Environ Sci Pollut Res
DOI 10.1007/s11356-016-7583-3

RESEARCH ARTICLE

Soil aggregation and aggregate-associated carbon under four typical halophyte communities in an arid area

Haichang Yang[1] · Jingya Wang[1] · Fenghua Zhang[1]

Received: 21 January 2016 / Accepted: 2 September 2016

Abstract The soil microbial biomass carbon (MBC) is considered as a sensitive index of soil carbon ecosystem. The distribution of aggregate-associated MBC determines the capacity of the soil to store soil organic carbon (SOC). We compared soil aggregate-associated SOC and aggregate-associated MBC under four halophyte communities: *Karelinia caspia* (Pall.) Less. (Abbr. *K. caspia*), *Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze. (Abbr. *B. dasyphylla*), *Haloxylon ammodendron* (C. A. Mey.) Bunge. (Abbr. *H. ammodendron*), and *Tamarix ramosissima* Lour (Abbr. *T. ramosissima*) on an alluvial fan in the Manasi River Basin, Xinjiang, China. The specific objectives of the study were to determine which aggregate size fraction was the most important for MBC and SOC retention in these soils of four halophyte communities. The results showed that the 0.053–0.25 mm fraction contained 47 to 75 % of the total soil mass. The amount of soil in the 0.053–0.25 mm fraction was significantly greater than that in the >0.25 and the <0.053 mm fractions. The >0.25 and the <0.053 mm fractions contained 7.8 to 43.0 % of the soil mass. Aggregate-associated SOC concentrations ranged from 1.70 to 13.68 g kg^{-1}, and the aggregate-associated SOC were the highest under the *H. ammodendron* and *T. ramosissima* communities. The aggregate-associated MBC ranged from 55.26 to 217.11 g kg^{-1}, and the aggregate-associated MBC were higher under the *K. caspia* and *B. dasyphylla* communities. The aggregate-associated SOC concentrations were significantly higher in the >0.25 and the <0.053 mm fractions than in the 0.053–0.25 mm fraction. The aggregate-associated MBC in the 20–40 cm depth was consistent with its law. However, in the 0–20 cm depth, the aggregate-associated MBC concentrations were significantly higher in the >0.25 mm fraction than the other two aggregate fractions, and there were no significant differences in 0.25–0.053 or <0.053 mm fraction. Correlation analyses showed that the aggregate-associated MBC positively correlated with aggregate-associated SOC in >0.25 mm fraction ($P < 0.01$). The microbial entropies ranged from 1.12 to 4.17 %, and the microbial entropy generally was higher in >0.25 mm fraction. Overall, the *H. ammodendron* community had the higher aggregate-associated SOC and aggregate-associated MBC, but the microbial entropy was low. This suggested that among the four halophyte communities in this study, the *H. ammodendron* community could be beneficial for soil carbon storage in arid regions.

Keywords Soil aggregate · Soil organic C · Soil microbial biomass C · Halophyte community · Arid region

Introduction

The soil carbon (C) pool is three times larger than the atmospheric C pool and 3.8 times larger than the biological C pool (Kalambukattu et al. 2013). Therefore, the soil C pool plays an important role in the global C cycle. Soil aggregates are special organic–inorganic complexes and the basic unit of soil structure (Blanco-Canqui and Lal 2004). The formation and stabilization of soil aggregates are closely related to soil organic C (SOC) (Zinn et al. 2007). The distribution of aggregate-associated SOC determines the capacity of the soil to store and retain C (Mohammadi and Motaghian 2011).

Responsible editor: Philippe Garrigues

✉ Fenghua Zhang
zhangfenghua6088@126.com

[1] Agricultural College, Shihezi University, Shihezi, Xinjiang 832003, China

Additionally, the metabolic transformation of matter and energy is located in the soil aggregate; it significantly impacts the soil physiochemical and biological properties (Six et al. 2004). As the most active part of the SOC pool, the soil microbial biomass carbon (MBC) only accounts for 0.3 to 9.9 % of SOC but is the driving force as the transformation and cycling of soil organic matter and nutrients. MBC is also considered as a sensitive index of soil carbon ecosystem (Ren and Stefano 2000). MBC significantly and positively correlates with SOC (Kara and Bolat 2008; Wright et al. 2005), and it also significantly correlates with stability of aggregates (Bidisha et al. 2010). Therefore, the distribution of aggregate-associated SOC and aggregate-associated MBC plays an important role in soil carbon circulation.

There are conflicting reports about the distribution of aggregate-associated SOC and MBC. Some studies report that aggregate-associated SOC and MBC are greater in macroaggregates than microaggregates (Li et al. 2007; Six et al. 2000b; Yang et al. 2009). One report indicated that in the hilly region of the Loess Plateau, the 0.25–2 mm aggregate fraction had the greatest aggregate-associated SOC concentration among all the aggregate fractions in the profile (An et al. 2010). In contrast, other studies indicated the opposite, with microaggregates having higher SOC concentrations than macroaggregates (Beare et al. 1994; Zou et al. 2014). The aggregate-associated MBC was mainly determined by the clay and organic matter, because soil microorganisms were primarily adsorbed into microaggregates (Hernández-Hernández and López-Hernández 2002). Most research about aggregate-associated SOC and aggregate-associated MBC is focused on land use and agroecosystems (including tillage (Beare et al. 1994; Zou et al. 2014) and fertilizer effects (He et al. 2015; Yu et al. 2012)) on soil properties. However, few studies have examined aggregate-associated MBC in saline soils undergoing natural vegetative succession.

