RESEARCH

Integrative effects of no-tillage and straw returning on soil organic carbon and water stable aggregation under rice-rape rotation

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ABSTRACT

No-tillage and straw returning are important practices for preserving and improving soil quality for the sustainable management system. The experimental field was established in 2007 with conventional tillage (CT), conventional tillage with straw returning (CTS), no-tillage (NT), and no-tillage with straw returning (NTS) practice in rice (*Oryza sativa* L.)-rape (*Brassica napus* L.) cropping system. The soil samples were collected in 2013-2015 from 0-20 and 20-40 cm depth to investigate the effects on soil organic C (SOC), water-stable aggregation (> 5, 5-2, 2-1, 1.0-0.5, 0.25-0.5, and < 0.25 mm), and their stability in paddy soil of the central China. In the last year (2015), the integrative use of no-tillage and straw returning significantly increased SOC content and contribution of the macroaggregates in 0-20 cm and microaggregates in 20-40 cm depth. Compared with CT, SOC content, mean weight diameter (MWD), geometric mean diameter (GMD), and fractal dimensions (FD) under NTS were increased 25%, 21%, 19%, and 12%, respectively, in the 0-20 cm depth. In 20-40 cm depth, the soil micro-aggregates were higher under CTS treatment. Percentages of macroaggregates and microaggregates under NTS were increased 60% and 40% in the 0-20 cm depth. The SOC had positive linear relationship with MWD, GMD, > 5, 2-5, 1-2, and 0.25-0.5 mm aggregates. Thus, long-term combine use of NT with straw returning practices significantly improved SOC and water-stable aggregation. No-tillage and straw returning appeared to be promising and sustainable strategies to conserve SOC sequestration and stable soil aggregates in rice-rape cropping system.

Key words: *Brassica napus*, conventional tillage, no-tillage, *Oryza sativa*, soil organic carbon, soil water-stable aggregation, straw returning.

INTRODUCTION

The soil organic C (SOC) plays an imperative role in regulating soil ecological and C cycling processes in the global scale (Chen et al., 2014). The soil management practices are considered essential to conserve soil quality (Kahlon et al., 2013), and can greatly affect the composition and stability of SOC through plough layer (Stone and Schlegel, 2010; Bhattacharyya et al., 2012; Ghosh et al., 2016). Conventional tillage (CT) could reduce the SOC content and accelerate SOC oxidation rate, probably due to the disturbance of soil aggregates and the increase of the soil aeration (Gathala et al., 2015). A global database of 67 long-term research trials reported that a change from conventional tillage (CT) to no-tillage (NT) can sequester about 57 ± 14 g C m^{-2} yr^{-1}, with the SOC sequestration rate expected to reach the peak within 5-10 yr after conversion from CT to NT practices (West and Post, 2002). Moreover, Six et al. (2002) reported a general trend to increase the SOC content about 325 ± 113 kg C ha^{-1} yr^{-1} under NT as compared with CT plots.

The continuous long term no-tillage systems in the surface layers may provide an incomplete view of changes occur in soil profile (Blanco-Canqui et al., 2011). Angers and Eriksen-Hamel (2008) found that no-tillage soils had significantly higher SOC than conventional soils at the 0-20 cm layers, but found inverse trend at 21-35 cm depth. Moreover, Poirier et al. (2009) reported that effects of tillage systems seems to be site specific for related SOC and soil properties. However, the magnitude of NT effects on SOC contents may vary and the variation is affected by regional and environmental factors (Poirier et al., 2009; Martinez et al., 2011), which can permit the further view of NT impressions on soil properties.

The aggregate stability indices can reflect the changing of soil aggregate size distribution and describe soil aggregate distribution status in many studies (Gwenzi et al., 2009; Paul et al., 2013; Zhang et al., 2014). Aggregates comprise both macroaggregates (> 0.25 mm) and microaggregates (< 0.25 mm) in the hierarchical model of aggregate organization as described by Tisdall and Oades (1982). Some studies reported that organic input in soil increased the content of those > 0.25 mm soil aggregates (Zhou et al., 2007), can increase the content of 0.25-5.00 mm water-stable aggregates in soil (Yang et al., 2012). Sandoval-Estrada et al. (2008) reported that standing residues and chopped residues had better structural stability and a higher proportion of macroaggregates (> 0.25 mm), as well as a significant increase in SOC. Soil aggregation be responsible for physical protection of SOC against rapid decomposition (Blanco-Canqui and Lal, 2004), and soil aggregate formation and stability of soil aggregates is closely linked with SOC storage (Gwenzi et al., 2009).

