



Effect of conservation tillage and rice-based cropping systems on soil aggregation characteristics and carbon dynamics in Eastern Indo-Gangetic Plain

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Abstract

Traditional rice–wheat cropping system, which follows wet puddling in rice and conventional tillage in wheat, is deteriorating soil health resulting yield stagnation in the Indo-Gangetic Plains of South Asia. Conservation agriculture which endorses minimum soil disturbance, residue retention and crop diversification not only improves soil health but also reduces the CO₂ concentration in atmosphere. We hypothesized that adoption of conservation agriculture could improve the soil health and soil organic carbon in comparison with conventional practices. A field experiment was conducted during 2012–2015 to observe the effects of different tillage practices and cropping systems on soil aggregation and carbon dynamics. The experiment comprised of three cropping systems, viz. rice–wheat, RW; rice–maize, RM; rice–lentil, RL, practiced in three tillage practices, viz. conventional tillage, CT; reduced tillage, RT; reduced tillage with 30% residue, RT30 in factorial randomized block design. Adoption of RT and RT30 resulted in higher macroaggregate content of 51.7 and 61.2%, respectively, in comparison with CT. Total water stable aggregates and mean weight diameter (MWD) of aggregates were considerably higher in RT and RT30 treatments, and the effect was most pronounced in the upper 0–15 cm soil layer. The rice–maize cropping system registered the highest macroaggregate content, water stable aggregates (WSA) and MWD of 55.6%, 80.0% and 2.28 mm, respectively, in the upper surface soil. The rice–maize cropping systems under RT30 recorded the highest total soil organic carbon (SOC) stock (51.0 Mg ha⁻¹) in comparison with other systems after 3 years of experimentation. Reduced tillage and residue management resulted in positive changes in soil infiltration rate. The effect of tillage operations and cropping systems on different soil properties (aggregate distribution, WSA, MWD and geometric mean diameter of aggregates, SOC stock, Bulk density) was mostly limited to surface layer of soil.

Keywords Carbon sequestration · Reduced tillage · Residue management · Water stable aggregates · Oxidizable organic carbon

Introduction

Rice (*Oryza sativa*)–wheat (*Triticum aestivum*), the most predominant cropping system of Indo-Gangetic Plain (IGP), is crucial for food security of India and occupies about 10.5 million hectare area (Timsina and Connor 2001). Current

practice involves intensive tillage practices for both crops and removal of crop residues. However, the sustainability of the system is threatened due to depletion or degradation of natural resources, increasing labor scarcity, and high costs of production (Ladha et al. 2009). Contrasting agronomic practices and anaerobic–aerobic field conditions in rice–wheat cropping system affect soil structure, nutrient relations, crop growth and associated pests and diseases (Kang et al. 2005). The repeated wet tillage in rice is not only labor, water, energy, time and carbon inefficient but also deteriorates soil quality and about 2–8% yield reduction in wheat has been reported as compared to wheat grown after direct seeded rice (Kumar and Ladha 2011). Therefore, diversification of cropping systems and adoption of new technologies of crop

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cultivation are needed to make the system sustainable and more profitable.

Conservation agriculture (CA) which involves minimum soil disturbance and residue retention or addition can well be adopted in IGP to offset the negative effects of conventional agriculture. Here, soil acts as a potential sink for atmospheric carbon in the form of soil organic carbon (SOC). The enhancement of C sequestration in soil due to CA practices not only improves soil fertility and its physical health but also reduces atmospheric CO₂ by fixing it in the soil for a longer period (Lal 2004). Soil aggregation, the most important indicator for evaluating soil structure, contributes to soil fertility by reducing soil erosion, improving water permeability, water infiltration and nutrient cycling by creating favorable environment for soil biota. Soil physical degradation due to erosion and soil compaction mostly attributed to intensive tillage practices is probably one of the most important negative consequences of modern agricultural practices (Lal 2004). Different tillage practices affect soil aggregation directly by breaking down of macroaggregates, and indirectly through alteration of biological and chemical factors (Barto et al. 2010). Conventional tillage generally destroys the network of mycelium by mechanical breakdown of macroaggregates (Borie et al. 2006) and decreases the content of SOC and microbial biomass (Mikha and Rice 2004).

Soil organic matter (SOM) and different physical properties are indicators of soil quality and play an important role in the production functionality of soil (Shukla et al. 2006). The dynamic properties, such as aggregation, bulk density, soil water transmission and aeration, have a greater impact on soil physical quality in the surface layers (Cavalieri et al. 2009). Generally, the cropping system with high C inputs favors the C sequestration in soil (Naik et al. 2017). However, the relationship between the C sequestration and the C input varies as suggested by different studies. Some studies reveal linear relationships (Ghosh et al. 2012; Majumder et al. 2008), while others suggested a logarithmic correlation (Cai and Qin 2006) based on long-term agroecosystem experiments. Several studies suggest that reduced or no tillage usually favors the formation of soil aggregates and minimizes the possibility of rapid oxidation of organic carbon of soil due to reduced soil disturbance. Macroaggregates (> 0.25 mm) are regarded as the best predictor of potential C response to tillage and residue management practices. The physical protection of C within macroaggregates limits its oxidation (Andruschewitsch et al. 2014) due to a less favorable environment for microbial activity. Several studies reported higher bulk density values in no or reduced tillage treatments compared to conventional tillage systems (Aikins and Afuakwa 2012; Czyż and Dexter 2008). However, Sekwakwa and Dikinya (2012) determined lowest bulk density under no tillage. Bulk density and cone index, which are normally evaluated for soil compaction, are also used

to predict the depth of soil hardpans (Afzalnia and Zabihi 2014). There are some contradictions on the effect of conservation tillage on penetration resistance. Some studies show that conservation agriculture (reduced tillage and no tillage) increases the cone index as compared to the conventional tillage (Taser and Metinoglu 2005).

The long-term effects of conservation tillage have been well-documented; however, less information is available regarding the short-term effects, particularly when converting to conservation tillage from conventional tillage (Salem et al. 2015). The long-term benefit from conservation tillage cannot be achieved easily unless farmers are satisfied with the short-term effects also (Chen et al. 2005). Moreover, the effect of conservation tillage on SOC storage is sometimes contradictory, especially for short term (≤ 10 years) (VandenBygaert et al. 2011; Liang et al. 2014). It varies with soil conditions, such as soil texture, climate and biomass return, as well as management itself, and is difficult to be generalized (Al-Kaisi et al. 2005; Liang et al. 2014). Hence, the studies on short-term impacts of tillage systems on SOC have to be verified in different soil conditions.

We hypothesized that short-term adoption of conservation tillage and residue retention has positive effects on soil physical properties and carbon storage over conventional practices in dominant cropping systems of eastern Indo-Gangetic Plain (IGP). The study was undertaken in a carefully designed field experiment, aimed at developing crop and resource management practices for sustainable future cereal-based systems.