The Xinjiang Uyghur Autonomous Region is China's most arid area, and it has the widest distribution of saline soil among all of China's provinces. The Manasi River Basin is the largest inland river of the Junggar Basin in Xinjiang. Soil salt concentrations are the highest in the alluvial fan area of the Manasi River Basin. These natural conditions have led to the development of a variety of halophyte communities (Yi et al. 2007). Relatively few studies have examined aggregate-associated SOC and aggregate-associated MBC under different halophyte communities in this region. An increasing number of man-made oases are being established in the region, and the area of these oases is increasing. Land and water resources in the region are being used irrationally. Overall, these conditions have contributed to declines in the number of halophyte species that are growing near these oases. The ecological benefit of halophytes has become an important research focus. Meanwhile, the impacts of different communities on soil structure and carbon sequestration are different (Abiven et al. 2009). Therefore, the objective of this study was to know the carbon sequestration by studying the aggregate-associated SOC and aggregate-associated MBC under four halophyte communities in an arid region. The aim of this study is to provide a scientific basis for evaluating soil structure and C fixation in saline soil. We also aim to provide a scientific basis for the conservation and restoration of halophyte communities in this region.

Material and methods

Study area

The study site was located on the alluvial fan in the Manasi River Basin, which is located at the center of Eurasia (44° 64′–44° 71′ N, 86° 03′–86° 08′ E, 354 m above sea level). The area has an arid climate, which is characterized by cold winters and hot summers, abundant sunshine, and little precipitation. The annual average temperature is between 6 and 7 °C. Temperatures range between 24 and 35 °C in July and between −18 and −25 °C in February. The average annual evaporation is 2005 mm, which is 13 times higher than the amount of rainfall. The high evaporation rates can cause soil salinization and, as a result, the abandonment of agricultural land. The water table in the area is high. The soil is primarily classified as saline sierozems. The soil saline content is high, with a surface convergence phenomenon. The area is covered by discontinuous shrub layers and relatively continuous herbaceous layers, forming a typical shrub/grass-type, dual-structure community (Yin et al. 2010). Most of the vegetation consists of xerophytic, super-xerophytic, and saline-resistant species.

Research methods

Site selection and soil sampling

We identified four typical halophyte communities on saline-alkaline wasteland that had been abandoned for more than 20 years. The plots were in a flat area of about 67,000 m^2. The sites were similar in slope, aspect, and elevation. The primary plant species were *Karelinia caspia* (Pall.) Less. (Abbr. *K. caspis*), *Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze. (Abbr. *B. dasyphylla*), *Haloxylon ammodendron* (C. A. Mey.) Bunge. (Abbr. *H. ammodendron*), and *Tamarix ramosissima* Lour (Abbr. *T. ramosissma*). The structural characteristics and species composition of each community were determined using standard survey methods. Three areas (20 m × 20 m) were surveyed in each community to determine the species composition, canopy height, canopy cover, Margalef index (M), and Shannon index (H) (Hill et al. 2003) (Table 1). Margalef index is a simple species diversity

Table 1 Description of the plant community at each site

Site number	Plant species distribution	Average height (cm)	Average crown (cm × cm)	Margalef index (M)	Shannon index (H)
I	*Karelinia caspia* (Pall.) Less., *Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze., *Suaeda microphylla* (C. A. Mey.) Pall., *Petrosimonia sibirica* (Pall.) Bunge., *Nitraria tangutorum* Bobr	32	38 × 47	0.693b	0.679b
II	*Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze., *Kalidium foliatum* (Pall.) Moq., *Karelinia caspia* (Pall.) Less.	3	–	0.420c	0.569b
III	*Haloxylon ammodendron* (C. A. Mey.) Bunge., *Kalidium foliatum* (Pall.) Moq., *Limonium sinense* (Girard) Kuntze. *Aeluropus pungens* (M. Bieb.), *Halocnemum strobilaceum* (Pall.) Bieb.	76	150 × 110	1.090a	0.949a
IV	*Tamarix ramosissima* Lour., *Karelinia caspia* (Pall.) Less., *Aeluropus pungens* (M. Bieb.) C. Koch.	57	110 × 80	0.857b	0.917a

Different letters within a column indicate significant differences among the plant communities at $P < 0.05$

I Karelinia caspia (Pall.) Less., *II Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze., *III Haloxylon ammodendron* (C. A. Mey.) Bunge., *IV Tamarix ramosissima* Lour

index emphasizing species richness developed by the Spanish ecologist Ramon Margalef. The Margalef diversity index can easily be calculated according to Eq. (1):

$$M = \frac{S-1}{\ln N} \tag{1}$$

where S is the number of species and N is the total number of individuals in the sample.

Shannon index is a popular diversity in the ecological literature. It is calculated according to Eq. (2):

$$H = -\sum_{i=1}^{s} p_i \ln p_i \tag{2}$$

where p is the proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), ln is the natural log, Σ is the sum of the calculations, and s is the number of species.

Soil samples were collected in mid-May in 2013. The samples were collected by digging three pits (50 cm wide × 100 cm length × 100 cm deep) in each treatment area. Soil samples were taken from under the canopies of primary plant. The pits were distributed in an S-shaped pattern within each area. Undisturbed soil samples were removed from the 0–10, 10–20, 20–40, and 40–60 cm depths of the pits. The samples were placed in square plastic boxes and then taken to the lab. These samples were used to determine aggregate size distribution. Additional samples were collected from each site for chemical analysis. Five mixed soil samples were collected from each treatment and put into ziplock bags. A 1 kg subsample was removed for analysis using the "quartering" method. The soil clods, while moist, were broken apart by hand into aggregates <8 mm by following the planes of least resistance, being careful to break them in traction rather than in compression, and then air-dried and stored prior to analysis for aggregate size distribution. The other soil samples were air-dried, passed sequentially through 1 and 0.25 mm soil sieves, and then stored for chemical analysis (Table 2).

