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Responses of soil nitrogen, phosphorous and organic matter to vegetation succession on the Loess Plateau of China

Man CHENG[1,2], ShaoShan AN[1,2*]

[1] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China;
[2] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China

Abstract: Revegetation is a traditional practice widely used for soil protection. We evaluated the effect of natural revegetation succession on soil chemical properties and carbon fractions (particulate organic carbon (POC), humus carbon (HS-C), humic acid carbon (HA-C) and fulvic acid carbon (FA-C)) on the Loess Plateau of China. The vegetation types, in order from the shortest to the longest enclosure duration, were: (a) abandoned overgrazed grassland (AbG3; 3 years); (b) *Hierochloe odorata* Beauv. (HiO7; 7 years); (c) *Thymus mongolicus* Ronnm (ThM15; 15 years); (d) *Artemisia sacrorum* Ledeb (AtS25; 25 years); (e) *Stipa bungeana* Trin Ledeb (StB36; 36 years) and (f) *Stipa grandis* P. Smirn (StG56; 56 years). The results showed that the concentrations of soil organic carbon, total nitrogen and available phosphorus increased with the increase of restoration time except for ThM15. The concentration of NH_4-N increased in the medium stage (for ThM15 and AtS25) and decreased in the later stage (for StB36 and StG56) of vegetation restoration. However, NO_3-N concentration significantly increased in the later stage (for StB36 and StG56). Carbon fractions had a similar increasing trend during natural vegetation restoration. The concentrations of POC, HS-C, FA-C and HA-C accounted for 24.5%–49.1%, 10.6%–15.2%, 5.8%–9.1% and 4.6%–6.1% of total carbon, respectively. For AbG3, the relative changes of POC, HS-C and FA-C were significantly higher than that of total carbon during the process of revegetation restoration. The higher relative increases in POC, HS-C and FA-C confirmed that soil carbon induced by vegetation restoration was sequestrated by higher physical and chemical protection. The increases of soil C fractions could also result in higher ecological function in semiarid grassland ecosystems.

Keywords: particulate organic carbon; humus carbon; humic acid carbon; fulvic acid carbon; carbon fraction; natural vegetation succession

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Revegetation has been reported as the most effective way to abate soil erosion and degradation (Hou et al., 2002) and to restore the ecological integrity of disturbed ecosystems (Montalvo et al., 1997). However, in many ecosystems, vegetation productivity may be limited by nutrient availability (Aerts and Chapin, 1999; Aaron and Sanford, 2001). Soil organic carbon (SOC) is fundamental to the maintenance of soil fertility and function and has been identified as a key indicator of soil quality, which influences a wide range of soil physical, chemical and biological properties. As vegetation succession progressed, carbon fixation via photosynthesis and subsequent transfer of C to soil via leaf litter and root turnover contribute to soil C accumulation (Leifeld and Kögel-Knabner, 2005). Revegetation restoration offers opportunities to sequester soil organic carbon and improve the quality of degraded soils (Su and Zhao, 2005; An et al., 2009, 2010; Hua et al., 2009; Zhang et al., 2012).

SOC consists of several components that differ in their physical-chemical properties and their degree of stabilization and turnover time. Different carbon

*Corresponding author: ShaoShan AN (E-mail: shan@ms.iswc.ac.cn)
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fractions, such as dissolved organic carbon, particulate organic carbon and light fraction organic carbon, have recently obtained researchers' attention due to their sensitivity to soil management practices (Abakumov et al., 2013). However, the effect of vegetation restoration on carbon fractions was not documented. Quantifying carbon fractions could help us to better understand the dynamic of carbon sequestration and carbon losses during vegetation restoration. Such information is essential for finding out the mechanism of carbon sequestration and improving SOC sequestration and soil environment which is crucial for ecological rehabilitation.

We investigated the concentration of soil chemical material, chemically divided carbon fractions into humus carbon (HS-C), humic acid carbon (HA-C), fulvic acid carbon (FA-C) and physically carbon fraction into particulate organic carbon (POC) at depths of 0–20 cm and 20–40 cm from different vegetation types of natural restored grasslands on the Loess Plateau of China. The objective of this study was to assess the potential impact of natural vegetation restoration on soil nutrient cycling and the dynamics of carbon fractions on the Loess Plateau. The following hypotheses were tested in this study: (1) natural revegetation would result in increases in soil nutrient because of the additional input of plant residue; (2) C fractions would change and increase with increasing total carbon; and (3) The increases in C fractions induced by vegetation restoration would been different.