Materials and methods

Experimental site

A field experiment was initiated in *kharif* (June–November) season of 2012 with a long-term perspective on the experimental farm of the Indian Council of Agricultural Research—Research Complex for the Eastern Region (ICAR-RCER) in Patna, Bihar, India. The soil is non-calcareous, non-saline old alluvium with a sandy clay loam texture and slightly below neutral pH. The basic soil characteristics of the experimental site measured just before laying out the field experiment are presented in Table 1. The climate of Patna is subtropical humid, with an average annual rainfall of 1130 mm (85–90% of which is received from June to September), daily minimum temperature of 7–9 °C in January, daily maximum temperature of 36–41 °C in May, and relative humidity of 60–90% throughout the year. Crop production is distributed across the three seasons that occur in this region: winter (*rabi*; November–March), summer (April–May) and rainy (*kharif*; June–November). Prior to the start of the experiment, a crop of puddled transplanted

Table 1 Physicochemical properties (Mean \pm SD) of the experimental site at the start of the experiment in 2012

Soil parameters	Soil depth (cm)		
	0–15	15–30	30–45
Bulk density (Mg m^{-3})	1.45 \pm 0.01	1.54 \pm 0.00	1.52 \pm 0.01
Particle density (Mg m^{-3})	2.63 \pm 0.00	2.63 \pm 0.00	2.64 \pm 0.00
Electrical conductivity (dS m^{-1})	0.11 \pm 0.03	0.08 \pm 0.00	0.09 \pm 0.00
pH (1:2.5 soil/water suspension)	6.8 \pm 0.17	6.8 \pm 0.14	6.9 \pm 0.11
Sand (%)	55.6 \pm 1.00	50.3 \pm 1.57	52.7 \pm 2.26
Silt (%)	15.5 \pm 1.35	17.3 \pm 1.10	16.1 \pm 0.96
Clay (%)	28.9 \pm 1.37	32.4 \pm 1.05	31.2 \pm 1.10
Soil texture	Sandy clay loam	Sandy clay loam	Sandy clay loam
Available N (kg ha^{-1})	219.4 \pm 15.0	212.2 \pm 11.5	195.6 \pm 2.79
Olsen P (kg ha^{-1})	21.4 \pm 1.90	18.5 \pm 2.03	15.1 \pm 0.90
1 N $\text{NH}_4\text{OAC K}$ (kg ha^{-1})	190.5 \pm 11.5	178.6 \pm 3.46	183.2 \pm 3.0
Infiltration rate (mm h^{-1}) at surface	8.31 \pm 0.43		
Saturated hydraulic conductivity (mm h^{-1})	8.16 \pm 1.23	7.44 \pm 0.41	8.58 \pm 0.21

SD standard deviation

rice was grown across the site to promote site uniformity. After harvest, the land was leveled and divided into 27 plots (8 m \times 4 m), which were separated by earthen bunds (0.2 m wide and 0.15 m high).

Experimental details and management

The design of the experiment was a factorial randomized block design (RBD) with three tillage practices and three cropping systems. Tillage practices were conventional tillage (CT), reduced tillage (RT) and reduced tillage with 30% residue retention (RT30). Three cropping systems, viz. rice–wheat (RW), rice–maize (RM) and rice–lentil (RL), were selected based on the dominant cropping systems of the region. The study has been carried out after completion of 3 years of the experiment in 2015.

The CT treatment was a transplanted puddled rice followed by conventional-till wheat, maize or lentil system. In puddled rice, two disking (\sim 15 cm) and two harrowings were employed under aerobic soil conditions, and each harrowing was followed by leveling. Finally, soil was puddled with water for easy transplanting of rice seedlings in soft mud of the field. In RT, one disking and one harrowing followed by planking were done and no puddling was done. After rice, field for wheat, maize or lentil was prepared with two disking and two harrowings followed by leveling in CT, whereas in RT, seeds of crops were drill sown in zero tilled plots. At maturity, crops were cut manually at 1/3rd height in RT30 plots to maintain 30% residue, whereas in CT and RT, crops were harvested at ground level with no standing crop residues.

All crops were applied with the recommended dose of fertilizers. The N, P and K were applied in form of urea, diammonium phosphate and muriate of potash, respectively. The

entire amount of P and K and half of the total N were applied before sowing/transplanting of the crops. The remaining N was applied in two equal halves, at the tillering and panicle initiation stages of rice, at the crown root initiation and flowering stages of wheat, at the knee height and tasseling stage of maize. A starter dose of N @ 20 kg ha^{-1} was applied to lentil at the time of sowing. Irrigation was applied through border strip method. A 2.0–2.5 cm standing water was maintained in rice through irrigating almost at every 5 days. All crops were irrigated at critical growth stages (wheat: crown root initiation, jointing, flowering, milking and dough stage; maize: six irrigation at 20–25 days interval; lentil: 45 days after sowing and pod formation stage).

Soil sampling and analysis

Baseline soil samples were collected after the harvest of the rice crop. Soil samples from 0–15, 15–30 and 30–45 cm depth were collected using a soil auger. The depth-wise soil samples from each plot were composited, air-dried, ground to pass through a 2-mm sieve, and stored until analysis was done. The soil samples were analyzed for pH, electrical conductivity (EC), available N (Subbiah and Asija 1956), 0.5 M sodium bicarbonate extractable-P (Watanabe and Olsen 1965) and 1 N neutral ammonium acetate extractable-K (Jackson 1973). Particle size distribution was determined by the hydrometer method (Bouyoucos 1962). The textural class was determined by textural triangle of the United States Department of Agriculture (USDA) system. In our experiment, tillage depth was \sim 15 cm, and therefore, analysis of soil parameters up to 30 cm depth was done. The main objective of our experiment was to see the effect of different tillage and residue

management practices on soil properties, and therefore, depth was not considered as a factor during statistical analysis and interpretation of results.

Soil aggregate analysis

Aggregate analysis was performed for two depths, i.e., 0–15 and 15–30 cm. Soil samples were prepared in the laboratory by carefully breaking larger clods (field moist soil) by hand into smaller segments along natural cleavage and then air-dried. Air-dried samples were then passed through an 8-mm sieve and retained on a 5-mm sieve. The aggregates were then wet-sieved through a nest of sieves (2, 0.25 and 0.053 mm mesh size) following the procedure as laid out by Yoder (1936). The air-dried soil sample (50 g) was placed on a 2-mm sieve and allowed to saturate by capillary intake of water for 30 min. Thereafter, shaking operation was performed in a Yoder apparatus for 15 min with 35 numbers of cycles per minute. After sieving, the content of each sieve was shifted to a separate beaker and allowed to dry. Thereafter, 50 ml 5% sodium hexametaphosphate was added, and again it was passed through the same sieve where it was retained. The colloidal suspension collected below was transferred to pre-weighed filter paper and oven-dried at 60 ± 5 °C for 48 h and weighed and stored at room temperature for organic C analysis. A subsample was taken from the collected soil suspension that passed through the 0.053-mm sieve ('silt + clay'-sized fraction). For moisture correction, during aggregate analysis, a subsample was taken in moisture box and dried at 105 °C for moisture content and necessary corrections were made. The mean weight diameter (MWD) was calculated as an index of aggregation along with other indices as follows:

- a. Macro- and microaggregates:

The line between macro- and microaggregates is commonly drawn at 0.25 mm (Oades and Waters 1991). In our study, the macroaggregate was determined by adding the aggregates retained over 2- and 0.25-mm sieves. Similarly, microaggregate was aggregates retained over 0.053-mm sieves.

- b. Mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates (Kemper and Rosenau 1986) were calculated as:

$$\text{MWD (mm)} = \frac{\sum_{i=1}^n X_i W_i}{\sum_{i=1}^n W_i}$$

$$\text{GMD (mm)} = \exp \left[\frac{\sum_{i=1}^n W_i \log X_i}{\sum_{i=1}^n W_i} \right]$$

where W_i is the weight of aggregates retained over the particular sieve, X_i the mean diameter of the size class (mm).

