Original Research

Soil Organic Carbon, Aggregates, and Fractions under Different Land Uses in the Loess Plateau, China

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Abstract

The dynamics of soil organic carbon (SOC) under different land uses can be beneficial for accurately assessing carbon sequestration to deal with global climate change. The aim of this study was to quantify the SOC content in various fractions under different land uses. Soil samples were collected from the top 0.1 m and 0.1-0.3 m of cropland, grassland, and forest in Huachi County of Gansu Province, China. Significant differences in physical fractions were found in the top 0.1-m layer, with cropland having the highest proportion of micro-aggregates (<250 μm), forest having the highest proportion of small macro-aggregates (250-2000 μm), and grassland tending to form large macro-aggregates (>2000 μm). SOC values were 6.9, 11.3, and 10.3 g kg^{-1} in the top 0.1-m layer for cropland, grassland, and forest, respectively. The difference in δ^{13}C between the light and heavy fraction in small macro-aggregates was smaller than that in both large macro-aggregates and micro-aggregates. These results indicated that small macro-aggregates conserved SOC relative to micro-aggregates and large macro-aggregates. The differences in δ^{13}C between the light and heavy fraction in all aggregate size fractions of grassland were much larger than in forest, indicating that there was higher microbial decomposition in grasslands. Overall, our results suggested that the accumulation of SOC in grassland was derived from the abundant carbon input, but the protection of SOC from small macro-aggregates was important to forest soil.

Keywords: soil organic carbon, aggregate, density fraction, land use, Loess Plateau

Introduction

Land use change is an important factor affecting soil organic carbon (SOC). Intensive decomposition of the SOC occurs when natural grassland and woodland change to cropland. In contrast, conversion of cropland to grassland or woodland causes a gradual increase in the SOC pool [1, 2]. In the context of global climate change, many researchers have begun to pay attention to controlling SOC storage by changing the land use types to mitigate carbon dioxide emissions [3-5]. Therefore, knowledge regarding the effects of land use changes on SOC is important for implementing these practical works.

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It has generally been found that the SOC distribution was lower in cropland than forest, shrub land, and grassland [6-9] due to the low litter input in long-term cultivation of cropland [5]. Especially when young forest was included in the SOC sequence, this forest could record higher SOC levels than cropland [10]. However, some exceptions to these results have been reported that converting cropland to forest was associated with a loss of SOC [11-13]. In addition, no significant differences in the influence of different vegetation types on SOC were also reported sometimes [14].

All above findings showed that results in different regions can be contradictory, which likely occurs because of complex terrain, climate, and soil environment [15]. Therefore, revealing the reasons for the above variation and dynamics of SOC under different land uses in the same region can be beneficial for accurately assessing carbon sequestration, as well as developing soil management techniques to deal with global climate change.

The SOC content is dependent on the litter input and degradation rate of existing SOC. It is well known that the litter input in cropland was much lower than that in grassland and forest. Fan et al. [16] found that the SOC content remained stable during 26 years of cultivation when only mineral nitrogen fertilizer was applied. They suggested that the contribution of litter to SOC input was extremely limited in cropland because it was rapidly decomposed. Zhang et al. [17] compared the dynamics of SOC in grass, shrub, young forest, and mature secondary forest ecosystems in Qinling Mountains and found that the accumulation of organic matter in the litter layer was related to the decrease in decomposition of litter. Taken together, these findings indicate that the stabilization of SOC should be considered further.

Aggregates are important factors affecting the persistence of SOC. Six et al. [18] indicated that the SOC content in macroaggregate was 1.65 times greater compared to microaggregate in cropland. An et al. [19] also found that macroaggregates had a higher SOC content than microaggregates in both forest and abandoned grazing land on the Loess Plateau. Gunina and Kuzyakov [20] reported that the C flows in the small macro and microaggregate size was more intensive than large macroaggregate, indicating a faster microbial decomposition rate in macroaggregate compared to microaggregate. Thus, it is possible to distinguish between stable organic carbon and readily mineralized organic carbon based on the SOC particle size [21].

In addition, the density fraction and stable C isotope analysis (^{13}C/^{12}C) have been successfully used to elucidate SOC dynamics [22]. The heavy fractions were always considered as microbial transformation products of the lighter fractions [20]. The density fraction dynamics in aggreagete could also illustrate SOC variations in aggregates. Tan et al. [23] found that the mass of light fraction significantly increased along with the increased aggregate size. They also found that the percentage of heavy fraction C in forest was lower than that in conventional tillage cropland. Therefore, integrating size fraction and density fraction methods may be useful for understanding the SOC content and dynamics.