Analytical methods

The air-dried soil samples were separated into three aggregate fractions (i.e., > 0.25, 0.25–0.053, and <0.053 mm) using a nest of sieves, shaken for 60 s at 2 mm amplitude on a Fritsch

Table 2 Selected physical and chemical properties of the soil (0–20 cm depth)

Site number	Water content (%)	pH	Bulk density (g cm^{-3})	Electrical conductivity (dS m^{-1})	Organic matter (g kg^{-1})	Total nitrogen (g kg^{-1})	Total phosphorus (g kg^{-1})	Total potassium (g kg^{-1})	Available nitrogen (mg kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})
I	7.67c	8.96ab	1.30a	5.14a	7.30b	0.37b	0.50a	21.6b	17.2a	6.29a	311b
II	9.37b	8.76b	1.57a	3.53b	5.90c	0.36b	0.44a	23.6a	12.1c	6.61a	454a
III	11.97a	9.08 a	1.52a	4.53b	9.79a	0.46a	0.51a	23.1a	15.4b	5.63b	405a
IV	4.40d	8.37c	1.44a	1.88c	9.21a	0.41a	0.55a	24. 0a	15.9b	5.18b	286c

Different letters within a column indicate significant differences among the plant communities at $P < 0.05$

I Karelinia caspia (Pall.) Less., *II Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze., *III Haloxylon ammodendron* (C. A. Mey.) Bunge., *IV Tamarix ramosissima* Lour

Analysette 3 (Fritsch GmbH Laborgeratebau, Oberstein, Germany) vibratory sieve shaker (Lee et al. 2009). Soil aggregates are generally divided into macroaggregates (>0.25 mm fraction) and microaggregates (<0.25 mm fraction). Soil pH was measured using a pH meter. Soil organic C was measured by the potassium dichromate oxidation/external heating method. Total nitrogen (N) was measured by the semimicro Kjeldahl method. Alkali-hydrolyzable N was measured by diffusion absorption. Total phosphorus (P) was measured by NaOH melt, Mo-Sb colorimetry, and UV spectrophotometry. Available P was measured by $NaHCO_3$ extraction, Mo-Sb colorimetry, and UV spectrophotometry. Total potassium (K) was measured by atomic absorption spectrometry. Available K was measured by NH_4Ac extraction and atomic absorption spectroscopy.

MBC was measured by chloroform fumigation and the potassium extraction method, using a TOC-VCHP analyzer (Vance et al. 1987). During experimentation, 10 g fresh soil was fumigated with chloroform vapor in a vacuum desiccator for 24 h. After application of repeated vacuum to remove the remaining chloroform, samples were vigorously shaken in 50 ml of a 0.5 M K_2SO_4 solution for 30 min. The filtered extracts were measured in a TOC automatic analyzer. Soil MBC was calculated by dividing the difference between the levels of organic carbon in the fumigated and nonfumigated soils by the conversion factor Kc (0.38).

Statistical analysis

Statistical analysis was conducted using the statistical software SPSS 11.5 (IBM, Armonk, NY). Data were reported as the mean ± standard error. A least significance difference (LSD) test for testing the equality of k population means in a one-way layout was examined as one of the first multiple comparisons procedures (Hayter 1986). The letter-marking method was used in the comparison of different treatments. Significant differences in soil aggregate content, soil aggregate-associated SOC content, and soil aggregate-associated MBC content among aggregate size classes within a site were indicated using different lowercase letters ($P = 0.05$). Significant differences in soil aggregate content, soil aggregate-associated SOC content, and soil aggregate-associated MBC content within the same aggregate size classes among the four sites were indicated using different uppercase letters ($P = 0.05$).

Results

Soil aggregate distribution

The 0.25–0.053 mm fraction contains 46.7 to 74.6 % of the total soil mass (Fig. 1); this is significantly more than other

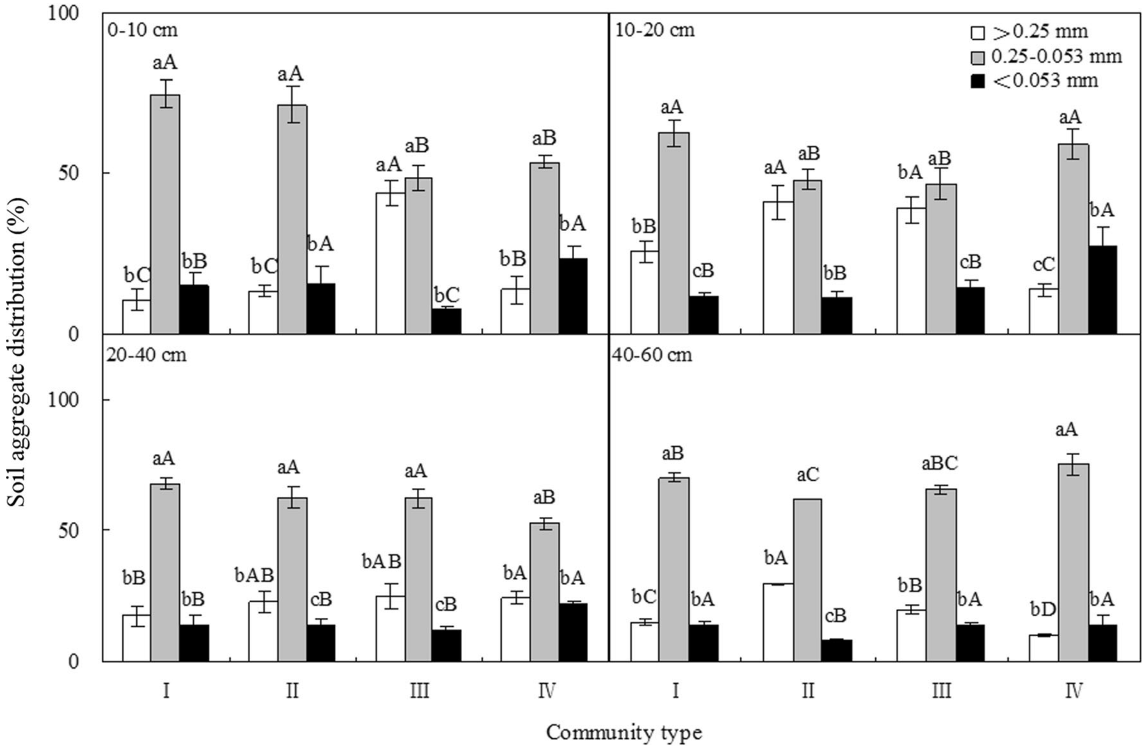

Fig. 1 Distribution of soil aggregates as affected by the halophyte communities. *I Karelinia caspia* (Pall.) Less., *II Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze., *III Haloxylon ammodendron* (C. A. Mey.) Bunge., and *IV Tamarix ramosissima* Lour. *Different lowercase letters* indicate significant differences among aggregate size classes within a site ($P < 0.05$). *Different uppercase letters* indicate significant differences within the same aggregate size class among the four sites ($P < 0.05$)

two fractions. >0.25 or <0.053 mm fractions accounted for only 7.8 to 43.0 % of the total soil mass. In addition, in the 0–60 cm depth, soil mass in the <0.053 mm fraction is significantly higher under the *T. ramosissima* community. In the 0–20 cm depth, soil mass in the 0.25–0.053 mm fraction is significantly the greatest under the *K. caspia* community. Soil mass in the >0.25 mm fraction is significantly higher under the *H. ammodendron* community. In the 20–40 cm depth, there are no significant differences in aggregate distribution under *K. caspia*, *B. dasyphylla*, and *H. ammodendron*.