1 Materials and methods

1.1 Study area

The method of space-for-time substitution, as an effective way of study changes over time (Sparling et al., 2003), was used to monitor plant and soil changes occurring along a vegetative chronosequence developed on similar soils and climatic conditions (Bhojvaid and Timmer, 1998). Sites stabilized by revegetation at different times offer an ideal opportunity to understand vegetation succession process, as soil conditions before revegetation are largely driven by geomorphologic processes.

The study was carried out at the Yunwu Observatory for Vegetation Protection and Eco-environment on the Loess Plateau of China. The observatory with permanent grassland is located at Guyuan city in the Ningxia Hui Autonomous Region (Fig. 1). The region is characterized by a semi-arid climate with heavy seasonally distributed rainfall resulting in seasonal local floods and droughts. The annual mean temperature is 5°C. Average annual precipitation is 445 mm (1941–2000) 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 precipitation.

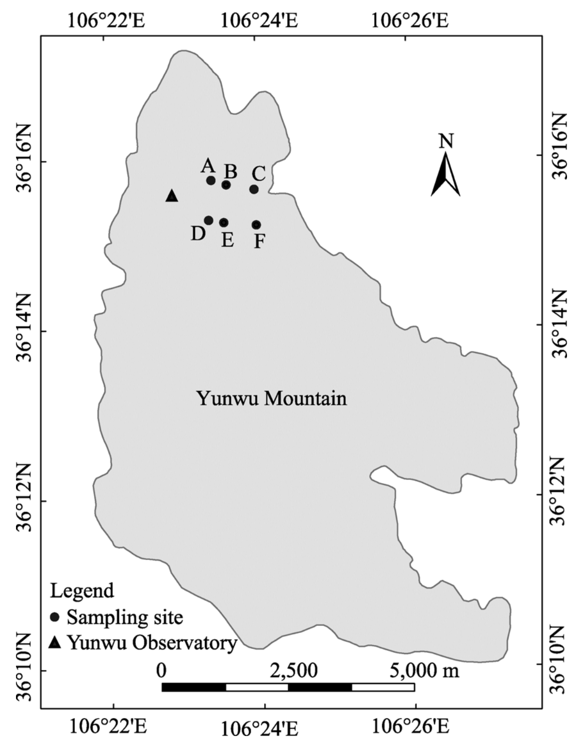

Fig. 1 The map of study area and sampling sites. A, 3-year-old abandoned overgrazing grassland (AbG3); B, 25-year-old *Artemisia sacrorum* Ledeb (AtS25); C, 7-year-old *Hierochloe odorata* Beauv. (HiO7); D, 56-year-old *Stipa grandis* P. Smirn (StG56); E, 15-year-old *Thymus mongolicus* Ronnm (ThM15); F, 36-year-old *Stipa bungeana* Trin Ledeb (StB36).

Soil type of the area is typical Loessi-Orthic primosols, and soil texture is medium loam. According to the process of plant succession in this area (Zou et al., 1997), we studied six succession stages: 3, 7, 15, 25, 36 and 56 years, respectively (Table 1). Depending on the time of natural succession, we classified the plant communities as follows: (a) 3-year-old

Table 1 Geographical and vegetation characteristics of the study area

Site name	Revegetation years (a)	Geographical coordinates	Elevation (m)	Slope gradient (°)	Dominant species	Accompanying species	Fresh biomass (g/m²)
AbG3	3	36°15.807′N 106°23.226′E	2,078	6	*Leymus secalinus*	*Artemisia scoparia* *Thymus mongolicus* *Potentilla bifurca.*	86.00
HiO7	7	36°15.807′N 106°24.592′E	2,080	10	*Hierochloe ordorata* *Leymus secalinus*	*Artemisia scoparia* *Thymus mongolicus*	179.55
ThM15	15	36°15.101′N 106°23.415′E	1,903	10	*Thymus mongolicus* Romm	*Stipa gradiss* *Artemisia sacrorum* *Potentilla bifurc.*	539.00
AtS25	25	36°15.751′N 106°23.415′E	2,082	12	*Artemisia sacrorum* Ledeb	*Stipa bungana* *Heteropappus altaicus* *Thymus mongolicus*	545.60
StB36	36	36°15.101′N 106°23.935′E	2,097	14	*Stipa bungean* Trin Ledeb	*Artemisia sacrorum* *Thymus mongolicu* *Leymus secalinu* *Potentilla bifurca*	618.40
StG56	56	36°15.143′N 106°23.204′	2,058	10	*Stipa grandis* P. Smirn	*Artemisia frigid.* *Potentilla acauli.* *Medicago ruthenica* *Potentilla angustiloba*	805.60

