Contents of soil organic carbon and nitrogen in water-stable aggregates in abandoned agricultural lands in an arid ecosystem of Northwest China

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Abstract: Soil organic matter content in water-stable aggregates (WSA) in the arid ecosystems (abandoned agricultural lands especially) of China is poorly understood. In this study, we examined the WSA sizes and stability, and soil organic carbon (OC) and nitrogen (N) contents in agricultural lands with abandonment ages of 0, 3, 12, 20, 30 and 40 years, respectively, in the Minqin Oasis of Northwest China. The total soil OC and N contents at depths of 0–20, 20–40 and 40–60 cm in abandoned agricultural lands were compared to those in cultivated land (the control). Agricultural land abandonment significantly ($P<0.05$) influenced the distribution of MWD (mean weight diameter), and OC and N contents. There were significant increases in MWD and the proportion of macroaggregates (sizes >0.25 mm) as the age of agricultural land abandonment increased. The effect of abandonment ages of agricultural lands on MWD was determined by the changes of OC and N accumulation in WSA sizes >2 mm. The total OC and N contents presented a stratification phenomenon across soil depths in this arid ecosystem. That is, both of them decreased significantly at depths of 0–20 and 40–60 cm while increased at the depth of 20–40 cm. The WSA sizes <0.053 mm had the highest soil OC and N contents (accounting for 51.41%–55.59% and 42.61%–48.94% of their total, respectively). Soil OC and N contents in microaggregates (sizes 0.053–0.25 mm) were the dominant factors that influenced the variations of total OC and N contents in abandoned agricultural lands. The results of this study suggested that agricultural land abandonment may result in the recovery of WSA stability and the shifting of soil organic matter from the silt+clay (<0.053 mm) and microaggregate fractions to the macroaggregate fractions. However, agricultural land abandonment did not increase total soil OC and N contents in the short-term.

The relationship of soil aggregate characteristics with soil organic carbon (OC) and nitrogen (N) has been reported extensively (Six et al., 2000a; Lützow et al., 2006). The concept of aggregation involving different organic binding agents at different scales was pioneered by Tisdall and Oades (1982). Subsequently, Waters and Oades (1991) introduced the concept of aggregate hierarchy and provided that organic matter is key to soil aggregate stability, and in turn is affected by aggregate

destabilization and turnover rate (Zagal et al., 2013). Determining OC pools in aggregates can provide important information on soil OC sequestration and mineralization in aggregate size fractions, and aggregate stability can be protected by using appropriate soil and crop management practices (Whalen and Chang, 2002).

Water-stable aggregates (WSA) are the foundation of both water and fertility conservation (Sui et al., 2012). Soil aggregate stability is influenced by land use change (e.g. agricultural abandonment) in the way that changes the proportion of WSA sizes (John et al., 2005; Ashagrie et al., 2007) and mean weight diameter (MWD) (Bonifacio et al., 2006). Microaggregates, however, seem to be less influenced by land use change (Puget et al., 2000). WSA and MWD fractions increase with increasing organic matter content (Onweremadu et al., 2007). Carter (1996) and Haynes (2000) noted that soil OC content is often associated with WSA percentage and macroaggregate stability. Jastrow (1996) observed that macroaggregate formation occurs first and develops rapidly in soil. Therefore, WSA and MWD can be used as indicators for evaluting the influence of land use change (e.g. agricultural land abandonment) on soil quality (Sui et al., 2012). Thus, accurate evaluation of the effects of land use change (e.g. agricultural abandonment) on soil OC and N contents is required to monitor the WSA and MWD dynamics.

Soils with higher WSA percentage and MWD often have high OC and N contents because such soils are likely to have greater resistance to degradation and erosion (Celik, 2005; Onweremadu et al., 2007). When agricultural abandonment occurs, soil properties such as organic matter content, structure and infiltration rate may be improved, resulting in more effective protection against soil erosion (Kosmas et al., 2000). These results may benefit soil evolution. Investigating the soil OC after agricultural land abandonment, as expressed in OC content in different size fractions of WSA is more crucial than studying the overall soil OC, because it leads to an improved understanding of soil OC dynamics. Thus, studies are needed on the influence of agricultural land abandonment on aggregate-associated soil OC representing the soil OC pool with different aggregate stabilities, especially in degraded soils with poor soil structure, low OC and N content, and compacted layers in semi-arid regions (Wiesmeier et al., 2012).

Recently, extensive areas of cultivated land have been abandoned in many countries worldwide (Cramer et al., 2008; Prishchepov et al., 2012; Six and Paustian, 2014). This phenomenon also happened in the interior northwestern provinces of China as a result of environmental degradation as well as economic and social changes (Yang and Li, 2000; Jin et al., 2008; Deng et al., 2013; Zhang et al., 2014). To date, studies on soil OC or N and WSA in abandoned agricultural lands focus either on the dynamics of soil OC pools or the changes of WSA (Novara et al., 2014; Gabarrón-Galeote et al., 2015). Limited information is available on the long-term changes of WSA stability and OC in different WSA sizes at different soil depths of abandoned agricultural lands, especially in Northwest China. Thus, the main objectives of this study were to: (1) characterize WSA fractions and stability in different soil layers; (2) determine the contents of OC and N within WSA at various soil depths; and (3) assess the dominant factors affecting soil OC, N and WSA stability after agricultural land abandonment.

The Minqin Oasis in Northwest China was selected as the study area because of the presence of different successional stages of abandoned agricultural lands and the existence of distinct vegetation patterns as a result of arid climate. This study may be useful in identifying the mechanisms responsible for WSA formation and stability in relation to soil OC and N sequestration after cessation of cultivation. The study can also enhance the understanding of the role played by soil spontaneous recovery ability in abandoned agricultural lands in arid regions, which is crucial to environmental quality and regional agricultural sustainability.

1 Materials and methods

1.1 Study area

The Minqin Oasis (38°03'–39°27'N, 101°49'–104°12'E) is located in the Shiyang River basin of Gansu province, Northwest China. It has a land area of 159.107 km^2 and a population of approximately 306,900. The elevation of the region ranges from 1,295 to 1,460 m, with the terrain

generally downward from southwest to northeast. The oasis is surrounded by the Badain Jaran Desert to the west and north and the Tengger Desert to the east. The area is characterized by an arid continental climate with an annual mean temperature of 7.8°C (average maximum of 23.2°C in July and average minimum of –9.6°C in January). The mean annual precipitation is 110 mm with uneven distribution, but the annual potential evaporation exceeds 2,664 mm (Sun et al., 2006) because of the arid climate in the area. The Minqin Oasis is one of the most severely desertified regions in China, and the ecosystems of the oasis are extremely fragile.