The aims of this study were to quantify the SOC content in various fractions under different land uses, and to evaluate the effects of carbon input and degradation on SOC distribution in various fractions in different land use. The SOC content and dynamics were analyzed in areas of different land uses based on: i) soil physical fractions under different land uses, ii) SOC content in bulk soil and different sizes of aggregates,
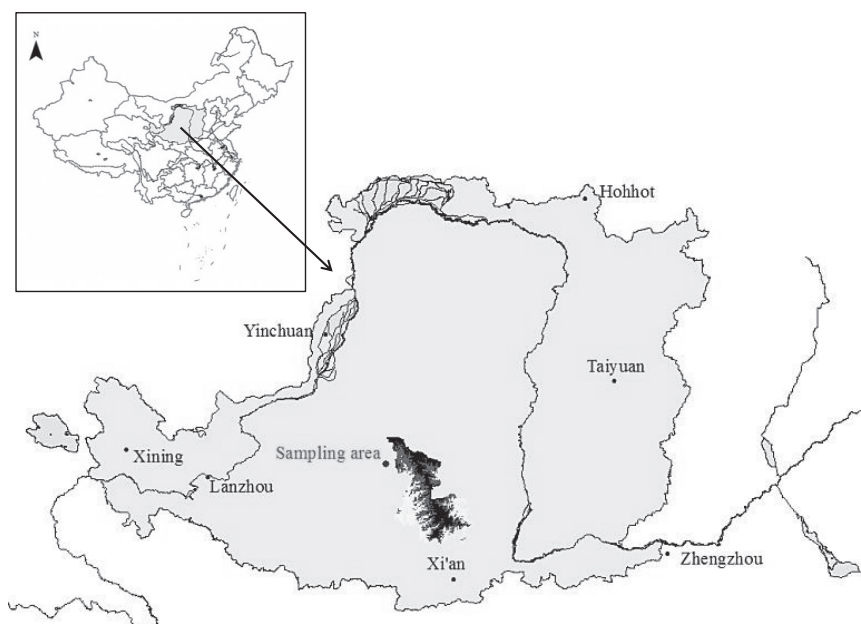

Fig. 1. Location of the study area in the Loess Plateau, China.

and iii) stable carbon isotope composition and density fraction in different sizes of aggregates. The Loess Plateau (6.2×10^5 km^2) was selected for study because it is known as the most severely eroded area in this region, and a large number of land use measurements are being carried out in this area.

Materials and Methods

Study Area

The investigation was carried out in Huachi County of Gansu Province, China (Fig. 1; E 107°52'–108°31', N 36°17'–36°22'). This county is located in western Ziwuling forest region situated in the middle part of the Loess Plateau, which is the largest natural forest region on the plateau. The area has a continental monsoon climate with an average annual temperature of 7.8ºC, annual precipitation of 445 mm, and average frost-free period of 172 days from 2000 to 2012 (according to the Huachi County Meteorological Bureau).

Land Uses

Three types of land uses (cropland, grassland, and forest) were selected in the current study. All the selected sites were distributed in the small valley plain. The loess layer in this valley plain is more than 60 m thick, having uniform soil parent materials with little spatial variation in silty clay. The soil type is a calcareous loamy soil, classified as Calcic Cambisols according to the Food and Agriculture Organization soil classification system. The bulk density of this soil is 1.28-1.32 g cm^{-3} and the clay content is about 23.7%. The cropland was intensively cultivated for more than 60 years and the staple crop was maize. The dominant species in grassland were *Stipa bungeana* and *Artemisia scoparia*, and the vegetation cover was more than 80%. An artificial woodland was selected as forest, and white poplar (*Populus alba*) was planted 30 years ago.

Sampling

Soil samples were collected from depths of 0-0.1 and 0.1-0.3 m using a stainless-steel cutting ring (0.05 m diameter, 0.65 m length) in August 2014.

For each site, three independent replications were collected from more than 200 m apart from each other. To obtain a representative sample, each replication consisted of a mixture of subsamples from four individual samples. All soil samples were air-dried at room temperature. Soil properties of soil samples collected from cropland, grassland, and forest are shown in Table 1. Soil homogeneity was assumed in the current study because all sites had the same soil type and similar topography.