Note: AbG3, recently abandoned overgrazed grassland (3 years); HiO7, *Hierochloe ordorata* Beauv (7 years); ThM15, *Thymus mongolicus* Ronnm (15 years); AtS25, *Artemisia sacrorum* Ledeb (25 years); StB36, *Stipa bungeana* Trin Ledeb (36 years); StG56, *Stipa grandis* P. Smirn (56 years). The symbols are the same as in Table 2 and Figs. 2–4.

abandoned overgrazing grassland (AbG3); (b) 7-year-old *Hierochloe odorata* Beauv. (HiO7); (c) 15-year-old *Thymus mongolicus* Ronnm (ThM15), (d) 25-year-old *Artemisia sacrorum* Ledeb (AtS25), (e) 36-year-old *Stipa bungeana* Trin Ledeb (StB36) and (f) 56-year-old *Stipa grandis* P. Smirn (StG56).

1.2 Soil sampling and processing

Soil samples were collected in July 2012. For each vegetation type, contours at 3 elevations (an upper slope, a middle slope and a lower slope) were determined. At each contour, 3 plots of 60 m×60 m were established. From each plot, soil samples were collected at depths of 0–20 and 20–40 cm. Five samples were taken from each plot and mixed to form a bulk soil sample of about 1 kg. A total of 108 soil samples were obtained from all vegetation types. Samples were dried at room temperature in laboratory. Each sample was passed through a 2-mm sieve to remove large roots, stones and macrofauna.

1.3 Soil chemical properties and carbon fractions

Soil samples were ground and passed through a 0.15-mm sieve for measuring the concentration of soil organic carbon (SOC) and total nitrogen (Total N). The SOC concentration (g/kg) of soil samples was analyzed by potassium dichromate volumetry, and total N was measured by the semi-micro Kjeldahl method. NH_4-N and NO_3-N were extracted from moist samples (5-g oven-dry equivalent) by shaking with 1 M KCl at a soil solution ratio of 1:10, followed by centrifuging at 2,000 rpm for 30 min. The supernatant for NH_4-N and NO_3-N was determined using a flow autoanalyzer. Available phosphorus (Available-P) was extracted and measured in a buffered alkaline solution with 0.5 M sodium bicarbonate. The extracts were quantified calorimetrically with a spectrophotometer (Hitachi, UV2300) at 660 nm.

Particulate organic carbon (POC) was determined by the method of Cambardella and Elliott (1992). Soil carbon factions were chemically divided into Humus (HS), humic acid (HA) and fulvic acid (FA) and determined by extraction method of NaOH and $Na_4P_2O_7$ mixed solution (Yan, 1988). The soil samples were extracted using a solution of 0.1 mol/L NaOH and 0.1 mol/L $Na_4P_2O_7$ at 70ºC for 60 min. The dark brown alkaline supernatant solution, corresponding to the total alkali-extractable humus fraction (HS), was separated into the acid-insoluble HA and the acid-soluble FA fractions by acidifying the alkaline supernatant to pH 1.0 with 0.5 mol/L H_2SO_4. HA was washed with washed with 0.025 mol/L H_2SO_4 and water, and then dissolved in 0.05 mol/L NaOH. The carbon concentrations of the HS (HS-C) and HA (HA-C) were determined through the $K_2Cr_2O_7$ oxidation method, whereas the carbon concentration of FA (FA-C) was calculated by subtracting the HA-C from HS-C.

1.4 Statistical analysis

Vegetation types and soil depths were considered as the main impact factors. SPSS 11.0 was used for statistical analysis. Analyses of variance were performed using ANOVA procedure in SPSS statistical software. The Tukey test (P<0.05) was used to assess the differences among vegetation types at the same depth, and significance was determined at P<0.05 for each vegetation type. In addition, for comparing the changes in C fractions induced by vegetation restoration, we used the relative change of total carbon and carbon fractions of AbG3 during the process of vegetation restoration as an indicator.