In this study, the agricultural lands with abandonment ages of 0 (control, cultivated land), 3, 12, 20, 30 and 40 years with well-known land use history and current management practices were selected in the northeastern part of the Minqin Oasis within a radius of 6 km. We used the historical records and aerial photos of the study area to determine the cultivation and management histories before and after land abandonment. The information and photos showed that all the abandoned and cultivated lands experienced similar tillage and cultivation practices in the cultivated years, and the lands were arable for many decades (Table 1).

All the studied lands have the same topography and soil type (anthropogenic alluvial soil), and the farming and tillage practices before abandonment were commonly conventional tillage with irrigation. Now, the abandoned lands are covered by natural vegetation and devoid of tree species. The selected lands were cultivated with mostly barley and cotton before abandonment and were kept fallow after abandonment.

Table 1   Cultivation time, dominant species and plowing methods in agricultural lands with different abandonment ages

Age of agricultural land abandonment (a)	Cultivation time	Dominant species	Plowing method
0	1989 to present	*Hordeum vulgare*, *Gossypium* spp.	Conventional ploughing in autumn and rotary tillage in spring
3	1983–2009	*Poa annua*, *Suaeda glauca*	Conventional ploughing in autumn and rotary tillage in spring before abandonment
12	1967–2000	*Halogeton glomeratus*, *Achnatherum splendens*	
20	1968–1992	*Kalidium foliatum*, *Salsola passerina*	Conventional ploughing in autumn before abandonment and light grazing by sheep after abandonment
30	1957–1982	*Nitraria sphaerocarpa*, *Reaumuria songarica*	
40	1953–1972	*Nitraria sphaerocarpa*, *Ephedra przewalskii*	

1.2   Soil sampling

In April 2012, a total of 18 sampling plots (6 chronosequence×3 replications) were selected within a distance of 1.0–1.5 km to avoid pseudoreplication. Five soil sampling sub-plots with each area of 10 m×10 m were randomly established at each sampling plot with a minimum separation distance of 100 m. Fifteen soil cores were randomly collected in each sub-plot at depths of 0–20, 20–40 and 40–60 cm by a sample probe. In each sampling plot, 25 sub-samples from the same depth (i.e. 5 soil cores for each depth in each sub-plot×5 sub-plots) were mixed to form one composite sample to reduce the effect of natural micro-variability. A total of 54 composite soil samples (i.e. 18 sampling plots×3 composite soil samples per sampling plot) were used for the analysis. Visible roots, coarse plant debris and stone fragments were removed manually at the time of sampling. In each sub-plot, we collected three additional soil samples to determine bulk density using ring method at depths of 0–20, 20–40 and 40–60 cm. Soil samples were crushed and divided into two portions. One portion was used to analyze aggregate-size distribution, and the other was used to determine the total soil OC and N contents, and other physical-chemical properties.

1.3   Laboratory analyses

1.3.1   Water-stable aggregate (WSA) fraction

WSA were fractionated according to the wet-sieving method (Six et al., 1998; Puget et al., 2000).

Briefly, 100 g soil was successively passed by 4 sieves with decreasing mesh diameter (2, 1, 0.25 and 0.053 mm) and gently suspended in water for 5 min at room temperature. Then, aggregates were separated by moving the sieves up and down (3 cm) 50 times for 2 min. Finally, soil aggregates were separated into five size classes: >2, 1–2, 0.25–1, 0.053–0.25 and <0.053 mm. In this study, we divided the size fractions of WSA into three classes: macroaggregates (>0.25 mm), microaggregates (0.053–0.25 mm; Miwa et al., 2014), and silt+clay particles (<0.053 mm; Manna et al., 2007). After a 2-min cycle, WSA remained on sieves were gently poured into pre-weighed aluminum pan, oven dried at 60°C for 48 h, weighed, and prepared for mean weight diameter (MWD) calculation. The MWD of each soil sample was calculated by Eq. 1 (Yamashita et al., 2006; Spohn and Giani, 2011).

$$\mathrm{MWD} = \sum_{i=1}^{n} X_i W_j. \tag{1}$$

Where, X_i is the mean diameter of each size fraction, and W_j is the proportion of total sample weight in the corresponding size fraction.

1.3.2 Sample analysis

We sieved soils through a 2-mm mesh to analyze pH, electrical conductivity (EC) and soil particle composition, and a 0.25-mm mesh to analyze soil OC and N contents. Soil pH values were determined with a glass electrode using a 1:1 soil:water ratio. Soil EC was measured with an EC meter using a 1:5 soil:water ratio. Soil particle composition was determined by the hydrometer method (Institute of Soil Science, Chinese Academy of Sciences, 1978). Soil OC and N contents of the entire soil profile and in all size fractions of WSA were determined by the $K_2Cr_2O_7$–H_2SO_4 digestion method (Nelson and Sommers, 1996) and Kjeldahl procedure (Bremner, 1996), respectively. Measurement of root biomass is detailed in the study of DuPont et al. (2010). In this study, 6-cm diameter soil cores from each sub-plot were collected at depths of 0–20, 20–40 and 40–60 cm (n=15 per plot). All root samples were hand-sorted in deionized water, and roots were recovered by filtering cleaned samples through a 0.25-mm mesh. Roots were dried at 50°C for 48 h and weighed for determining the root biomass.

1.3.3 Statistical analysis

We conducted Pearson correlation tests to examine the OC and N contents in WSA at different soil depths. We performed stepwise multiple-linear regression analysis to improve the understanding of how WSA fractions, and OC and N contents in different size fractions of WSA affected the MWD, OC and N in total soils. Two-way ANOVA was used to analyze the effects of abandonment age of agricultural lands, soil depth, and their interactions on soil properties, WSA sizes, MWD, and OC and N contents in different size fractions of WSA. All analyses were conducted using SPSS 19.0 software for Windows (SPSS Inc., IL, USA). The results were presented as mean±SD (n=3). SigmaPlot 10.0 software was also used for graphics.