- c. Aggregate stability (AS) of soils (Castro-Filho et al. 2002) was calculated as:

$$\text{AS} = \left[\frac{\text{Weight of the aggregates} - \text{wp25}}{\text{Weight of dry sample}} \right] \times 100$$

where wp25 is the weight of aggregates < 0.25 mm (g).

Aggregate ratio (AR) of soils was computed as (Choudhury et al. 2014):

$$\text{AR} = \frac{\text{Percent of water stable macroaggregate}}{\text{Percent of water stable microaggregate}}$$

Aggregate associated organic carbon (AAOC)

Soil samples retained over filter paper during wet sieving were ground and used for determination of AAOC by wet oxidation method (Walkley and Black 1934). The organic C present in soil aggregate size fractions of > 2.0 mm, 0.25–2.0 mm, 0.053–0.25 mm and < 0.053 mm was defined as macroaggregate C I (MacAOC I), macroaggregate C II (MacAOC II), microaggregate C (MicAOC) and 'silt + clay'-associated OC (Silt + ClayAOC), respectively (Choudhury et al. 2014). The sum of organic C in the > 0.25 mm aggregate size fractions was referred to as macroaggregate organic C (MacAOC), while organic C in the < 0.25 mm size fractions was dubbed microaggregated organic C (MicAOC).

Organic carbon content of bulk soil

For organic carbon content determination, composite bulk soil samples were collected after harvesting of rice crop from each treatment. Samples were air-dried, ground and passed through 0.1-mm sieve and stored in plastic containers. The organic carbon content was determined by dichromate oxidation of the sample and subsequent titration with ferrous ammonium sulfate (Walkley and Black 1934).

C stock and C sequestration rate

The C stock (Mg ha^{-1}) was calculated by the following equation:

$$C_{\text{stock}} = \text{SOC} \times \rho \times \text{Depth} \times 10$$

where SOC is expressed in g kg^{-1} soil, ρ is the soil bulk density (Mg m^{-3}), Depth in m and C stock in Mg ha^{-1} .

The C sequestration rate ($\text{Mg ha}^{-1} \text{ year}^{-1}$) during the period of the experiment was calculated using the following equation:

$$C_{\text{sequestration rate}} = \frac{(\text{SOC}_{2015} - \text{SOC}_{2012}) \times \rho \times \text{Depth} \times 10}{T}$$

where SOC_{2015} and SOC_{2012} are the SOC in 2015 and the initial year, i.e., 2012, (g kg^{-1}), respectively. T is the period of the experiment, 3 years.

Bulk density (BD)

Bulk density was determined by the core method (Blake and Hartge 1986). Fresh soil ce of 5 cm diameter and 5 cm length collected in triplicate from the field after rice harvest and were dried at 105 °C in an oven till constant weight. Bulk density of soil was calculated by dividing the dry weight to the core volume and expressed as Mg m^{-3} .

Soil infiltration rate

The ponding method was used to determine the infiltration rate of the soil (Bouwer 1986). Infiltration measurements were made after harvest of *rabi* (winter) crop for each plot using a double ring in filtrometer. The two concentric rings (Eijkelkamp) were inserted up to 5 cm deep into the soil by

hammering. The fall of water (i.e., soil intake) in the inner ring was determined at established time interval.

Statistical analysis

Statistical analysis was performed by windows based SPSS program (ver. 16.0, SPSS Inc. 1996) to determine the statistical significance of treatment effects. Tukey's HSD test was used to compare means through the least significant difference (LSD). The 5.0% probability level was regarded as statistically significant.

Results and discussion

Size distribution of aggregates

The distribution of different soil aggregate size classes in the soil profile was stratified, which was significantly different among the tillage practices and cropping systems (Table 2). In the surface layer (0–15 cm), significant differences among treatments in amount of aggregates of different size classes were observed. Amount of large macroaggregate (8–2 mm) was significantly lower in CT ($29.5 \text{ g } 100 \text{ g}^{-1}$) and

Table 2 Influence of tillage practices and cropping system on the distribution of aggregates into different size classes (Mean \pm SD)

Treatments	Aggregate size class (mm)							
	8–2		2–0.25		0.25–0.053		<0.053	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
	g aggregates 100 g ⁻¹ of dry soil							
<i>Tillage practices</i>								
CT	29.50 \pm 3.43 ^C	17.61 \pm 2.96 ^C	11.67 \pm 4.64 ^A	15.80 \pm 6.95 ^A	21.14 \pm 4.32 ^A	24.65 \pm 5.6 ^B	37.69 \pm 7.31 ^A	41.95 \pm 9.23 ^A
RT	38.19 \pm 3.43 ^B	22.84 \pm 3.05 ^B	13.55 \pm 1.49 ^A	13.23 \pm 4.49 ^A	23.53 \pm 6.35 ^A	28.19 \pm 6.94 ^{AB}	24.74 \pm 8.71 ^B	35.74 \pm 8.31 ^A
RT30	49.58 \pm 2.7 ^A	28.38 \pm 4.47 ^A	11.65 \pm 3.26 ^A	12.61 \pm 3.5 ^A	22.97 \pm 3.31 ^A	32.14 \pm 6.6 ^A	15.80 \pm 5.96 ^C	26.87 \pm 8.64 ^B
<i>Cropping systems</i>								
RW	37.19 \pm 9.1 ^B	24.47 \pm 6.86 ^A	11.17 \pm 2.87 ^A	10.44 \pm 2.44 ^B	23.08 \pm 3.52 ^A	30.94 \pm 7.54 ^A	28.57 \pm 10.32 ^A	34.15 \pm 12 ^{AB}
RM	41.49 \pm 9.05 ^A	22.27 \pm 3.47 ^A	14.16 \pm 3.84 ^A	16.65 \pm 3.11 ^A	24.39 \pm 6.17 ^A	31.28 \pm 4.9 ^A	19.96 \pm 12.3 ^B	29.81 \pm 8.66 ^B
RL	38.59 \pm 9.14 ^{AB}	22.09 \pm 6.35 ^A	11.53 \pm 2.83 ^A	14.54 \pm 7.0 ^A	20.17 \pm 3.54 ^A	22.76 \pm 4.64 ^B	29.71 \pm 10.65 ^A	40.60 \pm 8.54 ^A
<i>Interactions</i>								
CT-RW	27.59 \pm 2.8 ^e	18.43 \pm 2.46 ^{cd}	10.08 \pm 3.83 ^a	9.55 \pm 1.58 ^{bc}	22.28 \pm 1.8 ^a	25.30 \pm 6.84 ^{abc}	40.05 \pm 4.26 ^a	46.72 \pm 8.39 ^a
CT-RM	31.49 \pm 3.05 ^{de}	19.50 \pm 2.14 ^{cd}	15.35 \pm 4.93 ^a	16.71 \pm 3.74 ^{abc}	20.57 \pm 7.53 ^a	27.92 \pm 3.64 ^{abc}	32.59 \pm 10.65 ^{ab}	35.87 \pm 8.66 ^{ab}
CT-RL	29.42 \pm 4.28 ^e	14.90 \pm 2.67 ^d	9.58 \pm 4.05 ^a	21.13 \pm 8.63 ^a	20.57 \pm 3.44 ^a	20.72 \pm 5.06 ^{bc}	40.43 \pm 4.83 ^a	43.25 \pm 10.16 ^a
RT-RW	35.87 \pm 1.46 ^{cd}	22.08 \pm 2.56 ^{bc}	13.21 \pm 2.05 ^a	13.00 \pm 0.57 ^{bc}	24.44 \pm 5.62 ^a	33.58 \pm 1.91 ^a	26.48 \pm 6.51 ^{bcd}	31.33 \pm 1.24 ^{ab}
RT-RM	41.41 \pm 3.24 ^b	20.96 \pm 1.41 ^{bc}	14.15 \pm 1.49 ^a	17.22 \pm 4.56 ^{ab}	27.51 \pm 6.40 ^a	30.71 \pm 6.15 ^{ab}	16.92 \pm 9.39 ^{de}	31.11 \pm 7.96 ^{ab}
RT-RL	37.28 \pm 3.12 ^{bc}	25.47 \pm 3.48 ^b	13.28 \pm 1.29 ^a	9.46 \pm 3.78 ^{bc}	18.63 \pm 5.27 ^a	20.28 \pm 1.99 ^c	30.80 \pm 4.62 ^{abc}	44.79 \pm 5.25 ^a
RT30-RW	48.10 \pm 1.33 ^a	32.88 \pm 2.51 ^a	10.23 \pm 2.19 ^a	8.78 \pm 2.42 ^c	22.51 \pm 3.25 ^a	33.94 \pm 10.26 ^a	19.16 \pm 5.3 ^{cde}	24.40 \pm 10.6 ^b
RT30-RM	51.58 \pm 2.26 ^a	26.34 \pm 1.65 ^b	12.98 \pm 5.31 ^a	16.01 \pm 1.68 ^{abc}	25.09 \pm 4.19 ^a	35.19 \pm 2.13 ^a	10.36 \pm 4.55 ^e	22.46 \pm 4.8 ^b
RT30-RL	49.07 \pm 3.55 ^a	25.91 \pm 5.02 ^b	11.73 \pm 1.93 ^a	13.05 \pm 0.71 ^{bc}	21.31 \pm 2.17 ^a	27.29 \pm 3.18 ^{abc}	17.89 \pm 5.06 ^{de}	33.75 \pm 7.35 ^{ab}