Central China, one of the major rice and rapeseed producing regions, mainly adopts the rice-rape crop rotation farming system in this region. In this region, long-term data on the SOC contents and soil aggregates stability is scare, only few short term studies has been reported about the SOC and soil aggregation. However, there is lack of knowledge regarding long-term use of NT on soil aggregation and SOC contents under rice-rape cropping system in central China. Therefore, it is necessary to understand the soil aggregates response to different tillage/straw returning management practice in rice-rape cropping system. The interaction among soil aggregate size distribution, SOC contents and aggregate stability indices is still not well understood (Blanco-Canqui and Lal, 2004). Meanwhile, little information is available about whether soil aggregate stability is positively or negatively correlated with soil C (Six et al., 2002; Bhattacharyya et al., 2012). Based on recent literature, it is perceived that less studies have investigated the interactive effects of tillage and straw returning in rice-rape rotation system regarding SOC and water stable aggregation. It was hypothesized that whether NT or CT alone is more effective management in soil aggregation, either NT or CT together with straw returning or crop rotation system could be the sustainable management practices for SOC and stable soil aggregation. Thus, the objectives of current study were (1) to examine the interactive effects of no-tillage and straw returning on SOC and water-stable aggregation under a rice-rape rotation in 0-20 and 20-40 cm depths, and (2) to evaluate the relationship among the SOC and different aggregates (> 5, 5-2, 2-1, 1.0-0.5, 0.25-0.5, and < 0.25 mm) after no-tillage and straw returning practices in rice-rape rotation in central China.

MATERIALS AND METHODS

Site description and experimental design

The long-term field experiment was started in 2007 and conducted at Wuxue (29°59'21" N, 115°36'53" E; 20 m a.s.l.), Hubei province in central China, with continuous rice and rapeseed cropping each year. The experimental area was characterized as a humid monsoon subtropical climate zone. The annual average temperature was 16.9 °C, the highest temperature was in July with an average of 29.1 °C and the minimum was in January with an average of 4.1 °C (Figure 1). The annual average rainfall was about 1489 mm, the annual mean evaporation was 1361 mm and domestic frost-free period was about 262 d. The field experiment was arranged randomly with three replicates, each plot size was 15 m^2 (5 m × 3 m). Physico-chemical properties of tested soil is presented in Table 1. The experimental field was cultivated with rice-rape cropping system. There were four treatments as follows: (1) Conventional tillage (CT), (2) conventional tillage with straw returning (CTS), (3) no-tillage (NT), and (4) no-tillage with straw returning (NTS). There were two main seasons in experimental fields, in which rice was cultivated from June and harvested in October, rape was cultivated from November and harvested in May each year. In the CT and NT plots, rice-rape crops residues were removed and not returned in the field. In NT plots, no soil disturbance occurred except for herbicide, sowing and fertilizer application. In case of CT treatment, the plots were moldboard ploughed twice to 20 cm depth using a tractor (Shanghai New Holland Agriculture

Figure 1. Average rainfall and temperature of experimental site during 2013-2015.

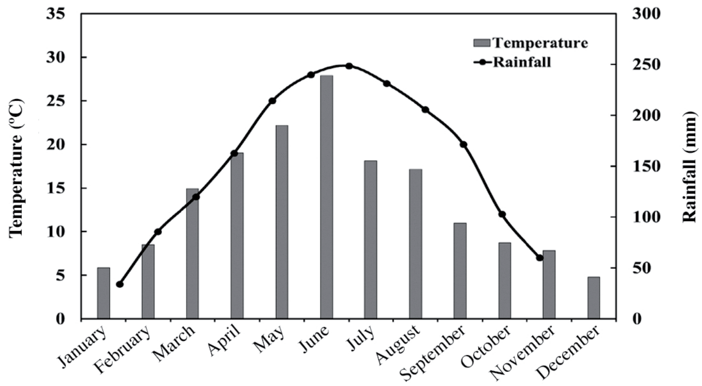


Table 1. Physico-chemical properties of tested soil.

Soil character	Mean value ± SE
Soil texture	Loam
Clay, %	17.3 ± 0.52
Silt, %	42.7 ± 0.42
Sand, %	39.9 ± 0.62
Soil pH	5.2 ± 0.02
Soil organic matter, g kg^{-1}	34.1 ± 0.20
Total N, g kg^{-1}	1.9 ± 0.01
Total P, g kg^{-1}	0.5 ± 0.03
Available P, mg kg^{-1}	6.6 ± 0.10
Total K, g kg^{-1}	21.7 ± 0.30
Available K, mg kg^{-1}	86.1 ± 0.90
SOC/TN	10.1 ± 0.25

The values are mean ± standard error.
SOC: Soil organic C; TN: total N.

Machinery, Shanghai, China) 2-3 d before rice or rape sowing. However, in case of CTS and NTS, rice-rape crops residues were taken out from preceding crops were chopped 5-8 cm length and retained back into fields. In CTS plots, chopped rice-rape residues were incorporated in field through ploughing to 20 cm depth. For NTS, chopped residues were retained or left on the soil surface; following this, the rice was transplanted or the rape was sowed with a no-tillage planter. In the straw returning plots, 4200 kg ha^{-1} straw for both rice and rape was returned back into the soil. After the rice was harvested, air-dried residues of rice were returned to the soil 3 wk before rape was seeded and rape residues were returned to soil 3 wk before rice was planted. Straw was equally incorporated in the field to reduce variation between treatments.

Chemical inorganic fertilizers were applied during rice-rape growing seasons. Fertilization was broadcasted before sowing or planting, with rape receiving basal doses of N, P, and K at 210 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, and 150 kg K_2O ha^{-1}, respectively, and rice receiving at 150 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1} and 135 K_2O_5 ha^{-1}, respectively. During rice crop growing seasons, N fertilizer was applied as urea fertilizer (containing N 46%) in three splits: 50% N (as 46% urea) was used as basal N, 30% at the tillering stage and 20% at the earing stage. In rape seasons, 60% was applied a basal dose, 20% was applied in wintering stage, and 20% applied at initiation of stem elongation stage. All P fertilizer (as single superphosphate, 12% P_2O_5) and K (as potassium chloride, 60% K_2O) was applied as a base dose in each cropping season after throwing rice seedlings or sowing rape.