2 Results

2.1 Basic properties of soils

The average soil pH and EC in abandoned agricultural lands at sampling depths were 8.04 and 1.72 ms/cm, respectively, which were slightly higher than those in cultivated land at the 0–40 cm depth and lower than those in cultivated land at the 40–60 cm depth (Table 2). Agricultural land abandonment affected the distributions of silt and clay considerably. That is, agricultural abandonment made an increase of silt percentage from 20.01% in cultivated land to 45.94% in 40-year abandoned agricultural land, and a decrease of clay percentage from 33.56% in cultivated land to 12.37% in 40-year abandoned agricultural land at the 0–20 cm depth (Table 2). Compared to the conditions in cultivated land, the total OC and N contents increased by 33.6% and 9.23% in the 20–40 cm soil layer after 40 years of agricultural land abandonment, respectively; however, the total OC and total N contents in the 0–20 and 40–60 cm depths decreased after agricultural land abandonment. Agricultural abandonment resulted in the soil bulk density decreased in the 0–40 cm

soil layer but increased in the 40–60 cm soil layer.

The age of agricultural land abandonment and soil depth had significant effects on soil EC, bulk density, total OC and N contents, and particle size distribution (Table 2). The interaction of land abandonment age and soil depth had a significant ($P<0.05$) effect on soil physical-chemical properties at depths of 0–60 cm (Table 2).

Table 2 Soil physical-chemical properties at different soil depths in agricultural lands with different abandonment ages

ALA (a)	pH	EC (ms/cm)	BD (g/cm³)	Total OC (g/kg)	Total N (g/kg)	Particle size proportion (%)		
						Sand	Clay	Silt
0–20 cm soil layer								
0	7.87±0.11ᵃ	0.91±0.11ᵃ	1.47±0.33ᵃ	5.94±0.12ᵃ	0.68±0.04ᵃ	46.43±0.47ᵃ	33.56±1.12ᵃ	20.01±1.73ᵃ
3	7.95±0.15ᵃ	1.02±0.21ᵃ	1.46±0.94ᵃᵇ	4.89±0.21ᵇ	0.57±0.03ᵇ	48.90±2.64ᵃᵇ	16.40±0.73ᵇ	34.70±2.03ᵇ
12	7.97±0.23ᵃ	1.97±0.24ᵇ	1.41±0.22ᵇᶜ	4.36±0.14ᶜ	0.51±0.01ᶜ	52.25±3.70ᵇ	14.20±2.20ᵇᶜ	33.54±3.74ᵇᶜ
20	8.13±0.19ᵃ	2.12±0.31ᵇ	1.34±0.42ᶜᵈ	3.98±0.11ᶜᵈ	0.47±0.03ᶜᵈ	57.09±1.14ᶜ	12.74±1.76ᵇᶜ	30.17±1.18ᶜ
30	8.18±0.32ᵃ	2.79±0.76ᶜ	1.33±0.14ᶜᵈ	3.87±0.15ᵈ	0.45±0.01ᶜᵈ	46.19±1.61ᵃ	13.54±1.25ᵇᶜ	40.27±2.82ᵈ
40	8.22±0.13ᵃ	3.12±0.35ᵈ	1.27±0.55ᵈ	3.82±0.15ᵈ	0.44±0.02ᵈ	41.69±3.86ᵈ	12.37±0.91ᶜ	45.94±2.56ᵉ
20–40 cm soil layer								
0	7.81±0.15ᵃ	0.96±0.82ᵃ	1.54±0.25ᵃ	4.05±0.12ᵈ	0.59±0.04ᵃᵇ	33.29±0.85ᵃ	48.32±1.03ᵃ	18.39±2.61ᵃ
3	8.01±0.25ᵃᵇ	1.09±0.38ᵃᵇ	1.50±0.17ᵃᵇ	4.07±0.17ᶜ	0.56±0.02ᵇ	52.56±2.20ᵇ	27.84±2.02ᵇ	19.60±4.10ᵃ
12	8.09±0.08ᵇᶜ	1.18±0.26ᵃᵇ	1.49±0.17ᵃᵇ	4.12±0.18ᶜᵈ	0.54±0.02ᵇ	62.60±1.76ᶜ	12.53±2.74ᶜ	24.87±1.20ᵇ
20	8.17±0.21ᵇᶜ	1.51±0.51ᵃᵇ	1.47±0.35ᵃᵇ	4.30±0.15ᶜᵈ	0.56±0.01ᵃᵇ	42.47±1.64ᵈ	19.38±2.91ᵈ	38.16±1.48ᶜ
30	8.21±0.15ᶜ	1.64±0.12ᵃᵇ	1.46±0.50ᵃᵇ	4.80±0.14ᵇ	0.63±0.01ᵃ	34.27±3.15ᵃ	17.18±1.53ᵈᵉ	48.56±2.42ᵈ
40	8.23±0.12ᶜ	1.74±0.46ᵇ	1.45±0.35ᵇ	6.10±0.25ᵃ	0.65±0.05ᵃ	32.27±1.16ᵃ	14.38±1.83ᶜᵈ	53.36±1.65ᵉ
40–60 cm soil layer								
0	8.04±0.12ᵃ	2.05±0.32ᵃ	1.52±0.12ᵃ	4.98±0.10ᵃ	0.67±0.05ᵃ	37.91±1.22ᵃᵇ	40.79±4.19ᵃ	21.30±5.22ᵃ
3	7.98±0.12ᵃ	1.93±0.38ᵃ	1.53±0.21ᵃ	4.98±0.08ᵃ	0.59±0.03ᵇ	37.58±1.63ᵃᵇ	38.84±2.07ᵃ	23.58±2.81ᵃᵇ
12	7.92±0.11ᵃ	1.74±0.15ᵃᵇ	1.53±0.33ᵃ	4.90±0.09ᵃ	0.57±0.01ᵇ	33.85±3.78ᵇᶜ	38.31±2.77ᵃ	27.84±4.03ᵇᶜ
20	7.90±0.28ᵃ	1.48±0.75ᵇᶜ	1.54±0.42ᵃ	4.71±0.08ᵃᵇ	0.55±0.04ᵇ	31.91±0.54ᶜ	36.82±1.74ᵃ	31.27±1.67ᶜᵈ
30	7.86±0.15ᵃ	1.29±0.74ᶜ	1.56±0.17ᵃ	3.77±0.12ᶜ	0.48±0.06ᶜ	34.89±4.26ᵇᶜ	31.87±3.53ᵇ	33.24±1.75ᵇᶜᵈ
40	7.78±0.15ᵃ	1.15±0.69ᶜ	1.56±0.26ᵃ	4.01±0.11ᵇᶜ	0.49±0.03ᶜ	42.70±2.87ᵃ	20.48±6.28ᶜ	36.82±8.81ᵈ
Least significant difference (LSD)								
ALA (A)	1.70	2.12**	33.45***	7.47**	5.18**	91.65***	47.48***	85.36***
Soil depth (B)	19.62***	3.84*	10.04***	19.76***	51.33***	184.20***	343.26***	24.91***
A×B	4.56*	18.31**	4.66***	32.98***	12.71***	30.65***	13.36***	21.51***