Physical Fractionation

Aliquots of soil samples were accurately weighed to 100 g and then dry sieved through 2000 and 250-µm meshes. Dry sieving was used to minimize the disruption of aggregates and provide results more representative of the field situation. Aggregate size classes >2000, 250-2000, and <250 µm were obtained. These fractions were defined as large macro-aggregate, small macro-aggregate, and micro-aggregate, respectively, according to Cambardella and Elliott [24]. Five grams of aggregates were placed into a centrifugation tube with 15 mL of sodium polytungstate (SPT) solution (the density was 1.85 g cm^{-3}). The tube was gently inverted several times, and then centrifuged at 4,000 rpm for 1 h. To obtain a light fraction of organic matter (OM) with a density ρ<1.85 g cm^{-3}, the supernatant with floating particles was filtered through a fiberglass membrane (GF/C, Whatman, UK) and washed with distilled water. The remaining soil was then washed four times with distilled water (20 mL each time) to generate a heavy fraction with a ρ>1.85 g cm^{-3}.

Analysis of SOC Content and δ^{13}C Values

All aggregate size classes and fractions obtained by density fractionation, as well as air-dried whole soil samples, were treated with 12 M HCl for 8 h [25], dried at 40ºC, and then weighed to ensure removal of carbonate from the samples before analysis. The treated samples were ground manually and sieved to <0.15 mm. The C contents of the bulk soils, aggregate size classes, and isolated density fractions were measured using an elemental analyzer (VARIO EL III, Elementar Co., Ltd; Germany). An isotope ratio

Table 1. Soil properties of soil samples collected from cropland (CL), grassland (GL), and forest (FL).

Horizon (m)	Land use	pH	TN (mg/kg)	P (mg/kg)	K (mg/kg)
	CL	8.44	0.50	18.1	166.0
0-0.1	GL	8.49	1.55	17.3	194.8
	FL	8.28	1.20	12.6	234.0
	CL	8.51	0.52	16.7	86.1
0.1-0.3	GL	8.48	1.05	7.6	140.2
	FL	8.55	0.57	6.2	201.9

mass spectrometer (C/N Isotope, Sercon, UK) was used to analyze the natural stable carbon isotope composition of all the samples. The C isotope ratios were expressed relative to the international PDB limestone standard as $\delta^{13}C$.

Analysis of Soil Chemical Properties

The soil sample was ground and sieved to <0.15 mm. Soil pH was measured using a soil-to-solution (distilled water) ratio of 1:2.5 by a pH meter (PHS-3C, Shanghai). Total nitrogen (TN), available phosphorus (P), and available potassium (K) were measured according to the methods described by Bao [26].

Statistical Analyses

All the results were presented as mean ± standard deviation. Differences in SOC content and the values of $\delta^{13}C$ in soil samples from different land uses were tested by one-way analysis of variance (ANOVA) using Tukey post hoc test. Data analyses were implemented using SPSS 10.0.

Results and Discussion

Aggregate Size Fraction

In the top 0.1-m layer, the proportion of micro-aggregates in cropland was significantly higher than that in both forest and grassland (Fig. 2). Conversely, the proportion of small macro-aggregates in forest was significantly higher than that in cropland and grassland. Moreover, the proportion of large macro-aggregates in grassland was more than 45%, which was significantly higher than that in forest. At a depth of 0.1-0.3 m, the variation in proportion of aggregate among different land uses was not significant, except that the proportion of micro-aggregates in forest (about 30%) was significantly lower than that in cropland and grassland.