2 Results and discussion

2.1 Soil chemical properties

There were substantial differences in soil chemical properties among the six vegetation types (Table 2). Except for ThM15, the concentrations of SOC and total N increased with the increase of restoration time both at the 0–20 and 20–40 cm soil depths. The concentrations of NH_4-N for AtS25 and ThM15 were the highest, followed by the soil types of StG56, StB36 and HiO7, and the lowest for AbG3-dominanted vegetation type. Compare to that of AbG3, the concentration of soil NO_3-N at the 0–20 cm depth significantly increased for the soil types of StB36 and StG56. The concentration of available P ranged from 2.35 to 4.39 mg/kg at the 0–20 and 20–40 cm soil depths, and ordered as following: ThM15>StG56>AtS25>StB36 >HiO7>AbG3.

Table 2 Soil nutrient content for different vegetation types

Vegetation type	Soil depth (cm)	SOC	Total N	NH_4-N	NO_3-N	Available-P	C/N
		(g/kg)		(mg/kg)			
AbG3	0–20	9.62±0.83^{Da}	1.22±0.07^{Ea}	4.12±0.22^{Ba}	14.47±0.04^{Ba}	2.28±0.16^{Da}	7.86±0.17^{Ba}
	20–40	9.23±0.87^{Ea}	1.25±0.14^{Ea}	3.67±0.02^{Ba}	11.98±0.39^{DEa}	2.35±0.29^{Ca}	7.38±0.27^{Ca}
HiO7	0–20	20.41±1.80^{Ca}	2.20±0.04^{Da}	5.03±0.084^{Ba}	10.29±0.41^{Ca}	3.39±0.25^{Ca}	9.27±0.10^{Aa}
	20–40	17.49±0.34^{Da}	2.03±0.03^{Db}	4.26±0.02^{Bb}	8.88±0.24^{Eb}	2.53±0.37^{Cb}	8.61±0.10^{ABb}
ThM15	0–20	29.82±0.09^{ABa}	3.19±0.04^{Ba}	6.94±0.49^{Aa}	14.37±0.13^{Ba}	4.39±0.26^{Aa}	9.36±0.02^{Aa}
	20–40	24.39±1.49^{Bb}	2.74±0.11^{ABb}	5.05±0.22^{ABa}	19.88±0.84^{Aa}	3.26±0.08^{Ab}	8.88±0.09^{ABa}
AtS25	0–20	23.57±0.95^{Ca}	2.61±0.03^{Ca}	6.78±0.51^{Aa}	14.13±0.45^{Ba}	3.65±0.10^{BCa}	9.02±0.07^{ABa}
	20–40	21.30±0.09^{Cb}	2.27±0.12^{Cb}	6.08±0.02^{Aa}	17.19±0.17^{ABa}	3.02±0.07^{ABb}	9.40±0.17^{Aa}
StB36	0–20	28.00±0.09^{Ba}	3.15±0.04^{Ba}	3.97±0.07^{Ba}	16.88±0.52^{Aa}	3.55±0.06^{Ca}	8.90±0.06^{ABa}
	20–40	21.29±0.14^{Cb}	2.66±0.04^{Bb}	4.82±0.81^{ABa}	13.76±1.79^{CDa}	2.74±0.13^{BCb}	8.00±0.01^{Bb}
StG56	0–20	32.25±0.18^{Aa}	3.45±0.02^{Aa}	4.90±0.47^{Ba}	18.18±0.22^{Aa}	4.06±0.30^{ABa}	9.35±0.27^{Aa}
	20–40	25.58±0.19^{Ab}	2.90±0.05^{Ab}	4.42±0.32^{Ba}	15.69±0.09^{BCa}	3.21±0.17^{ABb}	8.81±0.08^{ABa}

Note: Different capital letters indicate significant differences at P<0.05 level among different vegetation types. Different lowercase letters indicate significant differences at P<0.05 level between 0–20 and 20–40 cm depths. Data are means±SE.