Note: ALA, age of land abandonment; EC, electrical conductivity; BD, bulk density; OC, organic carbon; N, nitrogen. Lowercase letters indicate significance at $P<0.05$ level between different ages of agricultural land abandonment. Mean±SD, $n=3$. *, ** and *** indicate significance at $P<0.05$, $P<0.01$ and $P<0.001$ levels, respectively.

2.2 WSA sizes and stability

In cultivated land, the average MWD of WSA at soil depths of 0–20, 20–40 and 40–60 cm was 0.106±0.01, 0.152±0.03 and 0.150±0.06 mm, respectively. It increased to 0.435±0.09, 0.596±0.02 and 0.487±0.02 mm at soil depths of 0–20, 20–40 and 40–60 cm after 40 years of agricultural abandonment (Fig. 1). Agricultural land abandonment and the interaction of land abandonment age and soil depth had significant effect on MWD at depths of 0–60 cm ($P<0.001$; Table 3).

Soil depth had no impact on the proportion of WSA >2 mm; however, the age of agricultural land abandonment and interactive effect of land abandonment age and soil depth significantly affected the proportions of all WSA fractions ($P<0.001$; Table 3). The increment of MWD of aggregates in abandoned agricultural lands is caused by an increase in the proportion of aggregates with sizes 0.25–2 mm. The proportion of WSA sizes <0.053 mm decreased with increasing abandonment age at soil depths of 0–20, 20–40 and 40–60 cm (Fig. 1). The proportion of WSA sizes >2 mm remained less than 9% in all analyzed samples.
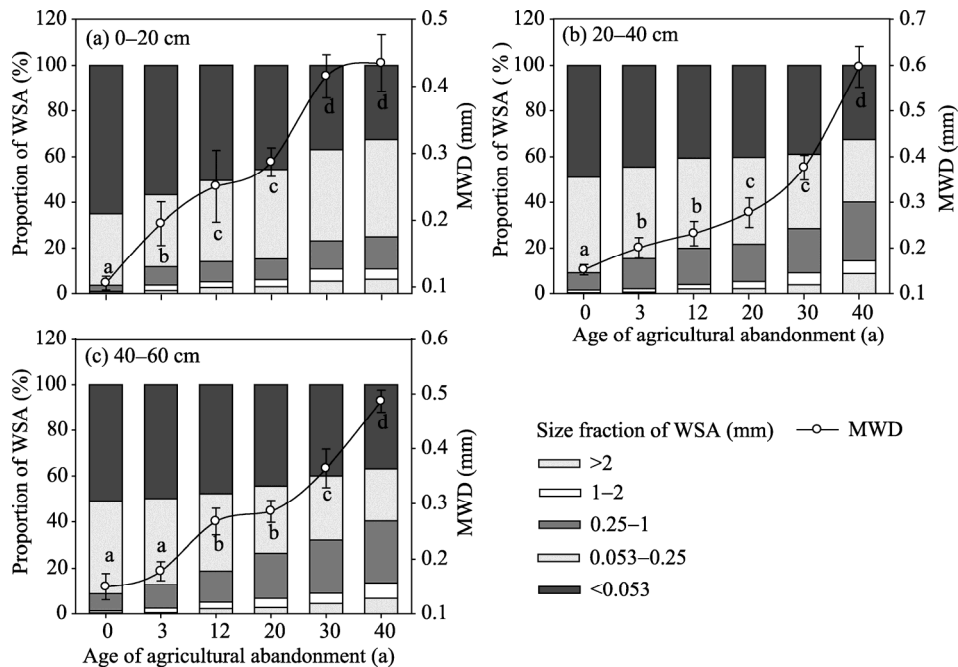
Fig. 1 WSA (water-stable aggregates) proportion and MWD (mean weight diameter) at different soil depths in agricultural lands with different abandonment ages. Values were calculated from three independent samples per sub-plot. Error bars depict standard deviations. Different lowercase letters indicate significance at P<0.05 level between different land abandonment ages.

Table 3 Two-way ANOVA for effects of agricultural abandonment age and soil depth on the proportion of WSA and MWD

Variable	Proportion of WSA					MWD
	Macroaggregates			Microaggregates	Silt+clay particles	
	>2 mm	1–2 mm	0.25–1 mm	(0.053–0.25 mm)	(<0.053 mm)	
Abandonment age (A)	210.99***	203.19***	58.69***	14.23***	18.01***	219.51***
Soil depth (B)	2.36	13.35***	82.69***	27.71***	28.10***	3.18
A×B	7.61***	10.98***	4.34**	9.16***	4.38**	8.72***

Note: WSA, water-stable aggregates; MWD, mean weight diameter. The F-ratio is indicated for abandoned agricultural lands (excluding cultivated land). ** and *** indicate significance at P<0.01 and P<0.001 levels, respectively. A×B: interactive effect of land abandonment age and soil depth.

2.3 Soil OC and N contents in WSA

Generally, the soil OC and N contents increased with decreasing sizes of WSA, and a majority of soil OC and N were concentrated in WSA sizes <0.053 mm across all depths over long-term agricultural land abandonment (Fig. 2). Soil OC content in WSA sizes <0.053 mm across the three depths ranged from 2.03 to 3.26 g/kg, accounting for 51.41% to 55.59% of the total soil OC content. Soil N content in WSA sizes <0.053 mm ranged from 0.21 to 0.33 g/kg, occupying 42.61% to 48.94% of the total soil N content.