CT conventional tillage, RT reduced tillage, RT30 reduced tillage with 30% residue, RW rice–wheat, RM rice–maize, RL rice–lentil

Within a column means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan multiple range test

the highest amount was recorded in RT30 (49.6 g 100 g⁻¹). No significant difference was observed in small macroaggregate (2–0.25 mm) and microaggregate (0.25–0.053 mm) size class among the tillage practices in the surface layer. As expected, silt and clay sized aggregates (<0.053 mm) were far higher in CT (37.7 g 100 g⁻¹) due to mechanical effect of machinery during plowing activities particularly in surface layer (0–15 cm). In the deeper layer (15–30 cm), the amount of large macroaggregate and microaggregate was significantly highest in RT30 (28.38 g 100 g⁻¹), while small macroaggregate was found nonsignificant among the tillage practices. The silt- and clay-sized aggregates showed significantly higher amount in CT and RT in the deeper layer. Systems that adopted conservation agriculture recorded higher macroaggregate content to the tune of 25.6% (for reduced tillage) and 48.7% (for reduced tillage with 30% residue) than conventional one (CT) in the upper layer.

Among the cropping systems, the rice–maize showed significantly highest macroaggregate of 41.5 g 100 g⁻¹ and significantly lowest silt- and clay-sized aggregates (19.96 g 100 g⁻¹) in the surface soil. However, small macroaggregate (2–0.25 mm) and microaggregate (0.25–0.053 mm) recorded higher value in rice–maize cropping system but found nonsignificant among the cropping systems in the surface soil. In the deeper layer, rice–maize cropping system recorded the highest value of small macroaggregate and microaggregate. The rice–lentil cropping systems recorded significantly highest amount of silt- and clay-sized aggregates of 40.6 g 100 g⁻¹ over rice–maize and rice–wheat cropping systems.

In the interaction effect, RT30 registered the highest macroaggregate of 51.6 g 100 g⁻¹ under rice–maize cropping system, which was at par with other cropping system combination (RT30-RL and RT30-RW) but it was significantly highest over the other tillage practice (CT and RT) with cropping system (RW, RM and RL) combination. However, the interaction effect was nonsignificant for small macro- and microaggregates in the 0–15 cm soil layer for all the treatment combinations. The silt- and clay-sized aggregates showed significantly highest amount of 40.43 g 100 g⁻¹ in rice–lentil cropping system practiced under CT over other treatment combinations of RT-RW, RT-RM, RT30-RW, RT30-RM and RT30-RL in the surface soil. In the lower layer (15–30 cm), significantly highest large macroaggregate of 32.8 g 100 g⁻¹ was noted over other treatment combinations in rice–wheat cropping system under RT30. The highest amount of small macroaggregates was recorded in CT-RL (21.13 g 100 g⁻¹), which was significantly higher than CT-RW, RT-RW, RT-RL, RT30-RW and RT30-RL treatment combinations. In the subsurface soil layer, the highest (35.2 g 100 g⁻¹) and lowest (20.3 g 100 g⁻¹) amount of microaggregates were recorded in RT30-RM and RT-RL, respectively. The silt- and clay-sized aggregates in the deeper layer showed significantly highest value of 46.72 g 100 g⁻¹

in rice–wheat cropping system under CT than RT30-RM and RT30-RW. A significantly higher amount of larger macroaggregates (8–2 mm) in the treatments, which received reduce tillage, was due to less physical disturbance of soil (Garcia-Franco et al. 2015). Residue addition combined with reduced tillage further improved the aggregation characteristics of soil (Pokharel et al. 2013). This could be due to firstly, physical protection of aggregates from direct rain-drop impact and secondly, due to organic materials, binding agent and root exudates produced by residue retention play important roles in aggregation (Pokharel et al. 2013). On the contrary, CT recorded lower amount of macroaggregates and higher amount of silt and clay sized particles. Results are explained by the possible breaking down of macro- and microaggregates into smaller fractions due to puddling and removal of crop residues, as argued by others (Grandy and Robertson 2006). The effect of reduced tillage and residue on soil aggregation was reduced with increasing soil depth, and it could be due to less physical disturbance in lower layer irrespective of tillage and residue management.

Aggregation indices

The impact of tillage could better be differentiated through different aggregation indices of which, MWD of aggregates and water stable aggregates (WSA) are the most sensitive ones (Unger and Cassel 1991). The tillage practices showed significant differences in the aggregation indices. In the upper layer, the WSA, MWD and GMD were significantly highest of 84.2 g 100 g⁻¹, 2.65 mm and 0.93 mm, respectively, in RT30 tillage practices compared to other tillage practices. In the 15–30 cm layer, no significant differences in WSA, MWD and GMD were observed among the tillage practices. In deeper layer (15–30 cm), RT30 tillage practice recorded higher WSA, MWD and GMD of aggregates than RT and CT, though the differences were not significant. In the surface layer (0–15 cm), adoption of reduced tillage (RT) significantly improved the water stability of aggregates by 20.7%, while residue addition (RT30) further improved the values by 35.1% in comparison with conventional tillage practices (Table 3). Furthermore, the RT30 practices improved the MWD and GMD by 59.6 and 126%, respectively, over CT.