Our results showed that soil physical fractions in areas of different land use differed significantly. Similarly, John et al. [27] found that the aggregate fraction of 53-1000 μm was the most abundant size fraction in the arable soils, while the >1000-μm fraction was most abundant in grassland and forest. The mean weighted diameter was greater in the grassland and forest soils than in cultivated soils [28]. Beare et al.
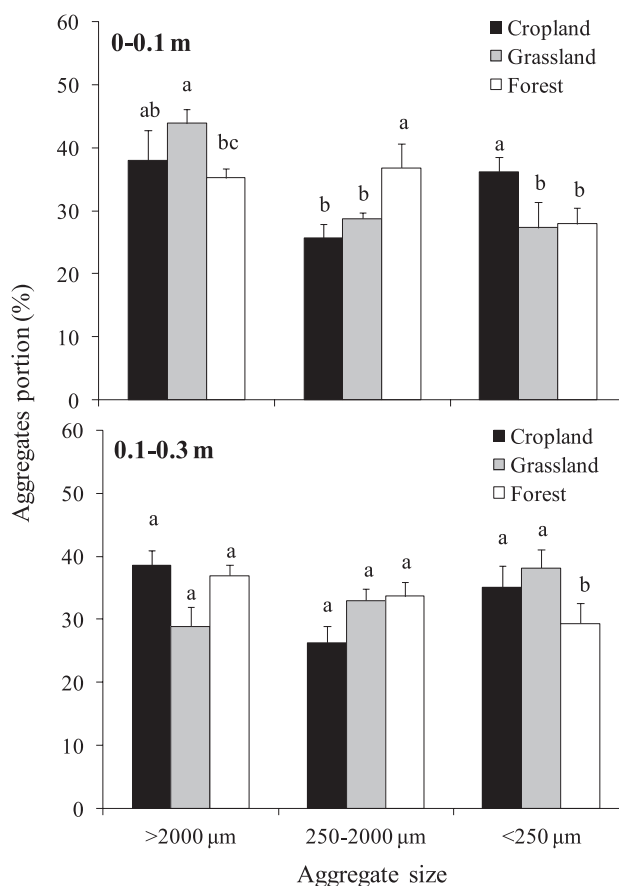

Fig. 2. Aggregate size fraction under different land uses in both topsoil and subsoil; letters at the top indicate significant differences in each aggregate size fraction between land uses (*P*<0.05).
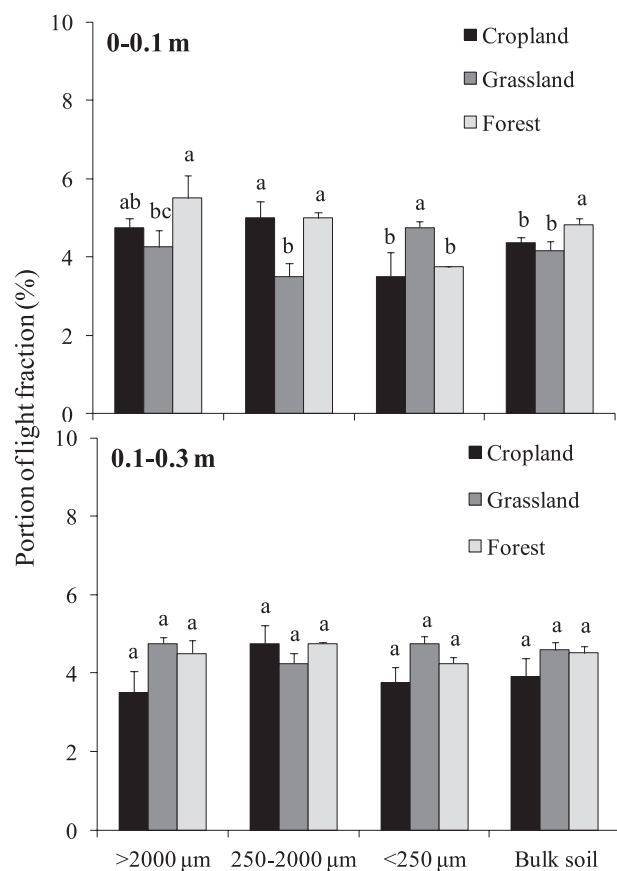

