.25–1 mm		1–2 mm		2–5 mm		5–8 mm			
Depth	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Ab.G3	14.24(0.01)cdA	9.30(1.59)bB	10.95(1.31)dB	12.52(1.74)bA	9.86(0.17)cB	11.64(0.68)dA	12.46(0.01)cB	14.05(1.89)bA	8.53(1.17)cA	8.81(0.50)bA	11.93(0.08)bA	10.14(0.94)bB
Hi.O7	16.34(0.62)cA	13.60(0.98)bB	16.52(0.97)cA	13.52(0.02)bB	17.38(0.01)bA	13.86(0.28)cB	13.78(3.11)bcB	15.28(0.36)bA	15.11(1.26)abA	13.51(3.06)abB	15.80(0.04)bA	13.72(1.27)bB
Th.M15	25.53(0.15)bA	19.51(0.01)aB	27.91(0.99)bA	22.41(0.41)aB	25.96(2.50)aA	21.79(0.39)bB	25.81(3.79)aA	22.11(1.33)aB	26.33(1.81)aA	22.39(4.88)aB	26.29(0.53)aA	21.52(1.72)aB
At.S25	12.60(0.01)dA	11.37(1.91)bB	16.94(3.55)cA	14.00(2.46)bB	14.68(0.40)bB	17.84(0.22)cA	21.02(0.79)abA	13.95(0.15)bB	15.87(0.51)abA	10.76(0.24)bB	15.22(1.83)bA	12.95(0.04)bB
St.B36	26.57(1.64)bA	20.27(0.32)aB	29.20(0.49)bA	21.85(0.73)aB	27.57(0.37)aA	22.56(0.41)bB	25.44(1.80)aA	20.95(0.15)aB	24.39(6.42)aA	21.87(0.91)aB	26.84(1.31)aA	21.17(0.23)aB
St.G56	29.66(0.46)aA	23.89(0.48)aB	34.79(1.40)aA	25.26(0.49)aB	30.19(0.72)aA	25.38(0.21)aB	26.58(2.04)aA	21.79(0.59)aB	22.92(4.45)aA	22.09(1.11)aA	29.72(0.65)aA	23.48(0.16)aB

Note: (1) Ab.G3: recently abandoned grazing on grassland (3 years); Hi.O7: *Hierochloe ordorata* Beauv (7 years); Th.M15: *Thymus mongolicus* Ronnm (15 years); At.S25: *Artemisia sacrorum* Ledeb (25 years); St.B36: *Stipa bungeana* Trin Ledeb (36 years); St.G56: *Stipa grandis* P. Smirn (56 years). (2) Different lowercase letters indicate significant differences at $P < 0.05$ among different vegetation types. Different capital letters indicate significant differences at $P < 0.05$ among soil depths.