The distribution of soil aggregate distribution varied among the plant communities. The average aggregate content of the 0.25–0.053 mm fraction is higher under *K. caspia* (69 %) than under *B. dasyphylla* (61 %), *T. ramosissima* (56 %), and *H. ammodendron* (60 %). The average aggregate content of the >0.25 mm fraction is the highest under *H. ammodendron* (32 %) and the lowest under *T. ramosissima* (16 %). The average aggregate content of the <0.053 mm fraction is the highest under *T. ramosissima* (22 %).

Aggregate-associated SOC

Aggregate-associated SOC concentrations range between 1.70 and 13.68 g·kg^{-1} (Fig. 2). Aggregate-associated SOC concentrations vary significantly among the three aggregate fractions. Aggregate-associated SOC concentrations in 0.25–0.053 mm fraction are the lowest and the highest in >0.25 or 0.25–0.053 mm fractions showing a V-shaped distribution. In the 0–10 cm depth, aggregate-associated SOC of the three diameters is higher in the *T. ramosissima* community than the other communities. In the 10–20 cm depth, aggregate-associated SOC of the three diameters is significantly higher in the *H. ammodendron* community than the other communities. In the 20–40 cm depth, aggregate-associated SOC of three diameters is significantly higher in the *K. caspia* community than the other communities. Aggregate-associated SOC concentrations generally decrease as soil depth increased under all four plant communities. The exceptions are that aggregate-associated SOC concentrations reach a peak at either the 10–20 or the 20–40 cm depths before decreasing under *K. caspia* and *H. ammodendron.* Multivariate analysis of variance indicates no significant difference in aggregate-associated SOC among *K. caspia*, *H. ammodendron*, and *T. ramosissima*. However, aggregate-associated SOC concentrations under those three communities are all significantly higher than under *B. dasyphylla*.

The aggregate-associated MBC

The aggregate-associated MBC concentrations range between 55.26 and 217.11 mg kg^{-1} (Fig. 3), in the 0–20 cm depth. The aggregate-associated MBC concentrations in >0.25 mm fraction are significantly higher than the other fractions, and there

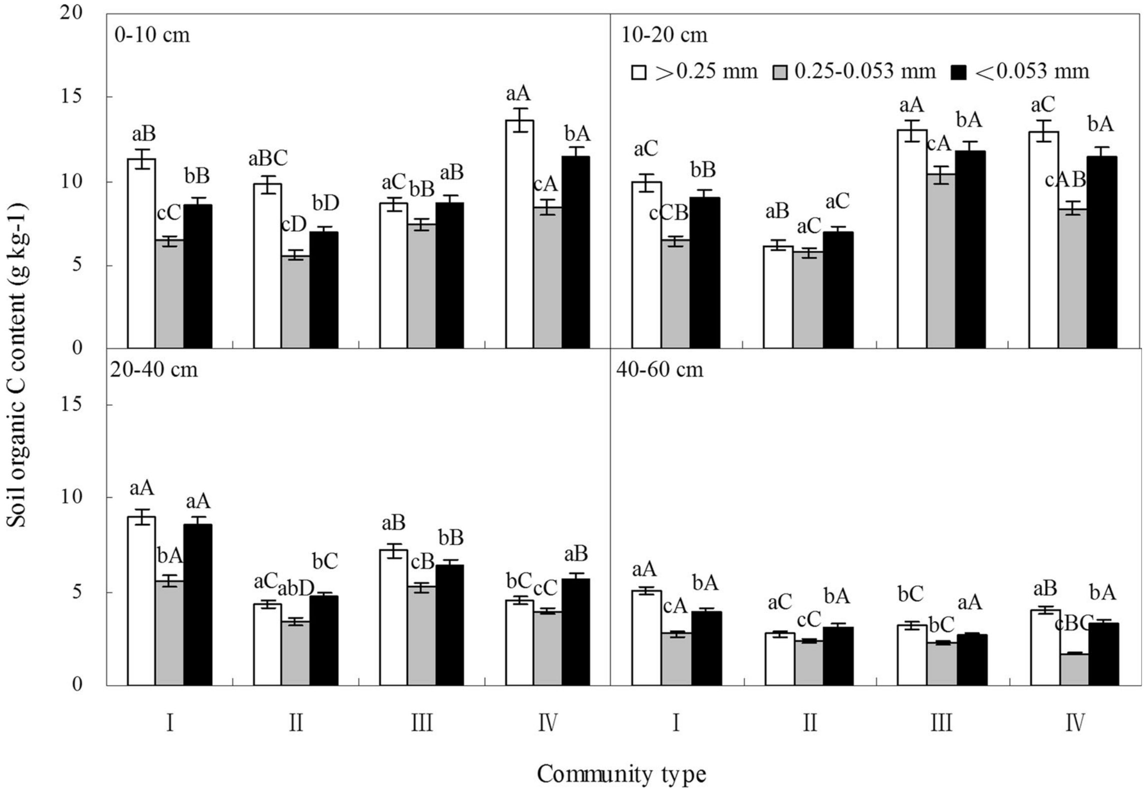

Fig. 2 Aggregate-associated SOC at different soil depths as affected by the halophyte community