Rice (Wu you308) and rape (Hua youza62) varieties were cultivated in this study; they were selected on the base of their local importance and extensive adaptability in Hubei province of central China. The nursery of rice crop was raised on a fertile seedbed and was transplanted to the field after 30 days of seedling emergence for each growing season. Rape was directly seeded at 4.5 kg ha^{-1} in November of each year and harvested manually in June. All other agronomic management practices such as, irrigation, weed control, disease control and herbicide application were performed using conventional practices of Hubei province. In rice growing seasons, weeds were controlled by local practices of herbicide as spraying 36% glyphosate at 3 L ha^{-1}, manual weeding was also done in rape crops to keep the plots weeds free.

Soil sampling and analytical methods

The soil samples were collected on May of each year after the rape harvest from each plot in the experimental field at depths of 0-20 and 20-40 cm. A total of 24 samples (four treatments × two depths × three replicates) were collected in 2013-2015 each year. Later, the soil samples were delivered to a laboratory, after carefully removing fine roots, residues and unwanted surface organic material. The portion of the soil samples were passed again through a 0.15 mm sieve to determine the SOC concentration. To determine the aggregate size distribution, undisturbed soil cores were collected from the 0-20 and 20-40 cm depths, with separate samples taken repeatedly from each depth. The texture of the soil was determined by the pipette method; soil pH was measured at a soil:water extract ratio (1:2.5); SOC concentration was measured by the potassium dichromate ($K_2Cr_2O_7$) wet oxidation method; total N was measured using the Kjeldhal digestion method. Total P was measured after perchloric and sulfuric acid digestion method. Available P was measured in extraction solution 0.5 M $NaHCO_3$, adjusted at pH 8.5 as suggested by Olsen and Sommers (1982). Total and available K was measured following Kundsen et al. (1982).

The proportions of water-stable aggregates were determined by placing 50 g air-dried soil samples on the top of different size sieves (> 5, 5-2, 2-1, 1.0-0.5, 0.25-0.5, and < 0.25 mm). The soil samples on a set of sieves were immersed in water, and agitated up and down within 10 cm at a rate of 35 cycles per minute for 10 min (Kemper and Rosenau, 1986). These samples were transferred to a container, oven-dried at 60 °C, and then weighed. Mean weight diameter (MWD) and geometric mean diameter (GMD), two indicators of aggregate stability, were calculated on the basis of aggregate size distribution of the soil samples (Kemper and Rosenau, 1986) by using the following equations:

$$\mathrm{MWD} = \sum_{i=1}^{n} \mathrm{XW_i} \qquad [1]$$

where X denotes the mean of the diameter of the aggregates remaining on the sieve, and W_i denotes the ratio of the persistent aggregate weight on the sieve to the total sample weight, and n denotes the total number of sieves used for separation.

$$\mathrm{GMD} = \exp\left(\frac{\sum_{i=1}^{n} \mathrm{Wi\log Xi}}{\sum_{i=1}^{n} \mathrm{Wi}}\right) \qquad [2]$$

In the above equation, W_i indicates the total dry weight of the aggregates, n indicates the number of sieves, and X_i indicates the mean diameter of aggregates over each size of sieve.

Fractal dimension (FD) was developed to determine stability of the soil aggregates with mass distribution of particles instead of size distribution of particles due fractal features of the soil (Tyler and Wheatcraft, 1989). The lesser the fractal dimension value, the greater the soil stability to resist mechanical or water dispersion. The fractal formula was defined as follows:

$$\frac{W(r < \bar{d}_\mathrm{i})M(X)}{\mathrm{W_T}} = \left[\frac{\bar{d}_\mathrm{i}}{d_{max}}\right]^{3-D} \qquad [3]$$

where, r is the soil particle size, d_i is the particle size of grade i in the particle size grading, d_{max} is the average diameter of the soil particles; $W(r < di)$ is the weight of the soil particles with a diameter less than d_i, W_T is the weight of all soil particles and D is the fractal dimension value. We took the logarithmic transformation on both sides of equation, and fractal dimensions D value of all soil samples was obtained on the base of the slopes of the logarithmic curves that fit the data.

Statistical analysis

The statistical analysis was carried out by the SPSS (Statistical Package for the Social Sciences; IBM, Armonk, New York, USA) package. The difference in SOC, water stable aggregate size distribution, MWD, GMD, and FD as affected by tillage practices, straw returning, year and their interaction were assessed by using a two-way ANOVA. Treatments were compared on the basis of significant difference with least significance difference (LSD, $P < 0.05$). The associations among SOC, MWD, GMD, FD, and water stable aggregates were observed through Pearson correlation analysis.