Significant increase in WSA, MWD and GMD of aggregates were noticed in different cropping systems in the surface layer (0–15 cm). The rice–maize cropping systems, irrespective of tillage practices showed significantly highest WSA, MWD and GMD of 80.0 g 100 g⁻¹, 2.28 mm and 0.76 mm, respectively, over the other cropping systems in the surface layer. However, the deeper layer did not show significant difference in aggregation indices among the different cropping systems. Interaction effects among tillage and cropping systems were only significant on aggregation

Table 3 Influence of tillage practices and cropping system on aggregation indices (Mean \pm SD)

Treatments	Water stable aggregates ($\text{g } 100 \text{ g}^{-1}$)		Mean weight diameter (mm)		Geometric mean diameter (mm)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
<i>Tillage practices</i>						
Conventional tillage (CT)	62.31 \pm 7.31 ^C	36.74 \pm 6.56 ^A	1.66 \pm 0.18 ^C	1.28 \pm 0.28 ^A	0.41 \pm 0.08 ^C	0.34 \pm 0.07 ^A
Reduced tillage (RT)	75.26 \pm 8.71 ^B	36.07 \pm 4.34 ^A	2.11 \pm 0.17 ^B	1.35 \pm 0.63 ^A	0.63 \pm 0.12 ^B	0.40 \pm 0.12 ^A
Reduced tillage with 30% residue (RT30)	84.20 \pm 5.96 ^A	40.99 \pm 3.35 ^A	2.65 \pm 0.14 ^A	1.62 \pm 0.20 ^A	0.93 \pm 0.13 ^A	0.45 \pm 0.07 ^A
<i>Cropping systems</i>						
Rice–wheat (RW)	71.43 \pm 10.32 ^B	38.24 \pm 3.78 ^A	2.03 \pm 0.45 ^B	1.57 \pm 0.24 ^A	0.59 \pm 0.21 ^B	0.41 \pm 0.07 ^A
Rice–maize (RM)	80.04 \pm 12.4 ^A	38.91 \pm 5.04 ^A	2.28 \pm 0.43 ^A	1.36 \pm 0.18 ^A	0.76 \pm 0.26 ^A	0.39 \pm 0.08 ^A
Rice–lentil (RL)	70.29 \pm 10.65 ^B	36.64 \pm 6.81 ^A	2.10 \pm 0.46 ^B	1.32 \pm 0.68 ^A	0.62 \pm 0.24 ^B	0.39 \pm 0.14 ^A
<i>Interactions</i>						
CT-RW	59.95 \pm 4.26 ^e	37.98 \pm 4.13 ^a	1.55 \pm 0.15 ^e	1.59 \pm 0.14 ^a	0.37 \pm 0.06 ^d	0.39 \pm 0.06 ^a
CT-RM	67.41 \pm 10.65 ^{de}	36.21 \pm 5.44 ^a	1.79 \pm 0.12 ^{de}	1.22 \pm 0.14 ^a	0.49 \pm 0.07 ^{cd}	0.34 \pm 0.07 ^a
CT-RL	59.57 \pm 4.83 ^c	36.03 \pm 2.31 ^a	1.63 \pm 0.20 ^c	1.04 \pm 0.22 ^a	0.38 \pm 0.06 ^d	0.30 \pm 0.09 ^a
RT-RW	73.52 \pm 6.51 ^{bcd}	35.09 \pm 2.06 ^a	1.99 \pm 0.05 ^{cd}	1.32 \pm 0.12 ^a	0.56 \pm 0.04 ^c	0.35 \pm 0.03 ^a
RT-RM	83.08 \pm 9.39 ^{ab}	38.18 \pm 5.79 ^a	2.28 \pm 0.16 ^b	1.30 \pm 0.11 ^a	0.75 \pm 0.13 ^b	0.37 \pm 0.07 ^a
RT-RL	69.20 \pm 4.62 ^{cde}	34.93 \pm 5.26 ^a	2.06 \pm 0.15 ^{bc}	1.43 \pm 1.24 ^a	0.57 \pm 0.06 ^c	0.47 \pm 0.20 ^a
RT30-RW	80.84 \pm 5.3 ^{abc}	41.66 \pm 2.06 ^a	2.56 \pm 0.09 ^a	1.81 \pm 0.10 ^a	0.84 \pm 0.10 ^b	0.49 \pm 0.05 ^a
RT30-RM	89.64 \pm 4.55 ^a	42.35 \pm 3.03 ^a	2.77 \pm 0.06 ^a	1.56 \pm 0.10 ^a	1.06 \pm 0.06 ^a	0.46 \pm 0.05 ^a
RT30-RL	82.11 \pm 5.06 ^{ab}	38.96 \pm 4.68 ^a	2.63 \pm 0.17 ^a	1.50 \pm 0.25 ^a	0.90 \pm 0.13 ^b	0.39 \pm 0.08 ^a

CT conventional tillage, RT reduced tillage, RT30 reduced tillage with 30% residue, RW rice–wheat, RM rice–maize, RL rice–lentil

Within a column means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan multiple range test

indices in the surface layer (0–15 cm), while these were nonsignificant in the deeper soil layer (15–30 cm). The rice–maize grown under RT30 tillage practices registered highest water stable aggregate (89.6 $\text{g } 100 \text{ g}^{-1}$) but not significantly highest with other cropping system combination, while the value was lowest for rice–lentil (59.6 $\text{g } 100 \text{ g}^{-1}$) followed by rice–wheat (59.9 $\text{g } 100 \text{ g}^{-1}$) grown under CT practices. In case of MWD, rice–maize cropping system under RT30 recorded highest value of 2.77 mm, which was at par with other cropping system but significantly higher than other tillage practices with cropping system combination. Furthermore, rice–maize cropping system under RT30 noted significantly highest GMD of 1.06 mm over all other treatment combinations. In 15–30 cm soil layer, no significant differences in aggregation characteristics (WSA, MWD and GMD of aggregates) were observed among different treatment combinations. However, rice–maize and rice–lentil under RT30 showed slightly better aggregation indices in comparison with rice–wheat in the surface soil.

In the surface soil, the aggregate stability was significantly higher in RT and RT30 over CT (Fig. 1). Further, the rice–maize cropping system registered significantly highest aggregate stability (0.56) over the other two cropping systems. The rice–maize cropping system practices under RT30 resulted in significantly highest aggregate stability of 0.65 over other treatment combinations, but was nonsignificant

with RT30-RL. In the lower depth, RT30 recorded significantly highest aggregate stability over RT and CT. No significant differences in aggregate stability were recorded by various cropping systems at lower depth. Moreover, the aggregate stability under RT30 showed nonsignificant with RT in combination with all cropping systems, but it was significantly highest over CT-RW in the 15–30 cm soil layer. The aggregate ratio was significantly highest in RT30 (2.7) over CT and was nonsignificant with RT in the 0–15 cm depth, whereas the aggregate ratio was nonsignificant among all the cropping systems. The treatment combinations of RT-RL (2.89) and RT30-RL (2.87) recorded significantly higher aggregate ratio over CT-RW but showed nonsignificant with other treatment combinations. In 15–30 cm soil depth, the rice–lentil (RL) cropping system showed significantly highest aggregate ratio (1.68) over RW and RM, while tillage practices showed nonsignificant difference. The interaction effect of tillage practice with cropping system on aggregate ratio was nonsignificant in 15–30 cm soil depth.