Fig. 3. Proportion of light fraction in varying aggregates under different land uses; letters at the top indicate significant differences in the proportion of light fraction in each aggregate size fraction between land uses (*P*<0.05).
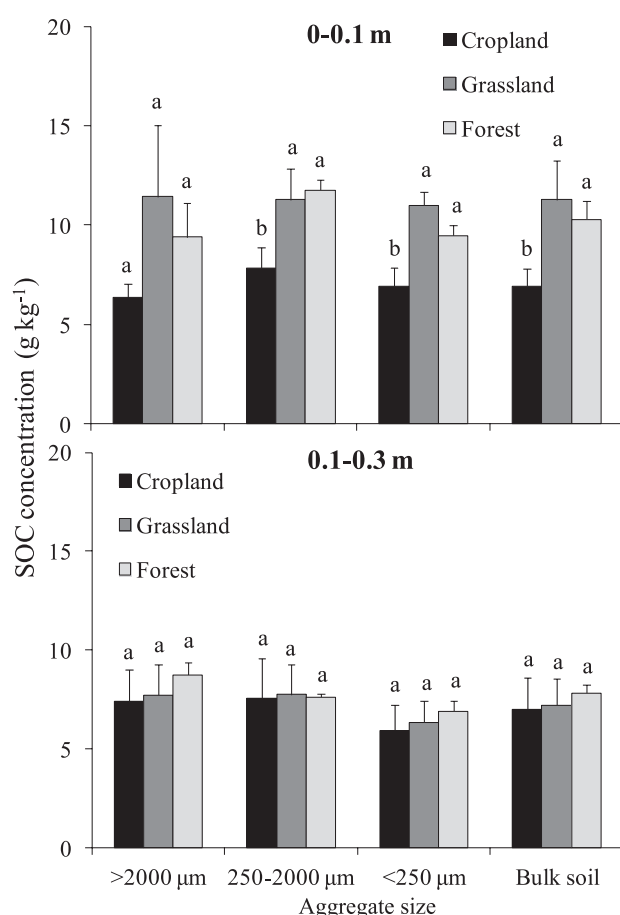
Fig. 4. SOC content in varying aggregates and bulk soil under different land uses; letters at the top indicate significant differences in the SOC content of each aggregate size fraction between land uses (*P*<0.05).
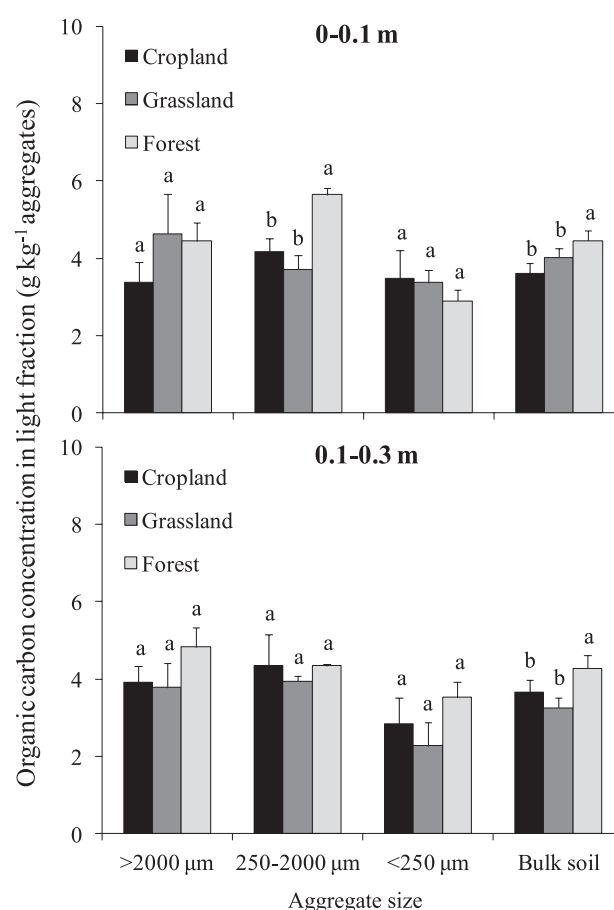

Fig. 5. Organic carbon concentration in light fraction in varying aggregates and bulk soil under different land uses; letters at the top indicate significant differences in the organic carbon concentration in light fraction in each aggregate size fraction between land uses (*P*<0.05).

[29] showed that the proportion of macro-aggregates in conventional tillage was lower than that in no-tillage, indicating that tillage broke up macro-aggregates. Thus, the high proportion of micro-aggregates in cropland may be due to cultivation in cropland because it is an important method of deconstructing macro-aggregates [3, 24].

Density Fraction

The proportion of light fraction in varying aggregates under different land uses is shown in Fig. 3. In the top 0.1-m layer, the proportion of light fraction in the bulk soil in forest was significantly higher than that in cropland and grassland. The proportion of the light fraction in the large macro-aggregate fraction in forest reached 6.0%, which was significantly higher than that in grassland. The proportion of the light fraction in the small macro-aggregate fraction in grassland was significantly lower than that in cropland and forest. However, in the 0.1-0.3 m layer, there was no significant variation in the proportion of light fraction in varying aggregates under different land uses.