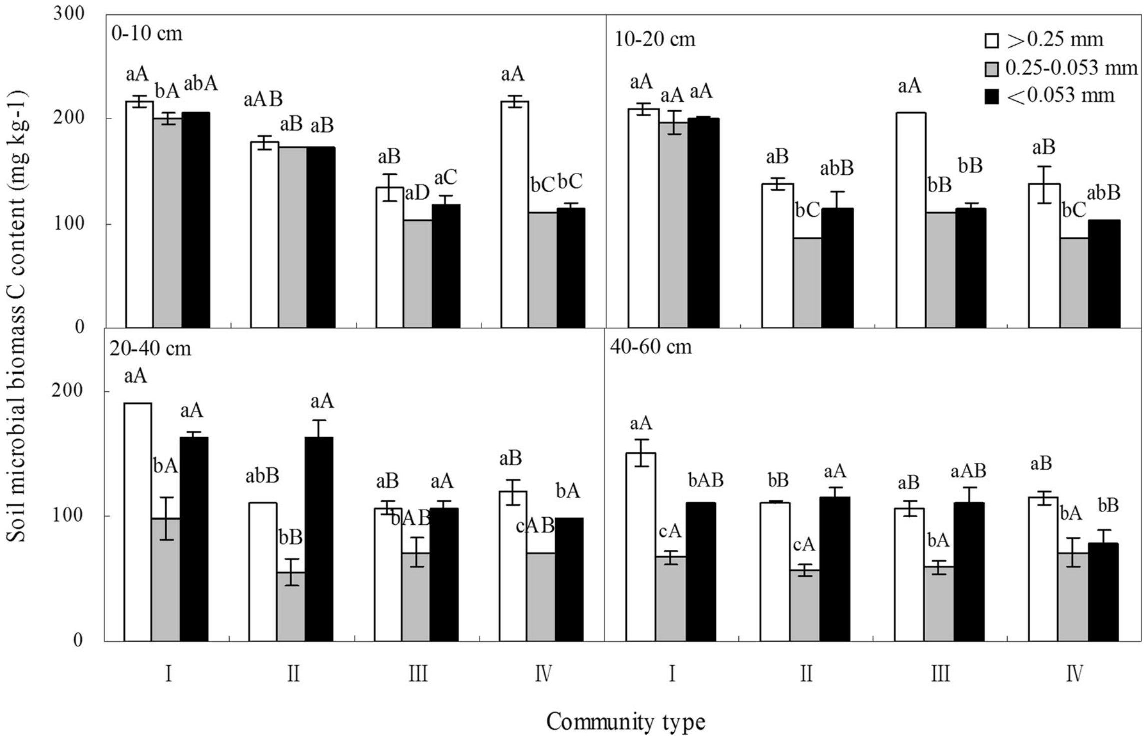

Fig. 3 Aggregate-associated MBC at different soil depths as affected by the halophyte community

are no significant differences in aggregate-associated MBC between 0.25–0.053 mm fraction and <0.053 mm fraction. In the 20–40 cm depth, the aggregate-associated MBC concentrations are the lowest in 0.25–0.053 mm fraction and the highest in >0.25 or 0.25–0.053 mm fractions, showing a V-shaped distribution. In the 0–40 cm depth, the aggregate-associated MBC concentrations are significantly the highest under the *K. caspia* community. The aggregate-associated MBC concentrations decrease as the soil depth increased. Overall, the aggregate-associated MBC is higher under the *K. caspia* and *B. dasyphylla* communities. Correlation analyses based on Table 3 show that the aggregate-associated MBC positively correlated with aggregate-associated SOC in >0.25 mm fraction ($P < 0.01$), suggesting a close relationship between MBC and SOC in macroaggregates.

The soil aggregate microbial entropy

Microbial entropy is the ratio of soil MBC to the total SOC. It fully reflects the proportion of soil active organic carbon and reveals the soil fertility as a microbiological perspective (Liu et al. 2011). The microbial entropies range between 1.12 and 4.17 % (Table 4). The microbial entropies are higher in the *K. caspia* and *B. dasyphylla* communities, with an average content of 2.66 and 2.56 % respectively, but in *H. ammodendron* and *T. ramosissima* communities are lower, with average content of 1.94 and 1.93 %, respectively. The

Table 3 Correlation coefficients of particle-sized soil aggregates MBC and SOC

	Soil aggregate size (mm)		
	>0.25	0.25–0.053	<0.053
r	0.798^{**}	0.485	0.268

** $P < 0.01$

Table 4 Microbial entropy in different-sized soil aggregates under different halophyte communities (%)

Community type	Aggregate size (mm)	Soil depth (cm)			
		0–10	10–20	20–40	40–60
I	>0.25	1.92	2.64	2.11	2.96
	0.25–0.053	3.13	3.84	1.77	2.43
	<0.053	2.39	2.79	1.89	2.81
II	<0.25	1.81	2.80	2.57	3.99
	0.25–0.053	3.12	1.89	1.62	2.41
	<0.053	2.50	2.07	3.39	3.70
III	>0.25	1.56	1.97	1.48	3.30
	0.25–0.053	1.38	1.33	1.35	2.64
	<0.053	1.35	1.21	1.66	4.09
IV	>0.25	1.59	1.32	2.63	2.82
	0.25–0.053	1.31	1.30	1.79	4.17
	<0.053	1.00	1.12	1.70	2.36

Different letters within a column indicate significant differences among the plant communities at $P < 0.05$

I Karelinia caspia (Pall.) Less., *II Bassia dasyphylla* (Fisch. et C. A. Mey.) Kuntze., *III Haloxylon ammodendron* (C. A. Mey.) Bunge., *IV Tamarix ramosissima* Lour microbial entropy is mainly concentrated in >0.25 mm fraction, suggesting a higher proportion of active organic C in macroaggregates. The aggregate microbial entropy increased with soil depth increased.