The relative aggregate-size fractions and the aggregation indices demonstrated that partial adoption of conservation agriculture (RT and RT30) promoted macroaggregation, while conventional tillage (CT) resulted in less aggregation due to more mechanical disturbances and less organic matter. Results showed significant improvement in soil aggregation and the improvement of average MWD due to the

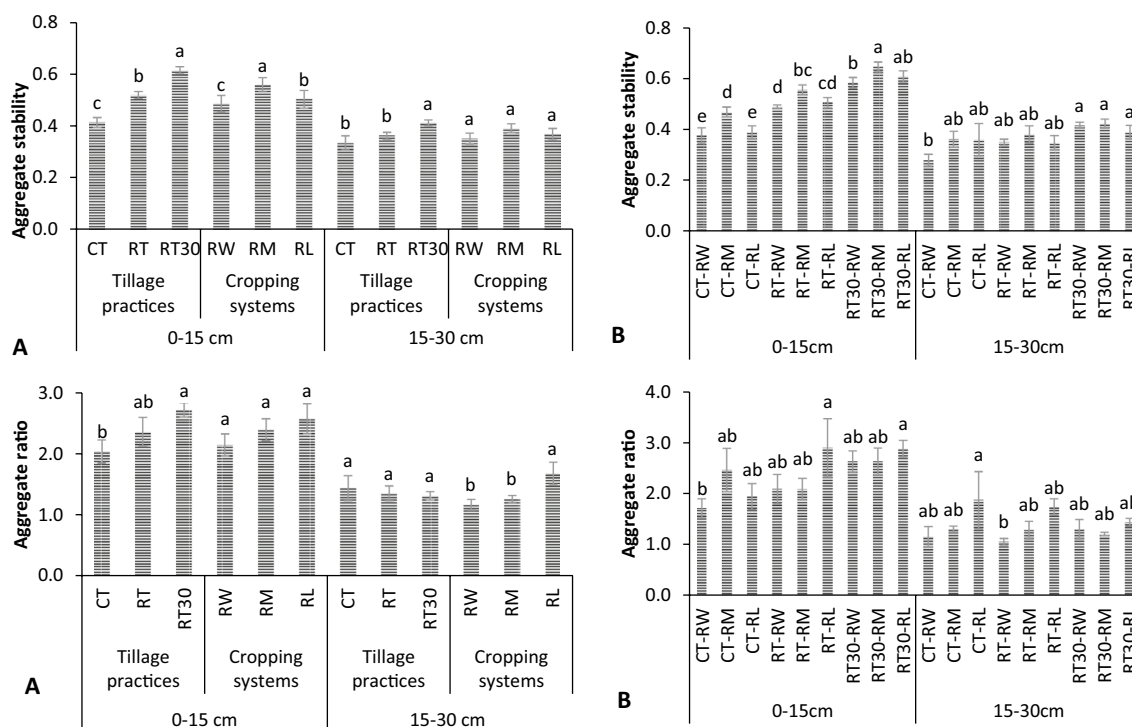


Fig. 1 Mean effect of tillage practices and cropping systems on aggregate stability and aggregate ratio (a) and interaction effect of tillage practices and cropping systems on aggregate stability and

aggregate ratio (b). Bars followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan multiple range test. Error bars indicate \pm standard error

interactive effect of the absence of soil disturbance and residue mulch cover under reduced tillage (Blanco-Canqui and Lal 2008). Higher values of aggregation indices were also reported elsewhere under reduced tillage or zero tillage systems (Xin et al. 2015). Nonsignificant variation in different aggregation indices in deeper layer (15–30 cm) suggests that effect of reduced tillage (RT) and residue retention (RT30) was limited to the surface layer of soil. The RM and RL cropping system showed an increasing trend in aggregation indices than RW system but the differences were not significant. The possible reasons that more root biomass and more surface protection from rain in RM cropping system, and leguminous nature of crop in RL cropping system that helped in better aggregation.

Aggregate associated organic C

The effect of tillage practices and cropping systems on aggregate associated organic carbon was most prominent in the surface 0–15 cm soil layer (Fig. 2). The total aggregate-associated organic carbon in 0–15 cm layer was significantly higher in RT30 compared to RT and CT. The macroaggregate-associated organic carbon was significantly higher in RT30 over other tillage practices. In case of microaggregate-associated organic carbon, both RT30 and RT were statistically at par but significantly higher than CT. The silt- and

clay-associated organic carbons were significantly highest in CT over RT and RT30. Among the cropping systems, rice–maize ($0.40 \text{ g } 100 \text{ g}^{-1}$) and rice–lentil ($0.42 \text{ g } 100 \text{ g}^{-1}$) showed significantly higher macroaggregate-associated organic carbon over rice–wheat. The interaction effect showed that the rice–maize and rice–lentil under RT30 contributed significantly higher macroaggregate-associated organic carbon of 0.54 and $0.59 \text{ g } 100 \text{ g}^{-1}$, respectively, in the surface soil in comparison with other treatment combinations, while rice–wheat under conventional tillage noted lowest value ($0.25 \text{ g } 100 \text{ g}^{-1}$). The contribution of mesoaggregate-associated organic carbon was nonsignificant irrespective of tillage practices and cropping systems. In 0–15 cm soil layer, both MacAOC and MicAOC were significantly higher in treatments, where conservation agricultural practices were adopted than conventional practices. Among the cropping systems, rice–maize and rice–lentil resulted in higher amount of AOC than rice–wheat. In the upper layer, the contribution of different aggregate fraction to total carbon in CT was in the order of MacAOC > Silt + Clay AOC > MicAOC > MesAOC, while in RT and RT30, it was in the order of MacAOC > MicAOC > MesAOC = Silt + Clay AOC. In the deeper layer (15–30 cm), MicAOC was significantly highest in RT30 over RT and CT, while the other fractions were nonsignificant among the tillage practices. Among the cropping systems, rice–wheat recorded

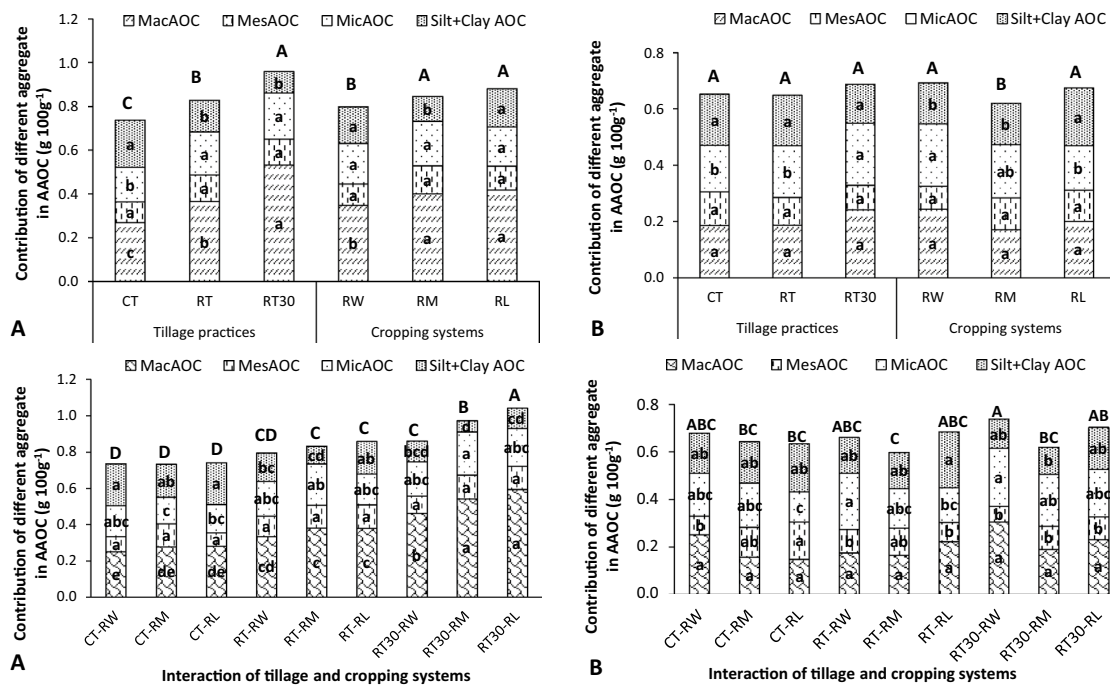


Fig. 2 Contribution of different aggregate size class in AAOC under different treatments in 0–15 cm (a) and 15–30 cm (b) soil layers. Within same class bars followed by the same letters are not significantly different at $p \leq 0.05$ by Duncan multiple range test

highest MicAOC of $0.22 \text{ g } 100 \text{ g}^{-1}$ which was at par with rice–maize, but it was significantly highest over rice–lentil in the deeper layer. Similarly, rice–lentil cropping system registered significantly highest Silt + Clay AOC over rice–wheat and rice–maize cropping system. The interaction effect of tillage practices with cropping systems on total aggregate-associated organic carbon was nonsignificant.