At the depth of 0–60 cm, soil OC and N contents in WSA sizes >2 mm increased with increasing age of agricultural abandonment. A significant positive linear relationship (P<0.01) was observed between soil OC content in WSA sizes >2 mm and age of agricultural land abandonment. However, a significant negative relationship (P<0.01) was observed between soil OC content in WSA sizes <0.053 mm and land abandonment age. Agricultural abandonment increased soil OC and N contents in WSA sizes 0.25–2 mm at the 20–60 cm soil depth but decreased their contents at the depth of 0–20 cm (Fig. 2). The changes of soil OC and N contents in agricultural lands with different land abandonment ages were approximated with a linear function. Age of agricultural land abandonment, soil depth, and interactive effect of agricultural abandonment age and soil depth significantly affected the distributions of soil OC and N contents almost in all size fractions of WSA (Table 4).
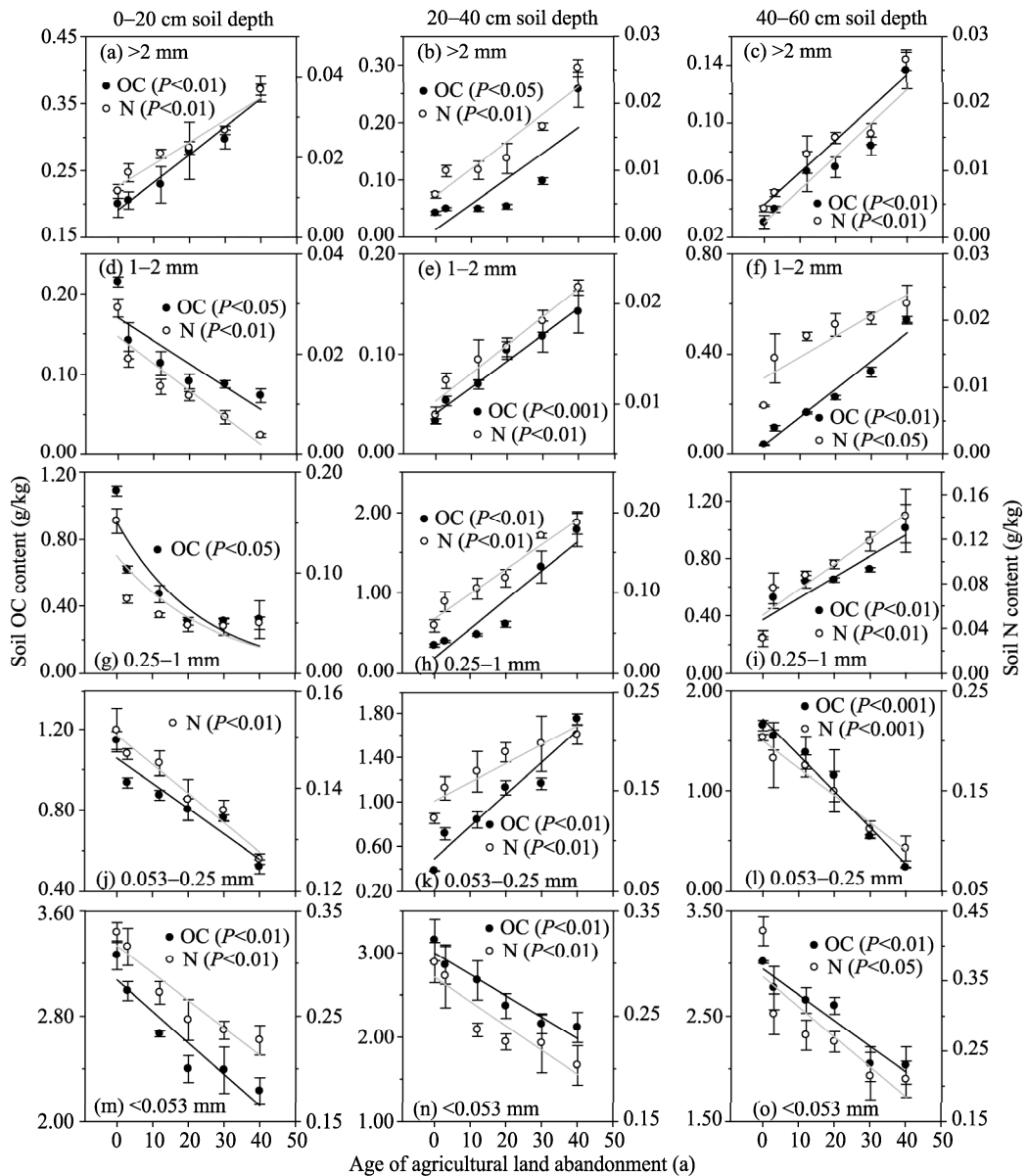
Fig. 2 Soil organic carbon (OC; the left vertical axis in each graph) and nitrogen (N; the right vertical axis in each graph) contents in different sizes of WSA at different soil depths in agricultural lands with different abandonment ages. Values were calculated from three independent samples per sampling plot. Error bars depict standard deviations. The black line indicates the relationship between soil OC content in WSA and age of agricultural land abandonment, and the gray line indicates the relationship between soil N content in WSA and age of agricultural land abandonment.

2.4   Relationship of MWD with soil OC and N contents

As shown in Table 5, at depths of 0–20 and 20–40 cm, total soil OC and N contents were significantly correlated with soil OC and N contents in WSA sizes 0.053–0.25 mm, respectively. At the depth of 40–60 cm, total soil OC content was significantly correlated with soil OC content in WSA sizes <0.053 mm, and total soil N content was significantly correlated with N content in WSA sizes 0.053–0.25 mm. At depths of 0–20 and 20–40 cm, MWD was positively correlated with soil OC and N contents in WSA sizes >2 mm ($P<0.001$). At the depth of 40–60 cm, MWD was negatively correlated with soil OC content in WSA sizes <0.053 mm ($P<0.001$) and positively correlated with soil N content in WSA sizes >2 mm ($P<0.001$).