Discussion

Effects of different halophyte communities on the distribution of soil aggregates

In arid and semiarid regions, the distribution of soil aggregates is closely related to stability of soil quality. Soil erosion resistance generally increases as the proportion of macroaggregates increases (Wang et al. 2010). In this study, the amount of soil in the 0.053–0.25 mm fraction is significantly greater than that in either of the other two aggregate fractions, accounted for 61.5 %. The amount of aggregates in >0.25 mm fraction is only 22.8 %. These findings suggest that soil structure and quality are poor in this region. The soil is affected by low precipitation amounts and sparse vegetation. Under these conditions, macroaggregates break down, and the proportion of microaggregates increases. Total SOC, aggregate-associated SOC, and aggregate mass in >0.25 mm fraction were all greater under *H. ammodendron* than under any other plant communities. Some studies have shown that organic matter promotes the formation of aggregates (Golchin and Asgari 2008; Verchot et al. 2011). Therefore, the *H. ammodendron* community can increase soil C sequestration in arid areas.

Effects of different halophyte communities on aggregate-associated SOC

Total SOC is mainly affected by plant litter, plant roots, animals, and microorganisms. Our results indicated that total SOC and aggregate-associated SOC concentrations were the highest under the *H. ammodendron* and the *T. ramosissima* communities. Aggregate-associated SOC under *B. dasyphylla* is significantly lower than under the other communities. Some studies have shown that the half spherical crown of *T. ramosissima* is conducive for capturing and protecting plant litter (Ma et al. 2009). This can increase litter input to the soil, while the soil nutrient, species richness was high, root systems were well developed, and vegetation crowns were large in the *H. ammodendron* and *T. ramosissima* communities. In comparison, the *B. dasyphylla* community consisted primarily of short, annual herbs, with relatively little biomass. Therefore, C inputs to the soil were greater under the *H. ammodendron* and *T. ramosissima* communities than under the *B. dasyphylla* community. Total SOC and aggregate-associated SOC decreased as soil depth increased. These results are consistent with previous studies and can probably be attributed to the contribution of surface litter to SOC in the upper part of the soil profile (Jiménez et al. 2011; Maia et al. 2010). Under *K. caspia*, the aggregate-associated SOC was higher in the 20–40 cm depth than in the 10–20 cm depth. One explanation is plant roots in the *K. caspia* community were mainly distributed in the 20–40 cm depth. These roots and their secretions would have altered physical, chemical, and biological properties related to the formation of soil aggregates (Bedini et al. 2009). The effect of vegetation on SOC decreased with soil depth. Furthermore, the parent material was the same under all four plant communities (Grimm et al. 2008). For these reasons, aggregate-associated SOC concentrations were similar in the deep soil layers, regardless of the vegetation type.

There are conflicting reports about the distribution of aggregate-associated SOC among aggregate size fractions. Some studies indicated that microaggregate SOC was higher, whereas others have shown that the microaggregate SOC was higher (44 to 88 % of the total mass) (Brodowski et al. 2006; Saha et al. 2010; Six et al. 2000b). In this study, aggregate-associated SOC concentrations were significantly higher in the >0.25 mm and the <0.053 mm fractions than in the 0.053–0.25 mm fraction. The reason is that organic matter can bind microaggregates together into macroaggregates. In addition, the degradation by plant roots and hyphae in macroaggregates significantly increases organic C (Gulde et al. 2008; Razafimbelo et al. 2008). Therefore, macroaggregates are usually associated with high organic C. Some researchers have suggested that SOC is younger in macroaggregates than in microaggregates (Puget et al. 2000; Six et al. 2000a). The SOC in macroaggregates mineralizes easier, whereas the SOC in macroaggregates primarily consists of stable humus which is not easily be mineralized, so the SOC in microaggregates is continuously accumulated. However, in this study, the aggregate-associated SOC was higher in <0.053 mm fraction than in 0.25–0.053 mm fraction. These findings may be because humic carbon is lower in 0.25–0.053 mm fraction than in <0.053 mm fraction.

Effects of different halophyte communities on aggregate-associated MBC

MBC is the most active ingredient in SOC. It generally accounts for only 1 to 3 % of the total SOC. However, it is commonly seen as a sensitive indicator of soil environmental response (Wen et al. 2004). In the 0–20 cm depth, the aggregate-associated MBC was significantly higher in >0.25 mm fraction than the other fractions. Other studies also have similar conclusions (Zheng et al. 2013; Franzluebbers and Arshad 1997), suggesting that the aggregate-associated active organic C is high in surface soil, providing more carbon sources for microbial activity. This is mainly because the organic C in macroaggregates is simpler than in microaggregates and it is easier to be utilized by microbes

(Liu et al. 2007; Deng et al. 2005). However, in the 20–40 cm depth, the aggregate-associated MBC concentrations were significantly higher in >0.25 mm fraction or <0.053 mm fraction than in 0.25 ~ 0.053 mm fraction. Studies have shown that mineral clay and organic matter in microaggregates can closely combine carbon, forming a complicated structure, which is not easily decomposed by microorganisms (Mao et al. 2007; Liu et al. 2006; Li et al. 2006).

Overall, the aggregate-associated SOC (1.70 to 13.68 g kg^{-1}) and the aggregate-associated MBC (55.26 to 217.11 mg kg-1) were relatively low in this area, suggesting the soil structure and quality are both poor in this region. The aggregate-associated SOC under the *T. ramosissima* community was the higher and under the *K. caspia* community was lower, but the aggregate-associated MBC under the *T. ramosissima* community was lower and under the *K. caspia* community was higher. Those findings indicate that the MBC is not only affected by organic matter but also by many other factors. Some studies show that the MBC is affected by soil organic matter input as well as the activity and mineralization of the organic matter (Wen et al. 2004). The aggregate-associated MBC in the *K. caspia* community was higher may be due to a lot of organic C being decomposed by a microbe (Liu et al. 2011). The aggregate-associated MBC was lower under the *T. ramosissima* community may be due to the activity of organic C in aggregate-associated SOC that was lower. At the same time, the amount of aggregates in <0.053 mm fraction was the highest (20 %) under the *T. ramosissima* community, due to the organic C in macroaggregates mineralizes easier, whereas the organic C in microaggregates primarily consists of stable humus and it is not easily mineralized (Mao et al. 2009). So those findings suggest that the aggregate-associated SOC is high inertia and is not easy utilized by microorganism under *T. ramosissima*.