RESULTS AND DISCUSSION

Soil organic C

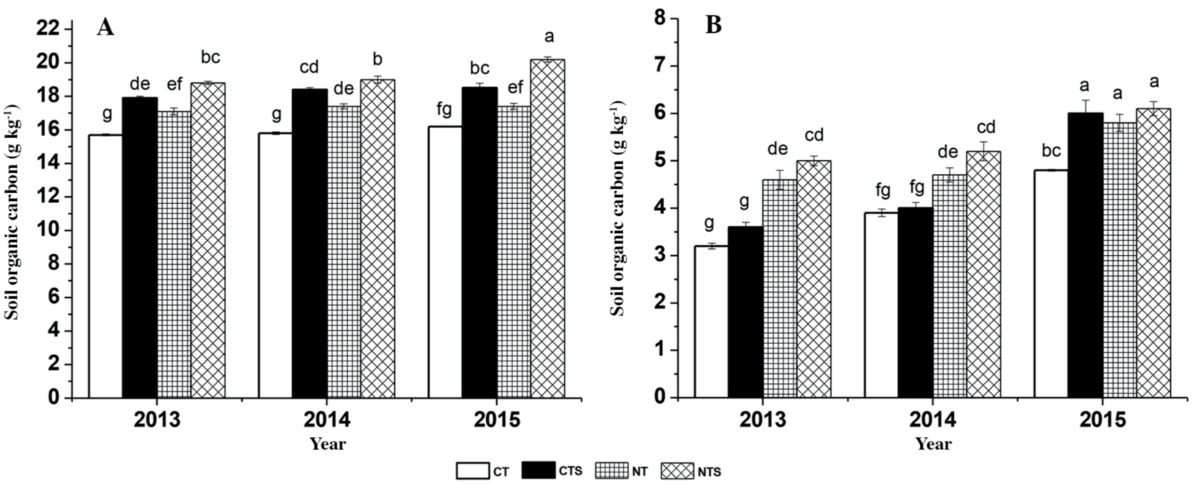
Tillage and straw returning treatments had a significantly higher SOC content than the other treatments in both soil depths (Figure 2). The greater SOC content in the 0-20 cm was observed under straw retuning plots NTS and CTS treatments throughout 3 yr (2013-2015). In year wise comparison, NTS treatment had comparatively higher results as compared to CT, which increased from 15.7 to 18.8 g kg^{-1} (2013), 15.8 to 19.0 g kg^{-1} (2014), and 16.2 to 20.2 g kg^{-1} (2015) in 0-20 cm depth (Figure 2). Similar higher changes were also found in NT or NTS treatment in other studies (Angers and Eriksen-Hamel, 2008; Zhang et al., 2014). However, a variable trend was observed between the treatments in 20-40 cm depth, which were changed from 3.2 to 5.0 g kg^{-1} (2013), 3.9 to 5.2 g kg^{-1} (2014), and 4.8 to 6.1 g kg^{-1} (Figure 2). The significant interactive effect of the straw returning and tillage treatments on the SOC content was obtained at the 0-20 cm for the whole soil profile (0-40 cm), during the 3 yr the trend was NTS > CTS > CT > NT. The average SOC content indicates that NTS significantly increased the SOC content the 0-20 cm depth in relative to the other three treatments. Similarly, Rajan et al. (2012) and Xin et al. (2015) reported that main differences occur between NT and CT in the upper top layer of the soil.

The present study divulged that NTS and CTS treatments significantly increase the SOC content of the 0-20 cm depth in comparison with CT treatment. Similar to this study, Six et al. (2002) discussed that the response of SOC under NT treatment was increase after 6-8 yr of the study at 0-30 cm. Another researcher (Singh et al., 2016) discussed that crop establishment techniques and residue management significantly increased SOC after 5 yr at 0-15 and 15-30 cm depths. Higher SOC content under straw returning plots NTS and CTS treatment in the surface layer may be associated higher inputs of straw residue, which resulting the high retention of SOC content in surface soil (Angers and Eriksen-Hamel, 2008; Gathala et al., 2015). The higher SOC content may also be because of the interactive effect of tillage and straw returning, due to higher conversion efficiency of straw residue C into SOC (Rajan et al., 2012; Al-Kaisi et al., 2014; Gathala et al., 2015). The diverse studies also suggest that tillage influences on SOC can be depended on regional factors, i.e., soil type, residue management, crop rotation, region, type of clay and land management practices (Rabbi et al., 2015).

Aggregate size distribution

Aggregate size distribution percentages were affected by tillage and straw returning practices in both soil depths (Tables 2 and 3). The percentage of the > 5, 2-5, 1-2, 0.5-1.0 mm under straw returning plots NTS and CTS were significantly or nonsignificantly higher than those of other treatments at 0-20 and 20-40 cm soil depth of 2013-2015. Meanwhile, the contribution percentages of 0.25-0.5 and < 0.25 mm were inconstant between the treatments from 2013-2015 for both 0-20 and 20-40 cm depth. The higher percentage of > 5 mm aggregates (57.90%) was recorded under NTS in

Figure 2. Soil organic carbon content in different treatments.



A: 0-20 cm and B: 20-40 cm.
CT: Conventional tillage, CTS: conventional tillage with straw returning, NT: no-tillage, NTS: no-tillage with straw returning.
Bars with different lower-case letters indicate significant differences at $p < 0.05$.

Table 2. Water stable aggregate size distribution (%) at 0-20 cm soil depth under different tillage and straw returning treatments.