Irrespective of tillage and cropping systems, organic carbon content was always higher in macroaggregates than the rest of the aggregate fraction in all soil layers. Macroaggregates are rich in labile carbon (Wei et al. 2013) and conventional tillage practices cause rapid loss of SOC by breaking larger aggregates into smaller ones. Our results were in agreement with the findings of Du et al. (2013) and Xin et al. (2015), who observed that more organic matter was associated with larger aggregates than micro- and silt + clay fraction. Furthermore, AAOC under RT30 resulted in significantly higher AAOC than RT and CT. This finding could explain the role of organic matter in forming macroaggregates and protection of SOC within aggregates (Tivet et al. 2013). A higher amount of AAOC in RT30 and RT than CT treatments can be attributed to non-disturbance of soil due to reduction in tillage intensity.

SOC stock and C sequestration rate

A visible trend of having an increased amount of organic carbon in RT and RT30 treatments compared to CT was

found in 0–15 cm soil depth (Table 4). The increase in organic carbon content in RT and RT30 was 10.26 and 18.52%, respectively, over CT. Further down the layer (15–30 and 45–60 cm), no significant differences were noticed among the different tillage practices. However, in 30–45-cm soil layer, RT30 noted significantly highest SOC stock of 11.87 Mg ha^{-1} over RT and CT treatments. The organic carbon stock in 0–60 cm soil depth was highest of 49.58 Mg ha^{-1} in RT30. The effect of RT and RT30 was clearly visible on increase in total SOC stock by 4 and 9.6%, respectively, over CT. In the surface layer, higher organic C was recorded in treatments that adopted conservation agriculture, and it could be attributed to high amount of crop residue retention after every crop and less physical disturbance of soil due to reduced tillage. Crop residues retention could have provided greater SOM input, and therefore increase in SOC concentration was restricted in the upper two layers only (Du et al. 2013). Roper et al. (2013) reported that residue addition slowed down the decomposition rate of binding agent by reducing contact between organic matter and soil microorganisms.

The rice–maize cropping system recorded the highest SOC stock of 15.11 Mg ha^{-1} in the surface soil and found nonsignificant among the cropping systems. The cropping systems did not show significant difference in organic carbon throughout the soil depth. The total SOC stock in 0–60 cm soil depth was highest of 47.93 Mg ha^{-1}

Table 4 Effect of tillage practices and cropping systems on soil organic C stock, total SOC stock and C sequestration rate (Mean \pm SD)

Treatments	Soil Org C Stock (Mg ha ⁻¹)				Total SOC stock (Mg ha ⁻¹)	C sequestration rate (Mg ha ⁻¹ year ⁻¹)
	Soil depth (cm)					
	0–15	15–30	30–45	45–60		
<i>Tillage practices</i>						
Conventional tillage (CT)	13.44 \pm 0.67 ^C	11.10 \pm 0.55 ^A	10.47 \pm 0.46 ^B	10.18 \pm 0.67 ^A	45.20 \pm 1.22 ^C	0.26 \pm 0.41 ^C
Reduced tillage (RT)	14.82 \pm 1.04 ^B	11.56 \pm 1.02 ^A	10.52 \pm 0.92 ^B	10.11 \pm 0.72 ^A	47.01 \pm 1.8 ^B	0.86 \pm 0.6 ^B
Reduced tillage with 30% residue (RT30)	15.93 \pm 1.48 ^A	11.77 \pm 0.57 ^A	11.87 \pm 0.66 ^A	10.00 \pm 0.71 ^A	49.58 \pm 1.74 ^A	1.72 \pm 0.58 ^A
<i>Cropping systems</i>						
Rice–wheat (RW)	14.53 \pm 1.52 ^A	11.61 \pm 1.01 ^A	11.18 \pm 0.85 ^A	9.91 \pm 0.64 ^A	47.23 \pm 2.59 ^A	0.94 \pm 0.86 ^A
Rice–maize (RM)	15.11 \pm 1.97 ^A	11.38 \pm 0.61 ^A	11.04 \pm 0.98 ^A	10.40 \pm 0.73 ^A	47.93 \pm 2.67 ^A	1.17 \pm 0.89 ^A
Rice–lentil (RL)	14.56 \pm 0.89 ^A	11.44 \pm 0.73 ^A	10.65 \pm 1.03 ^A	9.99 \pm 0.63 ^A	46.63 \pm 1.98 ^A	0.74 \pm 0.66 ^A
<i>Interactions</i>						
CT-RW	13.39 \pm 0.58 ^d	10.64 \pm 0.41 ^c	10.53 \pm 0.43 ^{bcd}	9.73 \pm 0.54 ^a	44.30 \pm 1 ^d	-0.04 \pm 0.33 ^d
CT-RM	12.97 \pm 0.78 ^d	11.60 \pm 0.51 ^{abc}	10.46 \pm 0.49 ^{cd}	10.52 \pm 0.68 ^a	45.56 \pm 0.98 ^{cd}	0.38 \pm 0.33 ^{cd}
CT-RL	13.97 \pm 0.33 ^{cd}	11.05 \pm 0.32 ^{abc}	10.43 \pm 0.63 ^{cd}	10.29 \pm 0.76 ^a	45.74 \pm 1.47 ^{cd}	0.44 \pm 0.49 ^{cd}
RT-RW	14.03 \pm 0.75 ^{cd}	12.22 \pm 1.07 ^a	11.35 \pm 0.73 ^{abc}	9.77 \pm 0.59 ^a	47.38 \pm 0.64 ^{bc}	0.99 \pm 0.21 ^{bc}
RT-RM	15.26 \pm 1.15 ^{bc}	10.78 \pm 0.38 ^{bc}	10.48 \pm 0.55 ^{cd}	10.71 \pm 0.55 ^a	47.22 \pm 1.98 ^{bc}	0.93 \pm 0.66 ^{bc}
RT-RL	15.17 \pm 1.02 ^{bc}	11.67 \pm 1.14 ^{abc}	9.74 \pm 0.79 ^d	9.86 \pm 0.78 ^a	46.44 \pm 2.82 ^{cd}	0.67 \pm 0.94 ^{cd}
RT30-RW	16.18 \pm 1.39 ^{ab}	11.96 \pm 0.77 ^{ab}	11.66 \pm 1.08 ^{abc}	10.22 \pm 0.89 ^a	50.03 \pm 0.88 ^{ab}	1.87 \pm 0.29 ^{ab}
RT30-RM	17.09 \pm 0.86 ^a	11.76 \pm 0.50 ^{abc}	12.19 \pm 0.57 ^a	9.96 \pm 0.95 ^a	51.00 \pm 0.41 ^a	2.19 \pm 0.14 ^a
RT30-RL	14.53 \pm 0.98 ^{bcd}	11.59 \pm 0.60 ^{abc}	11.77 \pm 0.19 ^{ab}	9.82 \pm 0.44 ^a	47.71 \pm 1.59 ^{bc}	1.10 \pm 0.53 ^{bc}

Within a column means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan multiple range test

in rice–maize cropping system but found nonsignificant among the cropping systems.