Soil aggregate microbial entropy

Microbial entropy is more effective than MBC or total C in quantifying the soil quality; this is because entropy is a ratio that avoids some problems about comparison soils with different organic matters (Liu et al. 2006). Some studies have shown that microbial entropy accurately reflects the impact of land use and management practices and also be used as an effective indicator of soil carbon dynamics (Franchini et al. 2007; Marinari et al. 2006). In this study, the microbial entropy was the highest under the *K. caspia* community while under the *T. ramosissima* community was the lowest. It suggested that although there was a lot of carbon for microorganisms under the *T. ramosissima* community, the relatively few SOC was utilized by microorganisms. Meanwhile, a lot of SOC was utilized by microorganisms under the *K. caspia* community. Overall, under the *H. ammodendron* community, the aggregate-associated SOC and aggregate-associated MBC were relatively higher, but its microbial entropy was low (1.94 %), suggesting that this community was beneficial for soil carbon fixation and accumulation. Microbial entropy is a good index of soil evaluation, and it can reflect soil carbon utilization combined with SOC and MBC.

Conclusion

In this study, the *T. ramosissima* community has higher aggregate-associated SOC and lower aggregate-associated MBC, indicated that it was rich in carbon sources, but relatively little carbon was utilized by microorganisms. The aggregate-associated SOC and aggregate-associated MBC were relatively higher under the *H. ammodendron* community; its microbial entropy was lower, indicated that among the halophyte communities in this study, the *H. ammodendron* community is beneficial for carbon accumulation in arid areas.

The aggregate-associated SOC concentrations in 0.25–0.053 mm fraction are the lowest and the highest in >0.25 or 0.25–0.053 mm fractions, showing a V-shaped distribution. The aggregate-associated MBC in the 20–40 cm depths was consistent with this regular. However, in the 0–20 cm depth, the aggregate-associated MBC concentrations were significantly higher in >0.25 mm fraction than the other fractions. It suggests that macroaggregates are beneficial for carbon accumulation due to it has higher organic C and active organic C.

Acknowledgments This research was supported by the National key research and development plan (2016YFC0501406), the National Natural Science Foundation of China (31360320), the National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2014BAC14B03). We gratefully acknowledge helpful comments by the anonymous referees who simulated significant improvements in the analysis and writing. We also thank Dr. Jeff Gale for his conscientious help with the English in this paper.

References

Abiven S, Menasseri S, Chenu C (2009) The effects of organic inputs over time on soil aggregate stability—a literature analysis. Soil Biol Biochem 41:1–12

An S, Mentler A, Mayer H, Blum WE (2010) Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China. Catena 81:226–233

Beare M, Hendrix P, Coleman D (1994) Water-stable aggregates and organic matter fractions in conventional-and no-tillage soils. Soil Sci Soc Am J 58:777–786

Bedini S, Pellegrino E, Avio L, Pellegrini S, Bazzoffi P, Argese E, Giovannetti M (2009) Changes in soil aggregation and glomalin-related soil protein content as affected by the arbuscular mycorrhizal fungal species Glomus mosseae and Glomus intraradices. Soil Biol Biochem 41:1491–1496

Bidisha M, Joerg R, Yakov K (2010) Effects of aggregation processes on distribution of aggregate size fractions and organic C content of a long-term fertilized soil. Eur J Soil Biol 46:365–370

Blanco-Canqui H, Lal R (2004) Mechanisms of carbon sequestration in soil aggregates. Crit Rev Plant Sci 23:481–504

Brodowski S, John B, Flessa H, Amelung W (2006) Aggregate-occluded black carbon in soil. Eur J Soil Sci 57:539–546

Deng X, Tan JC, Yin LR, Ren YH, Liu HY (2005) Preliminary investigation of the number of microorganism in different tea soils[J]. Tea Communication 32(2):7–9

Franchini JC, Crispino CC, Souza RA, Torres E, Hungria M (2007) Microbiological parameters as indicators of soil quality under various soil management and crop rotation systems in southern Brazil[J]. Soil and Tillage Research 92:18–29

Franzluebbers AJ, Arshad MA (1997) Soil microbial biomass and mineralizable carbon of water-stable aggregates[J]. Soil Science Society of America Journal 61:1090–1097

Golchin A, Asgari H (2008) Land use effects on soil quality indicators in north-eastern Iran. Soil Res 46:27–36

Grimm R, Behrens T, Märker M, Elsenbeer H (2008) Soil organic carbon concentrations and stocks on Barro Colorado Island—digital soil mapping using random forests analysis. Geoderma 146:102–113

Gulde S, Chung H, Amelung W, Chang C, Six J (2008) Soil carbon saturation controls labile and stable carbon pool dynamics. Soil Sci Soc Am J 72:605–612

Hayter AJ (1986) The maximum familywise error rate of Fisher's least significant difference test. J Am Stat Assoc 81:1000–1004

He Y, Zhang W, Xu M, Tong X, Sun F, Wang J, Huang S, Zhu P, He X (2015) Long-term combined chemical and manure fertilizations increase soil organic carbon and total nitrogen in aggregate fractions at three typical cropland soils in China. Sci Total Environ 532:635–644

Hernández-Hernández R, López-Hernández D (2002) Microbial biomass, mineral nitrogen and carbon content in savanna soil aggregates under conventional and no-tillage. Soil Biol Biochem 34: 1563–1570

Hill TC, Walsh KA, Harris JA, Moffett BF (2003) Using ecological diversity measures with bacterial communities. FEMS Microbiol Ecol 43:1–11

Jiménez JJ, Lorenz K, Lal R (2011) Organic carbon and nitrogen in soil particle-size aggregates under dry tropical forests from Guanacaste, Costa Rica—implications for within-site soil organic carbon stabilization. Catena 86:178–191

Kalambukattu JG, Singh R, Patra AK, Arunkumar K (2013) Soil carbon pools and carbon management index under different land use systems in the central Himalayan region. Acta Agriculturae Scandinavica, Section B–Soil and Plant Science 63:200–205