		Soil aggregate size distribution					
Year	Treatments	> 5 mm	2-5 mm	1-2 mm	0.5-1.0 mm	0.25-0.5 mm	< 0.25 mm
2013	CT	10.03h	4.05f	4.80cd	9.05cde	11.41cde	47.00b
	CTS	16.12g	5.31def	5.95a	10.69cd	11.74ab	55.63a
	NT	16.72g	4.50f	5.02bcd	10.28cde	10.81def	51.59b
	NTS	19.01dfg	6.08bc	5.58abc	10.42cd	13.31cd	49.40b
2014	CT	20.64f	6.76bc	5.37abc	10.69cd	8.72g	39.23d
	CTS	32.09e	4.77ef	5.84ab	11.70c	11.50def	43.08c
	NT	41.03d	4.55f	4.46de	9.85de	13.13cd	30.41f
	NTS	52.05b	5.84cde	4.06e	8.63e	11.30def	35.59e
2015	CT	38.57d	5.44a	4.89cd	10.66cd	11.97def	25.11g
	CTS	21.91f	6.22a	5.02cd	12.90b	12.81cde	27.39g
	NT	57.90a	7.88a	5.36ab	14.01ab	16.34a	34.39e
	NTS	46.93c	5.92a	6.08a	14.89a	14.54ab	20.88h
	ANOVA						
	T	**	**	NS	NS	**	**
	S	**	**	NS	*	NS	**
	Y	**	**	*	*	**	**
	T × S × Y	**	**	NS	NS	**	*

CT: Conventional tillage, CTS: conventional tillage with straw returning, NT: no-tillage, NTS: no-tillage with straw returning.
Different lower-case letter in a line denotes significant difference at the 5% level.
Values followed by the same lower-case letter are nonsignificantly different according to Duncan's multiple range test (p > 0.05) different years of the treatments.
T: Tillage, S: straw returning, Y: year, NS: nonsignificant.
*, **Significant at the 0.05 and 0.01 probability levels, respectively.

Table 3. Water stable aggregate size distribution (%) at 20-40 cm soil depth of under different tillage and straw returning treatments.

		Soil aggregates size (mm)					
Year	Treatments	> 5 mm	2-5 mm	1-2 mm	0.5-1.0 mm	0.25-0.5 mm	< 0.25 mm
2013	CT	8.33c	4.05ab	3.33efg	5.69	11.26de	45.62f
	CTS	15.21b	3.39abc	2.92g	8.82c	11.32de	54.26e
	NT	7.83c	4.37a	3.07fg	6.13ef	8.34f	44.39f
	NTS	18.14a	3.44abc	2.79g	6.52ef	10.68de	51.64e
2014	CT	2.16fg	3.31bcd	4.04bcde	7.20de	9.82ef	67.65cd
	CTS	2.14fg	2.37def	3.68cdef	10.76b	14.88b	70.17c
	NT	3.04ef	2.28ef	3.40defg	6.44ef	10.46ef	70.75bc
	NTS	4.44e	3.33bcd	4.10bcd	8.09cd	10.40de	64.92d
2015	CT	2.88ef	2.70cdef	4.26abc	9.45bc	12.92cd	70.22c
	CTS	3.10ef	3.20bcde	4.82a	13.92a	14.81b	78.46a
	NT	1.94ef	1.80f	4.57ab	12.64a	12.94cd	67.10cd
	NTS	3.82e	2.59cdef	3.99bcde	12.66a	17.89a	74.67ab
	ANOVA						
	T	NS	NS	NS	*	**	*
	S	**	NS	NS	*	**	**
	Y	**	*	*	**	**	**
	T × S × Y	**	NS	*	**	**	*

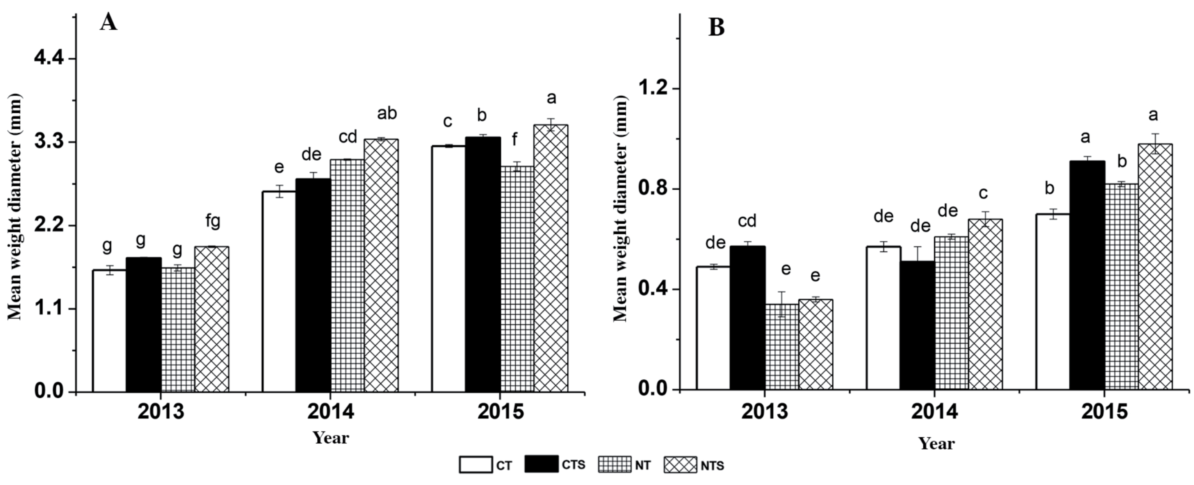
CT: Conventional tillage, CTS: conventional tillage with straw returning, NT: no-tillage, NTS: no-tillage with straw returning.
Different lower-case letter in a line denotes significant difference at the 5% level.
Values followed by the same lower-case letter are nonsignificantly different according to Duncan's multiple range test (p > 0.05) between the different years of the treatments.
T: Tillage, S: straw returning, Y: year, NS: non-significant.
*, **Significant at the 0.05 and 0.01 probability levels, respectively.