Distribution of SOC

The SOC content in each aggregate and the bulk soil were significantly higher in forest and grassland than in cropland (Fig. 4), except for the value in large macro-aggregates. The SOC content in bulk soil in the top 0.1-m layer was 6.9, 11.3, and 10.3 g kg^{-1} in cropland, grassland, and forest, respectively. However, the differences in the SOC contents of aggregates among land uses at the depth of 0.1-0.3 m were not significant. The average value was 7.3 g kg^{-1}.

The organic carbon concentration in light fraction in bulk soil in forest was significantly higher than that in cropland in both the top 0.1-m layer and the deeper layer (Fig. 5). The difference in the organic carbon concentration of light fraction in bulk soil between grassland and forest was significant in both the top 0.1-m layer and the deeper layer. The organic carbon content in small macro-aggregate in grassland was significantly higher than that in cropland and grassland in the top 0.1-m layer. Except for this difference, no difference in the organic carbon concentration in light fraction among different aggregates was found.

Table 2. δ13C values of organic matter in light and heavy fractions of aggregates within various size classes for the soils developed under cropland (CL), grassland (GL), and forest (FL)

Horizon (m)	Land use	Fractions	Aggregate size classes (µm)		
			>2000	250–2000	<250
0-0.1	CL	Light fraction	-20.36±0.33[a]	-20.80±1.61[a]	-22.55±1.53[a]
		Heavy fraction	-15.66±0.21[a]	-18.72±0.49[c]	-16.94±0.38[b]
	GL	Light fraction	-28.54±0.34[b]	-27.82±0.45[ab]	-27.01±0.68[a]
		Heavy fraction	-21.01±0.16[a]	-22.81±0.10[c]	-21.92±0.36[b]
	FL	Light fraction	-25.25±0.06[a]	-26.70±0.46[b]	-26.15±0.27[b]
		Heavy fraction	-22.29±0.36[a]	-24.19±0.37[b]	-21.84±0.18[a]
0.1-0.3	CL	Light fraction	-24.35±0.33[b]	-24.61±1.21[b]	-20.45±0.90[a]
		Heavy fraction	-19.82±0.61[b]	-18.66±0.58[ab]	-18.11±0.65[a]
	GL	Light fraction	-26.13±0.45[ab]	-26.92±0.62[bc]	-25.58±0.38[a]
		Heavy fraction	-23.03±0.66[a]	-21.81±0.75[a]	-22.14±0.58[a]
	FL	Light fraction	-26.46±0.65[a]	-26.77±0.46[a]	-25.91±0.27[a]
		Heavy fraction	-21.12±0.50[b]	-19.85±0.49[a]	-19.96±0.45[a]

Lowercase letters indicate significant differences in δ13C values between the aggregate size fractions (P<0.05).

As shown in Fig. 4, the SOC content in the top 0.1-m layer was significantly higher in forest and grassland than in cropland for most aggregate size fractions and the bulk soil. It is well known that SOC content in cropland is very low because of the low carbon input [30, 31]. Celik [28] reported that SOM content in forest and grassland was similar, while Lugo et al. [33] reported that soil in grassland often contained similar or greater amounts of SOC than adjacent mature forest soil. Chen et al. [34] also suggested that land use conversion from cropland to grassland was better for SOC sequestration than tree plantation in the west part of the Loess Plateau. These three studies support the results of the present study, and suggest that the SOC content in grassland is higher than that in forest, or at least similar to that in forest.

However, the differences in SOC contents among land uses were not significant at deeper layers in the current study. Liao et al. [35] also reported similar vertical variations of SOC content in the karst region of Guizhou in southwestern China. Chen et al. [34] suggested that SOC sequestration mainly occurred in the surface soil after land use conversion. In other words, the changes in SOC content in deeper layers were not obvious; thus, the differences in SOC content among land uses were not significant in deeper layers.

Stable Carbon Isotope Composition in Different Fractions

All values of δ13C in the heavy fractions were higher than those in the light fractions (Table 2). The values of δ13C in macro-aggregates were significantly ($p<0.05$) higher than those in micro-aggregates, for most cases

at both depths. However, the relationship between large aggregates and macro- (or micro-) aggregates was unclear.