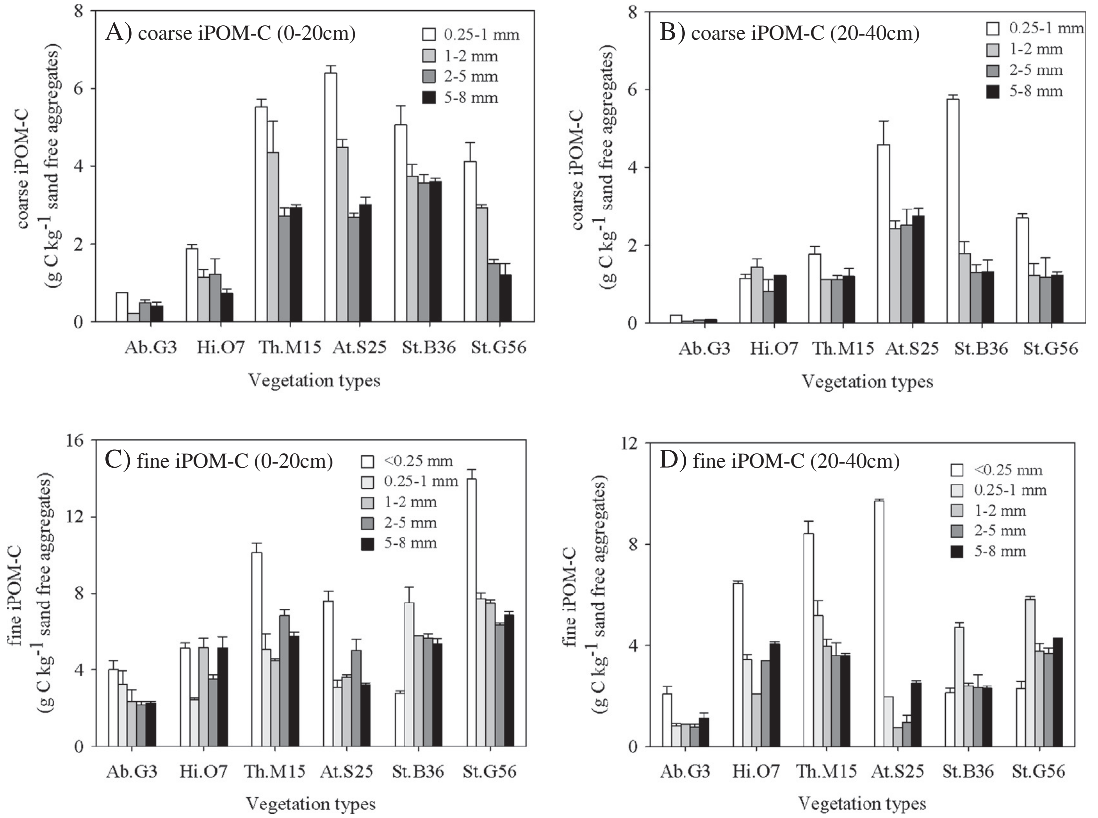
Marinissen, 2004; Six et al., 2004) and can reduce soil erosion, surface crusting and runoff (Barthes and Roose, 2002; Le Bissonnais, 1996). We found that revegetation benefited the formation of small water-stable macroaggregates (0.25–2 mm) and improved the uniformity of the soil aggregate size distribution. This finding is consistent with the results of Tang et al. (2010) and Lenka et al. (2012), who reported that vegetation restoration caused an increase in small macroaggregates (0.25–2 mm). The strongest influence on the proportion of macroaggregates is caused by the direct effect of fine roots and by the indirect effect of the association of the roots with external hyphae (Jastrow et al., 1998).

The soil aggregate stability was evaluated based on the mean weighted diameter (MWD) (Le Bissonnais, 1996). In our study, the MWD in the 0–20 cm soil depth increased during the early process of vegetation restoration (from Ab.G3 to Hi.O7) and decreased in the middle and later processes. This result is not consistent with the results of Tang et al. (2010) and Fattet et al. (2011), who suggested that the MWD increased with vegetation restoration. Wang et al. (2012) also reported that the MWD increased significantly in the 0–20 cm soil layer under secondary natural grassland. The MWD decrease was driven by changes in the soil aggregate size distribution, especially the decrease in the large aggregate fraction (5–8 mm) associated with vegetation restoration (from At.S25 to St.G56). Similar observations have been reported (Boix-Fayos et al., 2001; Cheng et al., 2006; Gros et al., 2004) and were associated with root and organic matter dynamics during natural vegetation succession; the growth of roots tends to break down large aggregates (Cheng et al., 2006). Moreover, the accumulation of soil carbon over time caused large aggregates (5–8 mm), which in our case consisted mostly of coarse sand and coarse silt, to break down into smaller aggregates (Boix-Fayos et al., 2001).