2015 at 0-20 cm depth. In 20-40 cm depth, the higher percentage of < 0.25 mm soil aggregates was 78.4% under CTS treatment in 2013. Likewise to our results, Kushwaha et al. (2001) observed that residue retention significantly increased the proportion of > 4.75 mm in minimum tillage and residue-retained treatments. The interactive effect of tillage and straw returning were significant for all size of aggregates except (1-2 and 0.5-1.0 mm) at 0-20 cm and except for 2-5 mm at 20-40 cm. With an increase in the duration of these treatments, CTS, NT, and NTS practices in 2015 significantly enhanced the percentage of macroaggregates (> 5, 2-5, 1-2, 0.5-1.0, 0.25-0.5 mm), but decreased the percentage of the microaggregates (< 0.25) at 0-20 cm depth. However, reverse trend was observed at 20-40 cm depth, increased the percentage of microaggregates (< 0.25 mm), but decreased the percentage of macroaggregates (> 5, 2-5, 1-2, 0.5-1.0, 0.25-0.5 mm). Alike to these findings that macro-aggregate (> 0.25 mm) proportion were significantly changed by NTS at upper soil layer (0-20 cm) but decreased at lower depth (Liu et al., 2014; Xin et al., 2015). In this study, NTS treatment significantly increased macroaggregates (> 0.25 mm) at the 0-20 cm depth and increased microaggregates (< 0.25 mm) at 20-40 cm depth in comparison with CT treatment. It was mainly because soil microaggregates (< 0.25 mm) consist of small particles, coated with fine organic and inorganic materials. However, macroaggregates (> 0.25 mm) are result of gathering of small particles (Gwenzi et al., 2009). The stability of these soil aggregates affected due to the tillage and residue management practices (Six et al., 2000), macroaggregates were of low stable and persistence because they are weekly cemented by organic residues (Six et al., 2000; Sandoval et al., 2007), such type of soil aggregates could readily disintegrate into smaller units under wet sieving. When soil aggregates were affected due mechanical disturbance of soil (e.g., under CT), the SOC interacted with aggregates released and aggregate size decreased. This was reported by Mikha and Rice (2004) that CT considerably decreased macroaggregates (> 2.0 mm and 0.25-2 mm) and with a coincident increase in microaggregates (< 0.25 mm) after 10 yr in a silt loam soil. Sandoval et al. (2007) also observed that there was a higher contents of macro-aggregates (> 0.5 mm) than in micro-aggregates (< 0.5 mm) in south-central Chile.

Mean weight diameter and geometric mean diameter of soil aggregates

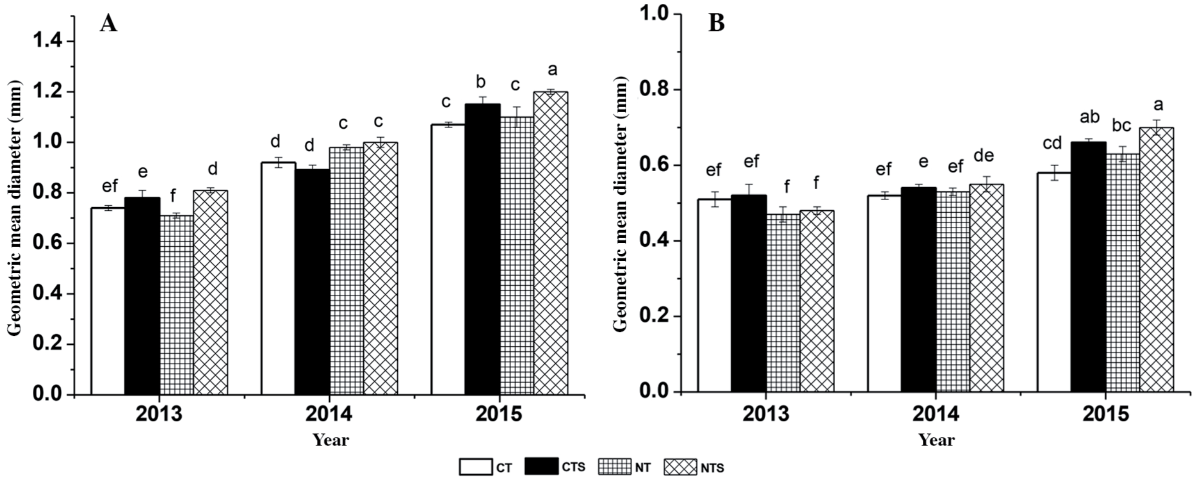
Mean weight diameter (MWD) and geometric mean diameter (GMD) of soil aggregates significantly varied with tillage, straw returning, year and their interaction (Figures 3 and 4). The average values of MWD and GMD in 2015 ranged from 3.25 to 3.53 and 1.0 to 1.3, respectively, as compared to 2013, ranged from 1.61 to 1.92 and 0.74 to 0.81, respectively. MWD and GMD under straw returning plots NTS and CTS were higher than those of other treatments with significant difference in 2015 than 2013. These results are same with another study that MWD was significantly affected by straw returning and no-tillage systems in the top 0-30 cm (Gwenzi et al., 2009). In agreement to our results, Kahlon et al. (2013) and Chen et al. (2014) reported that crop straw addition improved the aggregate stability of soil. The trend in depth regarding MWD decreasing from top to bottom of the soil with higher values under NTS treatments. Higher values under NTS than their counterpart CT treatments was due to less soil disturbance and residue retention. In 20-40 cm depth, MWD and GMD values in 2015 ranged from 0.70 to 0.98 and 0.58 to 0.72, respectively in comparison to 2013, which ranged from 0.34 to 0.47 and 0.47 to 0.53, respectively. The overall MWD and GMD values in the treatments followed the order of NTS > CTS > NT > CT at the 0-20 cm depth, and NTS > CTS > NT = CT at the 20-40 cm depth.