The differences in light and heavy stable carbon isotope composition can reflect the degree of microbial decomposition because isotope fractionation results in 13C enrichment of the residue [36]. In the current study, the difference in δ13C between light and heavy fractions in small macro-aggregates was smaller than those in both large macro- and micro-aggregates (Table 2). These results indicated that the degree of microbial decomposition in small macro-aggregates was low. In other words, small macro-aggregates conserve SOC. John et al. [27] also reported that the SOC content in macro-aggregates was much higher than that in micro-aggregates, suggesting that macro-aggregates helped conserve SOC. Tan et al. [23] also suggested that aggregates could protect SOC from disturbance.

Light fraction materials are useful indicators of labile organic matter in soil [37], while the heavy fraction is considered the product of microbial decomposition. The organic carbon concentration in light fraction in bulk soil in forest was significantly higher than that in cropland at both the top 0.1-m layer and the deeper layer, indicating that the new carbon input in forest was much higher than that in cropland. The organic carbon concentration in light fraction in micro-aggregates from grassland was also found to be higher than that in micro-aggregates of forest. This phenomenon suggested that the degradation rate of OC in micro-aggregates of grassland was higher than that in forest. Similarly, the difference in δ13C between the light and heavy fraction in all aggregate size fractions in grassland was much larger than that in forest (Table 2), demonstrating

Table 3. Relationship among soil chemical properties and organic carbon concentration in bulk soil and light fractions; SOC indicates SOC concentration, LF indicates proportion of light fraction, and OC in LF indicates organic carbon concentration in light fraction.

	pH	TN	P	K	SOC	LF	OC in LF
pH	1						
TN	-0.351	1					
P	-0.178	0.059	1				
K	-0.510	0.473	-0.226	1			
SOC	-0.415	0.870*	0.192	0.667	1		
LF	-0.615	0.242	-0.589	0.718	0.196	1	
OC in LF	-0.382	0.238	-0.102	0.781	0.641	0.364	1

*Relationship is significant at P<0.05

that microbial decomposition in grassland was high. Liu et al. [38] found that the degradation rate of straw (similar to grass litter) was much higher than that of tree leaves. The heterogeneous distribution of SOC in grassland might also have occurred because the local peak value of SOC stimulated microbial decomposition.

The decrease in SOC in surface soil was considered to be primarily due to the lower supply of organic matter to the soil system. Both grassland and forest had higher carbon input than cropland [31, 32]; however, the SOC content was dependent on both the litter input and microbial decomposition. As stated above, the degree of microbial decomposition was high in grassland but low in forest. Thus, the accumulation of SOC in grassland was derived from the abundant carbon input, but the protection of SOC provided by small macro-aggregates was important for forest soil.

Relationship Among Soil Chemical Properties and SOC

Table 3 showed the relationship among soil chemical properties and organic carbon concentration in bulk soil and light fractions. The SOC concentration was significantly related to total nitrogen (TN) because TN was mainly from SOM.

In the current study, dry sieving was used to separate aggregates with minimum disruption. The proportion of small macro-aggregates in forest was significantly higher than that in both grassland and cropland, but the proportion of large macro-aggregates in grassland was highest. The aggregation processes reportedly increased as the SOC content increased [3]; accordingly, the high proportion of small macro-aggregates in forest may be due to the high SOC content (Fig. 4). Different from forest, the high SOC content in grassland resulted in increased amounts of large macro-aggregates, but not small macro-aggregates. Wang et al. [39] revealed that

the particle size distribution was more homogeneous in forest than in grassland on the Loess Plateau.

In the current study, stabile and labile carbon was distinguished by density fractions. In future studies, the quantity of content of important biomarkers such as amino acids, lipids, and polysaccharides [40] should be analyzed to provide insight into the dynamics of SOC under various land uses.

Conclusions

Our results showed that variations in physical fractions and SOC contents occurred in the top 0.1-m layer. Cropland had the highest proportion of micro-aggregates, whereas forest had the highest proportion of small macro-aggregates. However, grassland always tended to form large macro-aggregates. The difference in δ^{13}C between light and heavy fractions in small macro-aggregates was smaller than that in both large macro-aggregates and micro-aggregates. These findings indicated that, when compared with micro- and large macro-aggregates, small macro-aggregates conserve SOC. The difference in δ^{13}C between the light and heavy fraction in all aggregate size fractions in grassland was much larger than that in forest, indicating that the degree of microbial decomposition in grassland was high. The physical fractions and stable carbon isotope composition suggested that the accumulation of SOC in grassland was derived from the abundant carbon input, but the protection of SOC from small macro-aggregates was important for forest soil.

Acknowledgements

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