Table 4   Two-way ANOVA for effects of land abandonment age and soil depth on soil OC and N contents in different sizes of WSA

Variable	Soil OC content in different sizes of WSA				
	>2 mm	1–2 mm	0.25–1 mm	0.053–0.25 mm	<0.053 mm
Age of agricultural abandonment (A)	76.12[***]	8.86[***]	52.99[***]	9.83[***]	10.48[***]
Soil depth (B)	461.81[***]	29.99[***]	54.01[***]	30.23[***]	0.81
A×B	5.79[***]	10.95[***]	72.01[***]	103.09[***]	0.49

Variable	Soil N content in different sizes of WSA				
	>2 mm	1–2 mm	0.25–1 mm	0.053–0.25 mm	<0.053 mm
Age of agricultural abandonment (A)	286.23[***]	0.441	35.41[***]	2.03	4.62[**]
Soil depth (B)	264.24[***]	16.93[***]	120.65[***]	15.40[***]	2.04
A×B	4.35[**]	93.49[***]	68.43[***]	13.14[***]	0.33

Note: The *F*-ratio is indicated for abandoned agricultural lands (excluding cultivated land). [**] and [***] indicate significance at $P<0.01$ and $P<0.001$ levels, respectively. $n=15$. A×B: interactive effect of land abandonment age and soil depth.

Table 5   Stepwise regression analyses between soil OC content in WSA sizes and total soil OC content, soil N content in WSA sizes and total soil N content, MWD and WSA, MWD and soil OC and N contents in WSA sizes at different soil depths in abandoned agricultural lands (excluding cultivated land)

Dependent variable	Regression equation	R^2
0–20 cm soil layer		
Total OC content	Total OC content=2.88+2.58($OC_{0.053–0.25\ mm}$)	0.862[***]
Total N content	Total N content=0.403+10.65($N_{0.053–0.25\ mm}$)	0.671[***]
	MWD=0.129+0.051($WSA_{>2\ mm}$)	0.975[***]
MWD	MWD=1.25($OC_{>2\ mm}$)–0.03	0.634[***]
	MWD=13.187($N_{>2\ mm}$)–0.062	0.875[***]
20–40 cm soil layer		
Total OC content	Total OC content=3.77+9.17($OC_{0.053–0.25\ mm}$)	0.924[***]
Total N content	Total N content=0.446+0.934($N_{0.053–0.25\ mm}$)	0.658[***]
	MWD=0.049($WSA_{>2\ mm}$)+0.165	0.967[***]
MWD	MWD=0.38($OC_{>2\ mm}$)–0.09	0.927[***]
	MWD=24.48($N_{>2\ mm}$)–0.01	0.889[***]
40–60 cm soil layer		
Total OC content	Total OC content=0.90+3.59($OC_{<0.053\ mm}$)	0.781[***]
Total N content	Total N content=0.7131.43($N_{0.053–0.25\ mm}$)	0.807[***]
	MWD=0.028+0.057($WSA_{1–2\ mm}$)	0.853[***]
MWD	MWD=0.505–0.20($OC_{<0.053\ mm}$)	0.878[***]
	MWD=0.087+15.07($N_{>2\ mm}$)	0.920[***]

Note: $OC_{>2\ mm}$, $OC_{0.053–0.25\ mm}$ and $OC_{<0.053\ mm}$ refer to soil organic carbon in WSA sizes >2, 0.053–0.25 and <0.053 mm, respectively. $N_{>2\ mm}$ and $N_{0.053–0.25\ mm}$ refer to soil nitrogen content in WSA sizes >2 and 0.053–0.25 mm, respectively. $WSA_{>2\ mm}$ and $WSA_{1–2\ mm}$ refer to the proportions of WSA with size fractions of >2 and 1–2 mm, respectively. [***] means significance at $P<0.001$ level.

2.5   Relationship of soil properties with soil OC and N contents

Soil OC and N contents in WSA sizes <0.053 mm were linearly positively correlated with silt+clay content ($P<0.001$; Fig. 3); however, soil OC and N contents in WSA sizes >2 mm were negatively correlated with silt+clay content. Soil EC was significantly negatively correlated with soil OC and N contents in WSA sizes 0.053–2 mm ($P<0.01$), and the relationship was linear. Soil bulk density had significant negative correlation with soil OC and N contents in WSA sizes >2

mm ($P<0.001$), and positive correlation with soil OC and N contents in WSA sizes <0.053 mm ($P<0.01$ for OC and $P<0.05$ for N). The root biomass was positively exponentially correlated with soil OC and N contents in WSA sizes 0.25–2 mm ($P<0.001$), and negatively correlated with soil OC and N contents in WSA sizes <0.053 mm with a linear function ($P<0.01$ for OC and $P<0.05$ for N).
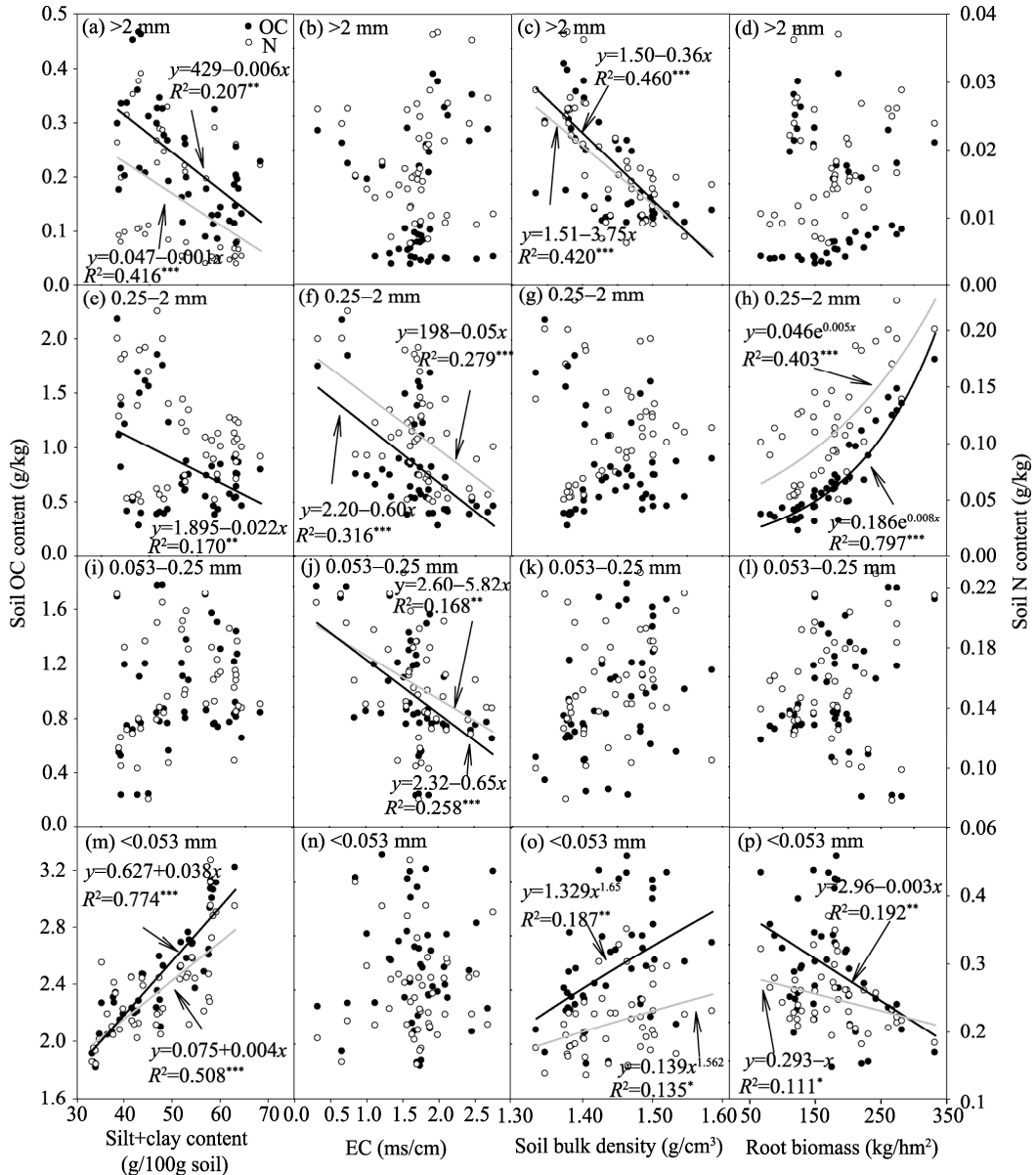