Figure 3. Mean weight diameter content of soil aggregates in different treatments.



A: 0-20 cm. B: 20-40 cm.
CT: Conventional tillage, CTS: conventional tillage with straw returning, NT: no-tillage, NTS: no-tillage with straw returning. Bars with different lower-case letters indicate significant differences at $p < 0.05$.

Figure 4. The geometric mean diameter content of soil aggregates in different treatments.



A: 0-20 cm. B: 20-40 cm.
CT: Conventional tillage, CTS: conventional tillage with straw returning, NT: no-tillage, NTS: no-tillage with straw returning.
Bars with different lower-case letters indicate significant differences at $p < 0.05$.

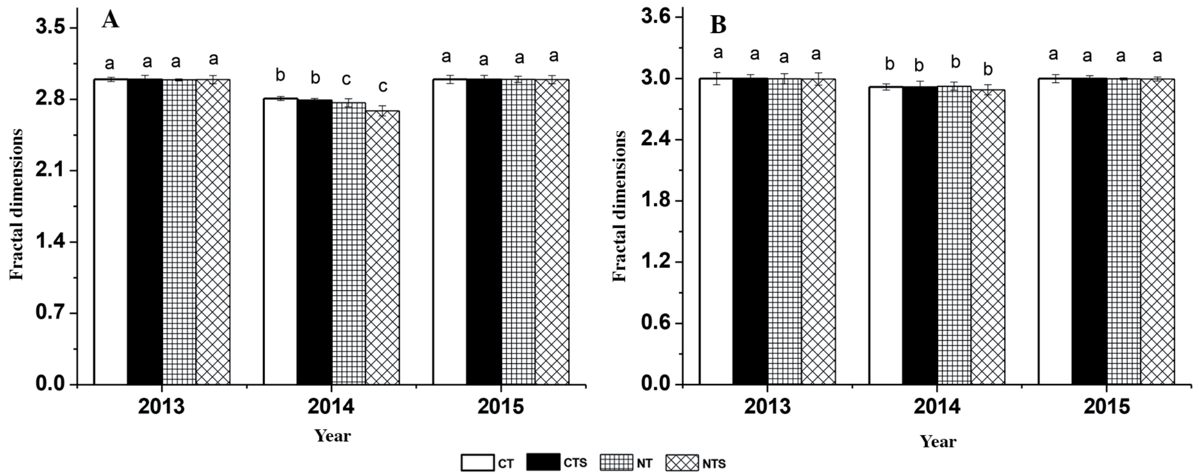
In present study, tillage and straw returning plots NTS and CTS treatments significantly increased MWD and GMD values of soil aggregates in both soil depths, but was more obvious at 0-20 cm depth. Soil aggregate stability always determined in relation to MWD and GMD, indicate the soil capability to resist degradation (Kemper and Rosenau, 1986). The effect of tillage on MWD and GMD was linked with residue placement, these finding consisted with others organic residues enhance MWD of soil aggregates (Dameni et al., 2010). Karami et al. (2012) reported that straw application improved the aggregate stability and other soil properties. This is coincident with these results that GMD values with the straw incorporation treatments improved significantly throughout under 3 yr study (Zhang et al., 2014). Improvement in stability of soil aggregates with NT may endorsed obviously near to the surface soil (< 10 cm) (Stone and Schlegel, 2010; Kahlon et al., 2013). In this study, we found distinct difference in GMD at surface soil, the distinct difference could be related with the continuous organic matter placement in the surface soil, the high stable soils always characterized due high addition of soil organic matter (Sandoval et al., 2007; Paul et al., 2013). These present study results were comparable with others studies (Zhou et al., 2007; Zhang et al., 2014), probably associated with change in aggregate size distribution during tillage processes and suggesting that increases in soil organic matter could also increase soil aggregation and stability in the study soil (Kibet et al., 2016).