The accumulation of nutrients and organic matter in soils results from complex interactions between biotic processes moderated by plants, soil biota and abiotic processes (Hooper et al., 2000). We found an increase in soil organic carbon in natural revegetation. This result is consistent with previous studies on the Loess Plateau. Jia et al. (2012) studied the dynamics of soil carbon in terrestrial systems and reported that soil carbon increased with vegetation restoration age. The increasing aboveground biomass with revegetation years may result in the increase of soil carbon. The prohibition of grazing resulted in the accumulation of aboveground plant litter. In addition, subshrub developed an extensive root system in the mid and later growth periods. Carbon fixation via photosynthesis and the subsequent transfer of C to the soil via leaf litter and root turnover contribute to soil C accumulation (Leifeld and Kögel-Knabner, 2005). From the 11th

year to the 15th year (for ThM15), faster natural regeneration speed of grassland communities resulted in the richest litter and the accumulation (Cheng et al., 2006). Moreover, litter from the stem and leaf of ThM15 was more easily decomposed, which could supply more source of soil organic carbon, and promoted carbon cycle. For above reasons, soil carbon concentration for ThM15 was relatively higher during vegetation succession.

The concentration of total N usually increased with the increasing SOC. We found that the concentration of total N significantly increased with the increase of vegetation restoration time. It is consistent with Hu et al. (2009) and Fu et al. (2010) who reported that vegetation restoration enhanced soil N accumulation. The concentrations of NH_4-N increased in the medium stage of vegetation restoration (for ThM15 and AtS25) and decreased in the later stage (under StB36 and StG56). However, NO_3-N concentration significantly increased in the later stage (for StB36 and StG56). This might be related to interactions of plant N uptake, N transformation and soil environmental condition (DeLaune et al., 2005; Hefting et al., 2005) in terms of different vegetation communities. Also we found that available-P increased with vegetation restoration time, which is consistent with the studies of Wen et al. (2005) and Li et al. (2007), who reported that revegetation can improve soil environment for colonization and establishment of plant species. These results demonstrated that vegetation restoration improved soil ecological environment by enhancing soil nutrients.

2.2 Soil carbon fractions

The results of soil organic carbon fractions are shown in Fig. 2. Under different vegetation types, the concentrations of POC varied from 4.8 to 15.5 g/kg at the 0–20 cm depth and from 2.3 to 9.7 g/kg at the 20–40 cm depth. With the exception of ThM15, at both the 0–20 cm and the 20–40 cm depths, the concentrations of POC increased with the increase of restoration time. The POC of soil for ThM15 was 2.7 and 4.4 times higher than that for AbG3 at the 0–20 and 20–40 cm depths, respectively. Humus-carbon (HS-C) varied between 1.2 and 4.9 g/kg during revegetation period at the 0–40 cm depth. The concentration of soil HS-C was higher for StG56 and ThM15 than that for other vegetation types. Soil humic acids (HA-C) and fulvic acids (FA-C) accounted for 34%–50% and 50%–66% of HS, respectively. The ratio of HA to FA decreased with vegetation time (Fig. 4).

Particulate organic matter (POM) is easily available to microorganisms and hence rapidly decomposable (Zimmermann et al., 2007). In our study, POC, which had a similar increasing trend with SOC, accounted for 24.5%–49.1% of SOC. The previous research showed that the percentage of POC in total C was above 10% (Carter et al., 1994). We also found that during vegetation succession, the relative change of POC was higher than that of SOC at the 20–40 cm depth (Fig. 3) and a little lower than that of SOC at the 0–20 cm depth. Therefore, we suggested that POC was more sensitive than that of SOC to vegetation succession. This is in agreement with the work done by previous researchers. Su (2006) found that more remarkable change of POC than that of SOC after cropland conversion from cropland to forage grassland. Additionally, Poeplau and Don (2013) proposed that POC may be the most sensitive index to land use changes. Hence, POC could be considered as a sensitive carbon fraction in relation to vegetation succession.

Soil humus is an important source of mineral nutrition and organic nutrients (Keeves, 1966). The concentration of humus is the result of mineralization and humification. During vegetation succession, the percentages of HS-C, HA-C and FA-C accounted for 10.6%–15.2%, 4.6%–6.1% and 5.8%–9.1% in the total C. In addition, the concentrations of HS-C, HA-C and FA-C had a similar increasing trend with total SOC during vegetation restoration. It is consistent with Abakumov et al. (2013) who suggested that HA-C and FA-C increased with restoration time. The relative changes of HS-C and FA-C induced by vegetation restoration were higher than that of total C, whereas HA-C had a lower relative change than that of total C (Fig. 3). These results indicated that HS-C and FA-C were more sensitive than that of total SOC at assessing the impact of vegetation succession on soil quality. This can be partly explained by the polyphenol theory (Stevenson, 1982). According to the theory, the formation of FA occurs prior to that of HA. FA has a lower molecular weight and more mobility than that of HA (Zhuo and Wen, 1994).