Fig. 3 Correlations of soil properties with soil OC and N contents in different size fractions of WSA in abandoned agricultural lands (excluding cultivated land). EC, electric conductivity. *, ** and *** indicate significance at $P<0.05$, $P<0.01$ and $P<0.001$ levels, respectively. The black line indicates the correlation of soil OC content and soil properties, and the gray line indicates the correlation of soil N content and soil properties.

2.6   Relationship of soil properties with MWD and C:N ratio of total soil

The MWD was significantly negatively correlated with soil silt+clay content, EC and bulk density, and exponentially positively correlated with root biomass ($P<0.001$; Fig. 4). The C:N ratio of total soil declined with increasing soil EC values. Moreover, there was no significant correlations of C:N ratio of total soil with silt+clay content, bulk density and root biomass.
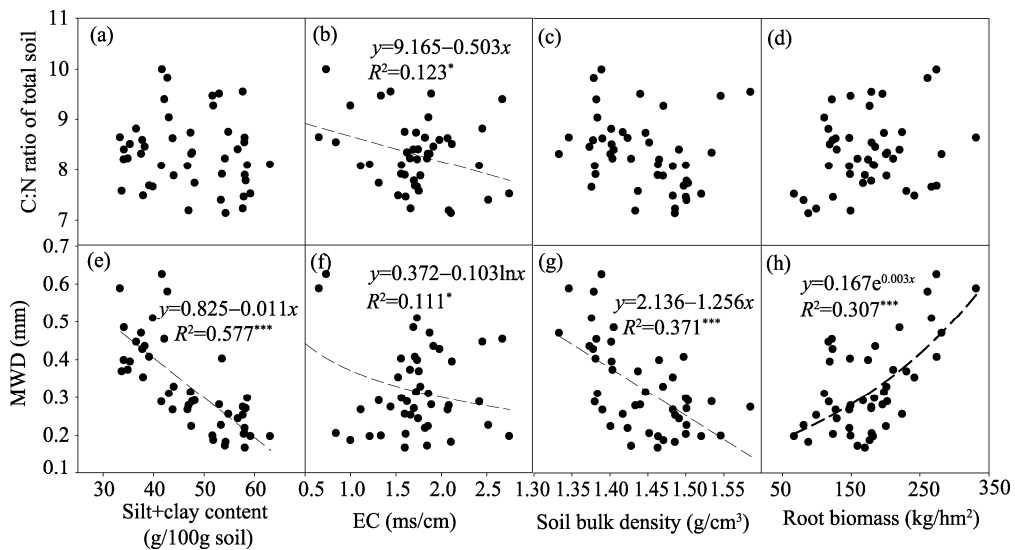
Fig. 4   Correlations of soil properties with MWD and C:N ratio of total soil in abandoned agricultural lands (excluding cultivated land). * and *** indicate significance at *P*<0.05 and *P*<0.001 levels, respectively.

3   Discussion

3.1   WSA sizes and stability

The results of this study showed that MWD increased with increasing age of agricultural land abandonment because of a significant restoration of the proportion of WSA sizes >0.25 mm and a decrease of the proportion of WSA sizes <0.053 mm. The increment of soil WSA stability was caused by the bonding of microaggregates and silt+clay particles, which resulted in an increase in the proportion of macroaggregates in abandoned agricultural lands. This study further demonstrated that WSA stability increased with increasing organic matter content enriched in macroaggregates (*P*<0.001; Table 5).

Large soil aggregates have high stability and persistence because they are strongly cemented by organic matter (Six et al., 2000b), which means that ploughing (compared with agricultural abandonment) has a stronger impact on the stability of WSA with larger sizes (Chrenková et al., 2014). This finding demonstrated that the proportion of soil aggregates with sizes >2 mm appeared to be a suitable indicator for evaluating the effect of land use change on soil aggregation (Huang et al., 2010). Cultivation can physically disrupt the formation of WSA with larger sizes and therefore soils become more susceptible to degradation and erosion (Ayoubi et al., 2012), especially in semi-arid areas. Soils with larger MWD are more likely to have greater resistance to soil degradation and erosion (Celik, 2005). Accordingly, the abandonment of cultivation has the potential to prevent the soils from wind erosion.