Fractal dimensions

Tillage and straw returning treatments had a nonsignificant effect on fractal dimensions of the soil aggregates in both soil depths (Figure 5). The fractal dimension (FD) value varied from 2.81 to 2.99 from 2013 to 2015 at 0-20 cm depth. The FD value also increased with increasing soil depth. In 2013-2015, NT and NTS treatments had comparatively higher FD values which varied from 2.88 to 2.99 at the 20-40 cm depth, but the difference was nonsignificant. Overall, a larger FD value was noted under NTS treatment than the other treatments at both depths during the 3 yr.

In this present study, the fractal dimension D of soil aggregates nonsignificantly increased in both depths under NTS treatments. The distinct difference in fractal dimensions D of water stable aggregates was obvious in the surface soil. Similarly also reported in some other studies (Zhou et al., 2007; Zhang et al., 2014). The improvement in the fractal dimensions may have been accelerated by the returned residue retention, which increased aggregate stability, SOC (Gwenzi et al., 2009), and significantly increased aggregate size distribution (Six et al., 2000). Fractal dimensions D can be more strongly affected by the changes in land management and residue management practices in agro-ecosystem. In this study, soil was characterized by the increased values of fractal dimensions in NTS, in comparison to CT treatments. Previous studies also suggested that organic residues treatments usually had higher fractal dimensions that other cropland system (Tripathi et al., 2012; Zhang et al., 2014).

Figure 5. Fractal dimensions of different treatments.



A: 0-20 cm. B: 20-40 cm.
CT: Conventional tillage, CTS: conventional tillage with straw returning, NT: no-tillage, NTS: no-tillage with straw returning.
Bars with different lower-case letters indicate significant differences at $p < 0.05$.

Relationship of SOC with different soil aggregates

The correlation analysis revealed that SOC was positively or negatively ($p < 0.05$) correlated with > 5, 2-5, 1-2, 0.25-0.5, < 0.25 mm, MWD, GMD, and FD except 0.5-1.0 mm soil aggregate size (Table 4). The correlation coefficients varied from -28 to 0.97. Compared to others, macroaggregates > 5 mm had positively higher correlation coefficient with SOC 0.80**, MWD 0.97** and MWD 0.97**. Correlation analysis further supported that the content of SOC had a distinct significant relationship with > 5 mm macroaggregates.

Gwenzi et al. (2009) pointed out that, when both SOC and aggregation were generally low, the correlation represented the lower extreme of the relationship between SOC and soil aggregates. Biswas et al. (2009) observed increased (linear) content of SOC for larger size soil aggregates, which similar to our results. However, most of the SOC in soils is concomitant with the fine soil fraction and the dominant mechanism is chemical protection of soil structure (Six et al., 2000). Macroaggregates (> 0.25 mm) and soil aggregates stability was associated to loosely and tightly combined SOC content in the soil (Blanco-Canqui et al., 2011). Xin et al. (2015) also observed that soil SOC content was positively correlated with MWD ($r^2 = 0.94$) and GMD ($r^2 = 0.92$).

Table 4. Pearson correlation coefficient (r-value) and significance among soil organic carbon, mean weight diameter, geometric mean diameter, fractal dimensions and different soil aggregates (n = 72).

	SOC	MWD	GMD	FD	> 5 mm	2-5 mm	1-2 mm	0.5-1.0 mm	0.5-0.25 mm
MWD	0.82**	1.00							
GMD	0.78**	0.98**	1.00						
FD	-0.28*	-0.39**	-0.34**	1.00					
> 5 mm	0.80**	0.97**	0.97**	-0.36**	1.00				
2-5 mm	0.72**	0.56**	0.51**	-0.07ns	0.50**	1.00			
1-2 mm	0.75**	0.57**	0.55**	-0.06ns	0.50**	0.63**	1.00		
0.5-1.0 mm	-0.18ns	-0.28*	-0.25*	0.22*	-0.26*	-0.02ns	-0.02ns	1.00	
0.5-0.25 mm	0.47**	0.48**	0.50**	0.13ns	0.44**	0.45**	0.70**	0.40**	1.00
< 0.25 mm	-0.78**	-0.92**	-0.92**	0.17ns	-0.90**	-0.62**	-0.66**	0.07ns	-0.68**

ns: Nonsignificant. *, ** Significant correlation at 0.05 and 0.01 probability levels, respectively.
SOC: Soil organic C, MWD: mean weight diameter, GMD: geometric mean diameter, FD: fractal dimensions.

CONCLUSIONS

No-tillage with straw returning (NTS) had significantly higher soil organic C (SOC) content, soil macroaggregates, mean weight diameter (MWD), geometric mean diameter (GMD) and fractal dimensions (FD) values in 0-20 cm depth. In 20-40 cm depth, the soil micro-aggregates were higher under conventional tillage with straw returning (CTS) treatment. Combined use of no-tillage (NT) and straw returning significantly increased the SOC content and contribution of macroaggregates and microaggregates at 0-40 cm depth. Interactive effects of NT and straw returning were significantly noticeable in 0-20 cm soil depth. SOC was significantly correlated with macroaggregates, microaggregates, MWD, GMD in 0-40 cm depth. The long-term maintenance of NT and straw returning over time enhanced the percentage of large macroaggregates and SOC content in rice-rape rotation. Therefore, this study concluded that integrative application of NTS is suitable option for improving SOC content and soil quality in rice-rape rotation system.

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