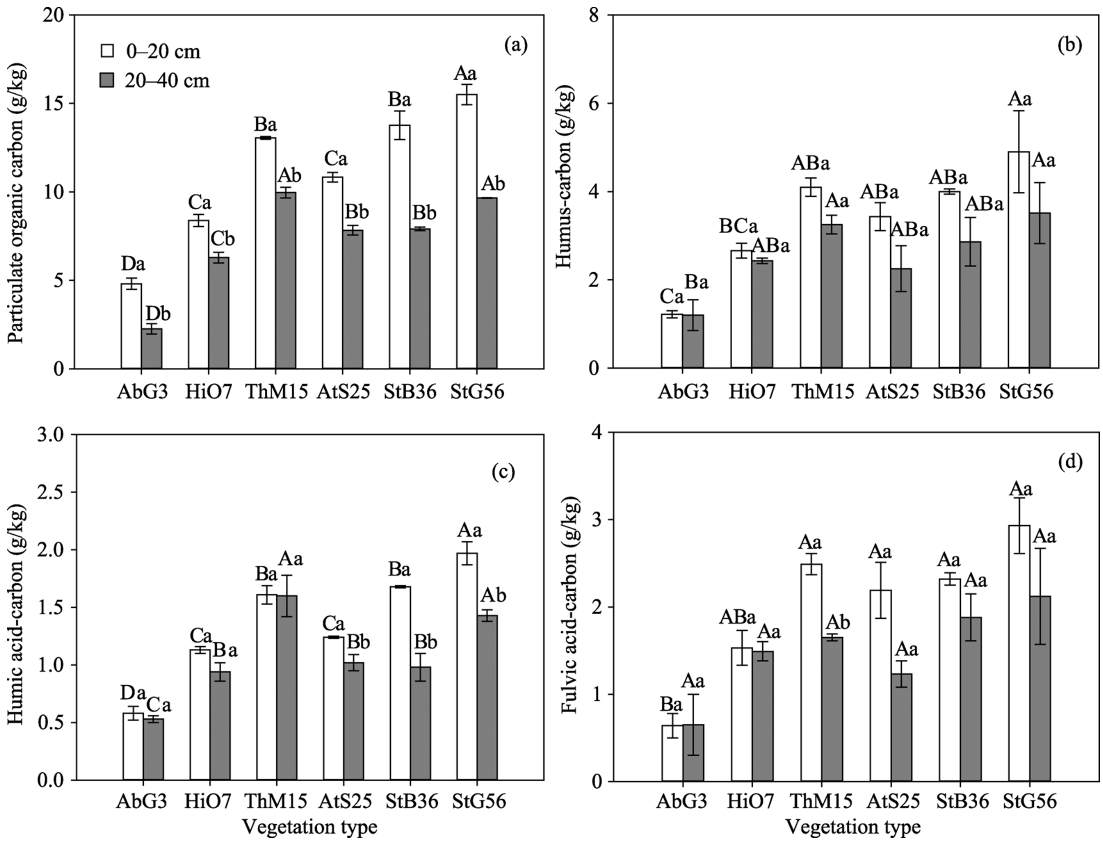

Fig. 2 The concentrations of particulate organic carbon (a), humus-carbon (b), humic acid-carbon (c) and fulvic acid-carbon (d) during vegetation succession. Different capital letters indicate significant differences at $P<0.05$ level among different vegetation types. Different lowercase letters indicate significant differences at $P<0.05$ level between 0–20 and 20–40 cm depths.