4.2. The influence of natural vegetation succession on bulk soil C, aggregate C and intra-aggregate POM-C

The soil organic carbon pool represents a major part of the terrestrial carbon reservoir and plays an important role in the global carbon cycle (Paul et al., 2008). In this study, apart from soil under At.S25-dominated vegetation, bulk soil C and aggregate C concentrations increased with vegetation recovery time. These results suggest that the natural vegetation succession had a positive impact on SOC sequestration on the Loess Plateau. This finding is consistent with Young et al. (2005), Fu et al. (2010), Jia et al. (2012) and Barua and Haque (2013) who suggested that vegetation restoration enhances the sequestration of SOC in soils by increasing inputs of organic materials. Plants are the main source of carbon to soils through tissue residues or via root exudates and symbiosis (Trumbore and Czimczik, 2008). We consider this a consequence of increasing aboveground biomass during vegetation succession (Table 1): the prohibition of grazing increased the accumulation of aboveground plant litter. Moreover, the SOC increase is likely related to larger underground root systems associated with vegetation recovery time, as well as a higher diversity of root systems following vegetation succession (Cheng et al., 2006). The higher concentration of SOC in the surface layer for all vegetation types except the Ab.G3 vegetation type is consistent with Fu et al. (2010), An et al. (2010), and Jia et al. (2012) who reported a similar result. Revegetation restoration significantly caused more increase in aggregate carbon in the 0–20 cm layer than that in the 20–40 cm layer. An et al. (2010) also found that aggregate carbon increased with revegetation in the surface layer. We consider the higher bulk soil carbon and aggregate carbon in the surface layer to be related to the higher C input. The surface layer is getting richer in SOC from the input of surface litter, roots, root exudates, and root debris. In the deeper layer, the C concentration will depend not only on input by roots, on the microbial activity but also on the transfer of C by the soil fauna (Fierer et al., 2003).

The concentration of aggregate C reflects the balance of SOC inputs and SOC losses. Our results showed that aggregate C



Note: (1) iPOM = intra-aggregate particulate organic matter; (2) Ab.G3: recently abandoned grazing on grassland (3 years); Hi.O7: *Hierochloe ordorata Beauv* (7 years); Th.M15: *Thymus mongolicus Ronnm* (15 years); At.S25: *Artemisia sacrorum Ledeb* (25 years); St.B36: *Stipa bungeana Trin Ledeb* (36 years); St.G56: *Stipa grandis P. Smirn* (56 years). (3) Error bars are standard errors.

Fig. 3. The concentration of intra-aggregate particulate organic carbon. Note: (1) iPOM = intra-aggregate particulate organic matter; (2) Ab.G3: recently abandoned grazing on grassland (3 years); Hi.O7: *Hierochloe ordorata* Beauv (7 years); Th.M15: *Thymus mongolicus* Ronnm (15 years); At.S25: *Artemisia sacrorum* Ledeb (25 years); St.B36: *Stipa bungeana* Trin Ledeb (36 years); St.G56: *Stipa grandis* P. Smirn (56 years). (3) Error bars are standard errors.

concentrations were concentrated mostly in the medium-sized aggregates (0.25–5 mm). This result was consistent with An et al. (2007) and Mohammadi and Motaghian (2011), who showed that the concentration of aggregate carbon was greatest in medium-sized aggregates. We considered this to be related to the formation and composition of different-sized aggregates (Boix-Fayos et al., 2001; Six et al., 2000). Microaggregates (<0.25 mm) are formed within macroaggregates (Angers et al., 1997; Oades, 1984) after the binding agents in macroaggregates have degraded. Consequently, microaggregates had lower C concentrations. The main links of large aggregates (5–8 mm) were plant roots, whereas medium-sized aggregates (0.25–5 mm) are largely associated with clay particles and are probably linked to each other by

Table 4
Correlations between the soil carbon fractions and soil properties.