In this study, the MWD exhibited a linear negative correlation with silt+clay content and bulk density (*P*<0.001), a logarithmic negative correlation with EC (*P*<0.05), and an exponential positive correlation with root biomass (*P*<0.001). Therefore, we concluded that the silt+clay content, EC and bulk density have a limited intrinsic capacity for soil aggregation, while the root biomass contributes to soil aggregation in abandoned agricultural lands (Fig. 4).

3.2   Soil OC and N contents in abandoned agricultural lands

As in the cases of many studies in the other regions (e.g. Knops and Tilman, 2000), we had no data on vertical distributions of soil OC and N contents within particle size fraction before agricultural land abandonment. In addition, the temporal patterns of soil OC and N dynamics after agricultural abandonment in the study area was not well-documented. Thus, we compared the abandoned agricultural lands to the adjacent long-term agricultural lands, and assumed that the abandoned

agricultural lands had the similar conditions on the basis of planting and farming practices before abandonment with the cultivated lands.

The variation of soil organic matter in abandoned agricultural lands of semi-arid area was debated over the years because of differences in soil background, aboveground and belowground biomass, as well as management practices. Novara et al. (2014) reported that the organic matter content increased by 13% after 15 years of vineyard abandonment in a semi-arid environment. A similar increase of OC stocks in soils after cropland abandonment was reported recently for large areas of abandoned lands (Kurganova et al., 2014; Shang et al., 2014). However, these results should be interpreted with caution. According to our data, abandoned agricultural lands contained a lesser amount of OC and N contents than the cultivated land at depths of 0–20 and 40–60 cm (Table 2). Presumably, the lack of rainfall in the study area causes low vegetation productivity and reduces the return of root biomass, resulting in low replacement rate of organic matter pool. This finding is inconsistent with the results of a study in the same climatic region (Li et al., 2006), yet the reasons for the difference are still not understood. The increase of total OC and N contents at the depth of 20–40 cm with increasing land abandonment age indicated that soil organic matter content exhibited vertical difference in abandoned lands. This information is essential to predict total soil OC and N contents, as well as the vegetation regeneration potential.

In abandoned agricultural lands, soil OC and N contents in silt+clay particles decreased linearly with increasing land abandonment age ($P<0.01$). The silt+clay content was significantly correlated with organic matter ($P<0.001$). This may be due to the greater contents of silt+clay particles and the stronger bond between microaggregates and silt+clay particles (Huang et al., 2010). In addition, the silt+clay particles can protect soil OC and N from microorganises decomposition (Li et al., 2006; Grüeneberg et al., 2013). An important consideration in this study was that the silt+clay particles are susceptible to soil erosion by wind, resulting in the loss of soil organic matter. In our study, agricultural land abandonment resulted in soil OC and N shifting from silt+clay particles to macroaggregates. The larger size particles were found to be more stable than the smaller ones in deeper soil layers because the cementing agent involved in macroaggregates was dominantly inorganic in nature (Barral et al., 1998). The C:N ratio at the 0–20 cm depth decreased with increasing age of agricultural abandonment, which indicated that abandoned agricultural lands own the recalcitrant organic matter pools than agricultural land in the study area (Knops and Tilman, 2000).

According to our findings, soil OC and N contents in microaggregates and silt+clay particles were the dominant factors influencing the variations of total OC and N contents in abandoned agricultural lands (Table 5). Our results confirmed that microaggregates rather than macroaggregates protect the soil organic matter in the long-term (Six and Paustian, 2014). Soil EC was negatively correlated with soil OC and N contents in microaggregates ($P<0.01$), implying that OC and N in microaggregates were more sensitive to the influence of salinization.

3.3   Relationship of WSA stability with soil OC and N contents

Stepwise regression analysis revealed that the differences of aggregate stability caused by agricultural land abandonment mainly resulted from the differences in the contents of OC and N in macroaggregates with sizes >2 mm (Table 5). Root biomass was significantly positively correlated with soil OC and N contents in macroaggregates with sizes 0.25–2 mm ($P<0.001$; Fig. 3). Therefore, roots seemed highly important for the formation of macroaggregates (Fig. 4). This finding is in accordance with the hierarchical model by Tisdall and Oades (1982) and the recent research by Linsler et al. (2013).

In this study, the soil OC and N contents increased with increasing size of WSA, which indicated the important effect of agricultural abandonment on organic matter dynamics and aggregate stability (Six et al., 2000a; Zhu et al., 2010). These results are in agreement with the concept of aggregate hierarchy that microaggregates are bound together into macroaggregates by transient binding agents (Six et al., 2000b; Ayoubi et al., 2012). Thus, OC and N likely play a major role in improving soil WSA stability. Furthermore, the amount of macroaggregates and subsequent aggregate stability were greater in abandoned agricultural lands than in cultivated lands.

This fact demonstrated that the recovery of macroaggregates may protect the organic matter against microbial mineralization and losses, and facilitate the OC and N accumulation in soils. In turn, the physically protected soil organic matter may foster the formation of WSA to improve the soil structure (Ahn et al., 2009; Raiesi, 2012). In general, the different distributions of soil OC and N contents across different sizes of WSA as a result of agricultural land abandonment reflected the differences in formation mechanisms and water stability of aggregates in arid region of the Minqin Oasis.

4   Conclusions

Our findings demonstrated that abandoned agricultural lands tend to change the soil particle composition, resulting in higher WSA stability. Total soil OC and N contents presented the phenomenon of stratification across soil depths. Agricultural land abandonment contributed to the accumulation of soil OC and N in macroaggregates with sizes >0.25 mm. Soil OC and N contents in macroaggregates with sizes >2 mm were the key factors that affected the MWD in abandoned agricultural lands. Moreover, the majority of soil OC and N still contained in microaggregates (0.053–0.25 mm) and silt+clay particles (<0.053 mm), which are the dominating factors influencing the variations of total OC and N contents in abandoned agricultural lands. The mentioned OC and N in WSA sizes <0.25 mm were relatively more sensitive to the influences of salinization dynamics, silt+clay content, bulk density and root biomass after agricultural abandonment. The potential for soil OC and N sequestration in silt+clay particles suggested that smaller particle sizes play a key role in the formation and stabilization of organic matter in abandoned agricultural lands in arid ecosystems.

Acknowledgements

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