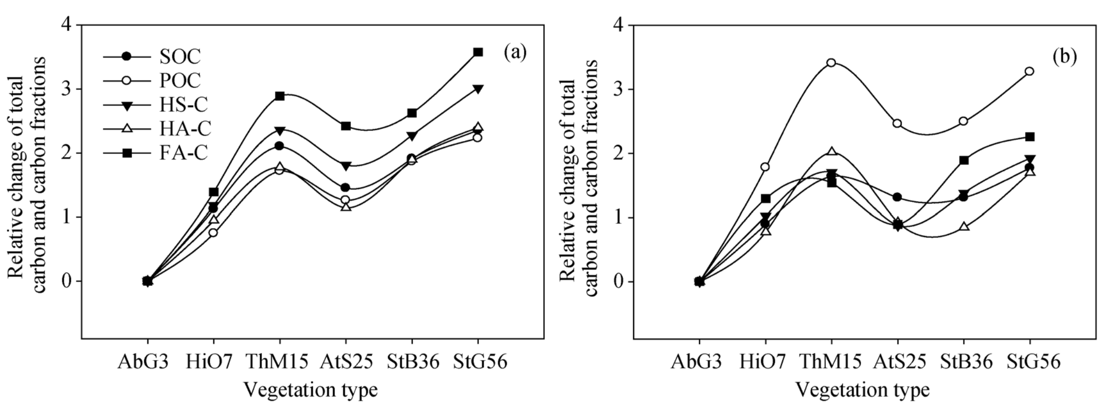

Fig. 3 The relative change of total carbon and carbon fractions at the 0–20 cm depth (a) and 20–40 cm depth (b) under different vegetation types. SOC, soil organic carbon; POC, particulate organic carbon; HS-C, humus carbon; HA-C, humic acid carbon; FA-C, fulvic acid carbon.

HA/FA reflects the humification degree of HS. In our study, HA/FA was 0.5–1.0 during vegetation succession, and it decreased with vegetation time (Fig. 4). This result indicated that the concentration of HS increased but the quality is not improved in natural revegetation. It is not consistent with the study of Li et al. (2008), who compared the HA/FA of soil under natural vegetation and cropland and suggested that HA/FA was higher under natural vegetation. The formation of HA-C and FA-C was closely related to environmental factors. Martin et al. (1998) suggested that high annual rainfall at higher

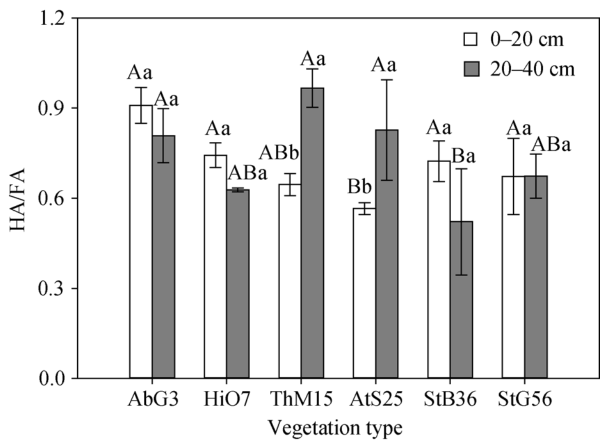

Fig. 4 The ratio of HA to FA under different vegetation types. HA, humic acid; FA, fulvic acid.

and cooler altitudes appears to reduce lignin degradation and formation of high molecular weight condensed aromatic structure, but encourages the formation of lower molecular weight humic substances rich in polysaccharides. In this study, the increase in HA-C was lower than in FA-C induced by vegetation succession in this phase. The significant increasing in HA-C would require longer restoration. Therefore, we concluded that carbon sequestration induced by vegetation restoration was micro molecule organic carbon such as FA-C, by far.

3 Conclusions

Our research demonstrated that vegetation restoration could improve soil chemical properties and tend to sequester POC and FA-C on the Loess Plateau of China. During vegetation succession, expect for the ThM15 community, soil organic carbon and total N increased with restoration time. These trends were likely due to more plant residues and root accumulation. As the succession progressed, all the C fractions (POC, HS-C, HA-C, FA-C) had a similar increasing trend with SOC. The increases in POC, HS-C and FA-C induced by vegetation restoration were higher than in HA-C. The higher relative increases in POC, HS-C and FA-C confirmed that soil carbon induced by vegetation restoration was sequestrated with physical and chemical protection. The increases of soil C fractions could also result in higher ecosystem function in semiarid grassland ecosystems. Natural vegetation restoration could improve the quality of degraded soil, and therefore it should been recommended to improve soil quality and ecological environment in the northern Loess Plateau of China.

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