C fractions	Aggregate size (mm)	pH	Bulk density(g/cm^3)	Porosity (%)	SOC content (g kg^{-1})	Total N (g kg^{-1})	NO_3^--N (mg kg^{-1})	NH_4^+-N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})
Aggregate C	<0.25	0.490	−0.619*	0.421	0.816**	0.843**	0.476	0.025	0.688*	0.843**
	0.25–1	0.573	−0.594*	0.270	0.890**	0.913**	0.547	0.129	0.775**	0.913**
	1–2	0.717**	−0.538	0.313	0.908**	0.931**	0.562	0.151	0.738**	0.931**
	2–5	0.537	−0.498	0.014	0.876**	0.913**	0.547	0.274	0.782**	0.913**
	5–8	0.596*	−0.385	0.075	0.872**	0.916**	0.446	0.243	0.741**	0.916**
Fine iPOM-C	<0.25	0.497	−0.166	−0.140	0.539	0.517	0.345	0.573	0.498	0.517
	0.25–1	0.505	−0.532	0.320	0.781**	0.821**	0.554	−0.066	0.660*	0.821**
	1–2	0.118	−0.419	0.075	0.633*	0.605*	0.264	0.148	0.703*	0.605*
	2–5	0.296	−0.550	0.146	0.809**	0.790**	0.232	0.379	0.871**	0.790**
	5–8	0.216	−0.714**	0.648*	0.566	0.495	−0.065	0.168	0.574	0.495
Coarse iPOM-C	0.25–1	0.595*	−0.399	−0.123	0.682*	0.698*	0.321	0.671*	0.643*	0.698*
	1–2	0.457	−0.499	−0.081	0.739**	0.714**	0.253	0.705*	0.802**	0.714**
	2–5	0.494	−0.44	0.006	0.674*	0.649*	0.36	0.562	0.677*	0.649*
	5–8	0.346	−0.508	0.145	0.512	0.46	0.168	0.525	0.479	0.460

Notes: (1) iPOM = intra-aggregate particulate organic matter. (2) the soil property data are taken from An et al. (2013). (3) *$P < 0.05$; **$P < 0.01$.

roots, hyphae, and calcium carbonate. Therefore, we concluded that medium-sized aggregates facilitated carbon sequestration in soil during vegetation succession.

Intra-aggregate POM-C is a highly accurate and broadly applicable diagnostic for total SOC changes in response to changes in management practices in terrestrial ecosystems (Six and Paustian, 2014). Our results showed that fine and coarse iPOM-C concentrations featured different trends associated with vegetation restoration. The fine iPOM-C always increased from Ab.G3 to St.B36, and decreased from St.B36 to St.G56. The coarse iPOM-C always increased from Ab.G3 to Th.M15, decreased from Th.M15 to St.B36, then increased from St.B36 to St.G56. De Gryze et al. (2004) found that forested soils sequestered C mainly in the fine intra-aggregate particulate organic matter. Yan et al. (2012) also suggested that coarse and fine iPOM-C contributed to the increase in soil carbon (49 and 51% of the total carbon increase, respectively) associated with the conversion of cereal fields to highly intensive vegetable systems. Ayoubi et al. (2014) reported that the POM decreased by approximately 19% in cultivated soils relative to natural pasture. This indicated that iPOM-C is a carbon fraction that is sensitive to vegetation restoration.

We studied the coarse and fine iPOM-C in response to vegetation restoration here. Our study showed that iPOM-C can be used for early detection of changes in soil carbon arising from vegetation restoration. The correlations between medium-sized aggregate C fractions and soil chemical properties showed that the coarse and fine iPOM-C within medium-sized aggregates (0.25–1 mm, 1–2 mm, and 2–5 mm aggregates) were significantly correlated with soil carbon, total N, available P, and available K. This finding implies that there is a synergy between intra-aggregate carbon fractions within medium-sized aggregates and these chemical properties during vegetation succession. This confirms that the analysis of intra-aggregate carbon fractions is a relevant measurement to complement usual soil chemical, biological and physical measurements, as proposed by Ashagrie et al. (2007). Above all intra-aggregate carbon fractions will begin to provide a measurable and functionally meaningful fraction that could be included in simulation models of SOC sequestration. Further long-term monitoring is necessary to draw additional inferences about the dynamics of carbon sequestration and soil aggregate formation following vegetation restoration.

5. Conclusions

Vegetation restoration caused an increase in small macroaggregates (0.25–1 and 1–2 mm-size). Aside from soil under At.S25-dominated vegetation, the bulk soil carbon and aggregate carbon concentrations increased with recovery time. It is worth noting that both fine and coarse iPOM-C showed promising potential for early detection of changes in soil carbon arising from vegetation restoration. Additionally, we found a high degree of synergy between intra-aggregate carbon fractions within medium-sized aggregates and soil chemical properties during vegetation succession. Overall, the results showed that the vegetation succession improved soil organic carbon sequestration, and iPOM-C provides a measurable and functionally meaningful fraction associated with vegetation restoration.

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