Kara Ö, Bolat I (2008) Soil microbial biomass C and N changes in relation to forest conversion in the northwestern Turkey. Land Degrad Dev 19:421–428

Lee SB, Lee CH, Jung KY, Do Park K, Lee D, Kim PJ (2009) Changes of soil organic carbon and its fractions in relation to soil physical properties in a long-term fertilized paddy. Soil Tillage Res 104:227–232

Li XH, Yuan YL, Huang QR, Hu F, Pan GX (2006) Effects of fertilization on soil organic carbon distribution in various aggregates of red paddy soil[J]. ACTA PEDOLOGICA SINICA 43(3):422–429

Li H, Han X, Wang F, Qiao Y, Xing B (2007) Impact of soil management on organic carbon content and aggregate stability. Commun Soil Sci Plant Anal 38:1673–1690

Liu Y, Li SQ, Shao AM, Zhang YX (2006) Distribution of organic carbon pools in different sizes of soil aggregates in Loess Plateau[J]. Chinese Journal of Applied Ecology 17(6):1003–1008

Liu Y, Li SQ, Li SX (2007) Distribution of Nitrogen Pools in Different Sizes of Loess Plateau Soil Aggregates[J]. Scientia Agricultura Sinica 40(2):304–313

Liu MY, Zheng ZC, Li TX (2011) Distribution Characteristics of Microbial Biomass Carbon and Nitrogen in Soil Aggregates Under Tea Plantation[J]. Scientia Agricultura Sinica 44:3162–3168

Ma Q, Wang J, Li X, Zhu S, Liu H, Zhan K (2009) Long-term changes of Tamarix-vegetation in the oasis-desert ecotone and its driving factors: implication for dryland management. Environ Earth Sci 59:765–774

Maia SM, Ogle SM, Cerri CC, Cerri CE (2010) Changes in soil organic carbon storage under different agricultural management systems in the Southwest Amazon region of Brazil. Soil Tillage Res 106:177–184

Mao YL, Yang YS, Zou SQ, Cheng GS, Wang GQ (2007) Effects of Land Use on Soil Organic Carbon in Aggregates of Hilly Red Soil in SubtropicalChina[J]. Journal of Mountain Science 25:706–713

Mao YL, Yang YS, Cui JC (2009) Effects of Land Use on Soil Microbial Biomass Carbon in Aggregates[J]. Journal of Soil and Water Conservation 23(4):227–231

Marinari S, Mancinelli R, Campiglia E, Grego S 2006: Chemical and biological indicators of soil quality in organic and conventional farming systems in Central Italy. ECOL INDIC., 6, 701–711

Mohammadi J, Motaghian M (2011) Spatial prediction of soil aggregate stability and aggregate-associated organic carbon content at the catchment scale using geostatistical techniques. Pedosphere 21:389–399

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

Razafimbelo TM, Albrecht A, Oliver R, Chevallier T, Chapuis-Lardy L, Feller C (2008) Aggregate associated-C and physical protection in a tropical clayey soil under Malagasy conventional and no-tillage systems. Soil Tillage Res 98:140–149

Ren T, Stefano G (2000) Soil bioindicators in sustainable agriculture. Sci Agric Sin 33:68–75

Saha SK, Nair PR, Nair VD, Kumar BM (2010) Carbon storage in relation to soil size-fractions under tropical tree-based land-use systems. Plant Soil 328:433–446

Six J, Elliott E, Paustian K (2000a) Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol Biochem 32:2099–2103

Six J, Paustian K, Elliott E, Combrink C (2000b) Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci Soc Am J 64:681–689

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 Tillage Res 79:7–31

Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. Soil Biol Biochem 19:703–707

Verchot LV, Dutaur L, Shepherd KD, Albrecht A (2011) Organic matter stabilization in soil aggregates: understanding the biogeochemical mechanisms that determine the fate of carbon inputs in soils. Geoderma 161:182–193

Wang J, He Z, Wang L, Long X, He S, Wang J, Guo L, Hong C (2010) Properties of humus and content of soil aggregates in soils on Gaoligong Mountain. Acta Pedol Sin 47:723–733

Wen Q, Zhao XR, Cheng HW, Tuo DB, Lin QM (2004) Distribution Characteristics of Microbial Biomass Carbon in Different Soil Aggregates in Semi-arid Area[J]. Scientia Agricultura Sinica 37(10):1504–1509

Wright AL, Hons FM, Matocha JE (2005) Tillage impacts on microbial biomass and soil carbon and nitrogen dynamics of corn and cotton rotations. Appl Soil Ecol 29:85–92

Yang Y, Guo J, Chen G, Yin Y, Gao R, Lin C (2009) Effects of forest conversion on soil labile organic carbon fractions and aggregate stability in subtropical China. Plant Soil 323:153–162

Yi L, Ma J, Li Y (2007) Soil salt and nutrient concentration in the rhizosphere of desert halophytes. Acta Ecol Sin 27:3565–3571

Yin CH, Feng G, Zhang F, Tian CY, Tang C (2010) Enrichment of soil fertility and salinity by tamarisk in saline soils on the northern edge of the Taklamakan Desert. Agric Water Manag 97:1978–1986

Yu H, Ding W, Luo J, Geng R, Ghani A, Cai Z (2012) Effects of long-term compost and fertilizer application on stability of aggregate-associated organic carbon in an intensively cultivated sandy loam soil. Biol Fertil Soils 48:325–336

Zheng ZC, Liu MY, Li YX (2013) Distribution Characteristics of Organic Carbon Fractions in Soil Aggregates Under Tea Plantation of Different Ages[J]. Scientia Agricultura Sinica 46(9):1827–1836

Zinn YL, Lal R, Bigham JM, Resck DV (2007) Edaphic controls on soil organic carbon retention in the Brazilian Cerrado: texture and mineralogy. Soil Sci Soc Am J 71:1204–1214

Zou LQ, Chen FS, Duncan DS, Fang XM, Wang HM (2014) Reforestation and slope-position effects on nitrogen, phosphorus pools, and carbon stability of various soil aggregates in a red soil hilly land of subtropical China. Can J For Res 45:26–35