Comparing the interaction effect, it was observed that in most of the cases, the SOC stock gradually decreased with increasing soil depth. In the surface soil (0–15 cm), the RT and RT30 in combination with all cropping systems showed higher SOC stock over their corresponding CT. In the surface soil layer, the highest (17.1 Mg ha⁻¹) and lowest (13.0 Mg ha⁻¹) SOC stock was observed in rice–maize cropping system under RT30 and CT, respectively. Similarly, in subsurface soil layer (15–30 cm), RT-RW recorded highest SOC stock of 12.22 Mg ha⁻¹, which was at par with other tillage practice and cropping system combinations except RT-RM and CT-RW. In 30–45 cm soil depth, RT30 registered highest SOC stock of 12.19 Mg ha⁻¹ under rice–maize cropping system, which was at par with other cropping system combination (RT30-RL and RT30- RW) but it was significantly highest over the other tillage practice with cropping system combination (CT-RW, CT-RM, CT-RL, RT-RL and RT-RM). However, in the lower depth (45–60 cm), the total SOC stock was found nonsignificant. The rice–maize cropping system under RT30 registered highest total SOC stock of 51.0 Mg ha⁻¹, while lowest SOC stock was recorded in CT-RW (44.3 Mg ha⁻¹). A higher amount of organic carbon in RT30-RM could be attributed to the higher amount of biomass added after maize crop, and it was in agreement

with Du et al. (2013) who observed an improvement in SOC stock depends on amount and placement depth.

C sequestration rate in CT (0.26 Mg ha⁻¹ year⁻¹) was significantly lower than RT (0.86 Mg ha⁻¹ year⁻¹) and RT30 (1.72 Mg ha⁻¹ year⁻¹). Soil processes that control C sequestration are strongly affected by climate. Some studies in temperate regions of the world reported that SOC stabilization is slower in arid regions compared to humid climatic conditions (Six et al. 2004). Our results showed higher organic C stock in reduce tilled and residue treated plots compared to the conventional one. It was due to retention of higher amount of crop residue, non-disturbance of surface soil and resulting higher soil moisture, which helps in slow decomposition of added residues (Balesdent et al. 2000). Long-term studies have shown that higher C input does not necessarily increase soil C stock (Stewart et al. 2007), and the efficiency of SOM stabilization decreases in soils with high C levels compared to soils with lower C levels under the same management practices. In case of cropping system, greater sequestration of SOC in RM and RW than RL system was probably linked to amount of organic residues added after each cropping cycle. The interaction of RT30 with rice–maize cropping system recorded significantly highest C sequestration rate of 2.2 Mg ha⁻¹ year⁻¹ over all other treatment combinations except with RT30-RW. Higher C sequestration rate in RT30 could be attributed to the more

organic input and less physical disturbance leading to higher SOC deposition.

Bulk density

The BD of the soil showed significant differences among the different tillage practices in the soil depth of 0–15 and 30–45 cm. The surface soil showed higher BD of 1.50 Mg m⁻³ in RT and RT30 and was significantly higher over the CT, while CT showed significantly higher BD of 1.53 Mg m⁻³ over RT and RT30 in 30–45 cm soil depth. The cropping systems did not show significant difference in

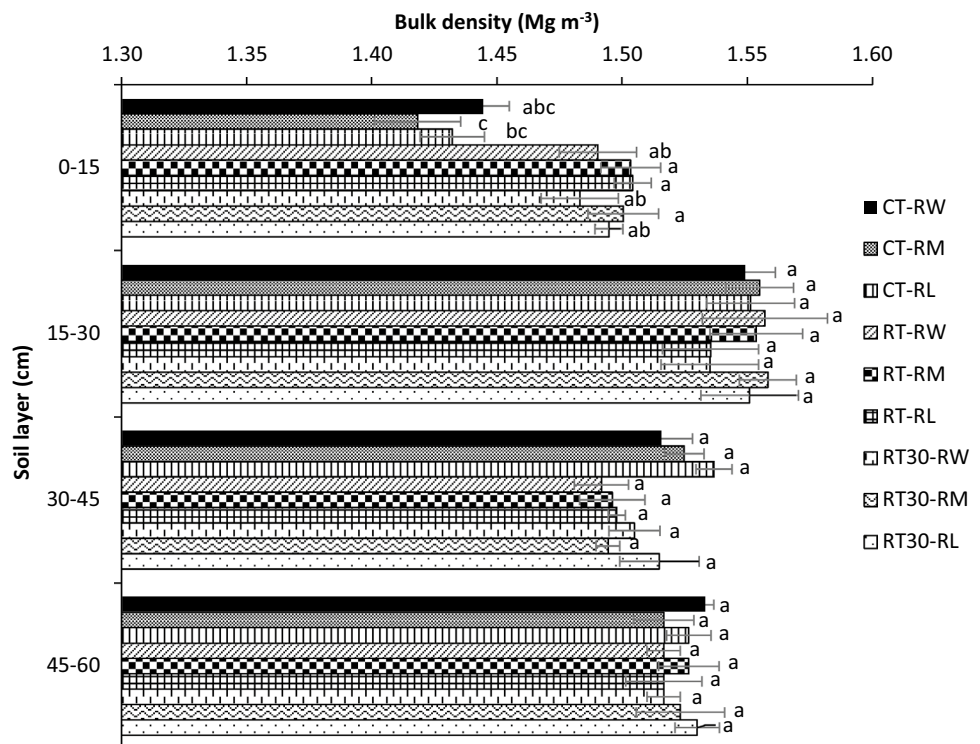
BD among themselves throughout the soil depth of 0–60 cm (Table 5). Comparing the interaction effect of tillage practices and cropping systems, the highest variation in BD value was registered in the upper 0–15 cm soil layer. The interaction effect between cropping systems and tillage practices was nonsignificant (Fig. 3). Irrespective of tillage and cropping management, all the treatment combinations showed higher BD values in the second layer than their upper and lower layer values. In the second layer (15–30 cm), no consistent trend in BD was observed among the treatments. Further down the layer, no significant differences were observed among the treatments.

Table 5 Mean effect of tillage practices and cropping systems on soil bulk density (Mean ± SD)

Treatments	Bulk density (Mg m ⁻³)			
	Soil depth (cm)			
	0–15	15–30	30–45	45–60
<i>Tillage practices</i>				
Conventional tillage (CT)	1.43 ± 0.024 ^b	1.55 ± 0.022 ^a	1.53 ± 0.017 ^a	1.53 ± 0.015 ^a
Reduced tillage (RT)	1.50 ± 0.019 ^a	1.55 ± 0.033 ^a	1.50 ± 0.020 ^b	1.52 ± 0.015 ^a
Reduced tillage with 30% residue (RT30)	1.49 ± 0.020 ^a	1.55 ± 0.028 ^a	1.50 ± 0.013 ^b	1.52 ± 0.022 ^a
<i>Cropping systems</i>				
Rice–wheat (RW)	1.47 ± 0.030 ^a	1.55 ± 0.031 ^a	1.50 ± 0.020 ^a	1.52 ± 0.012 ^a
Rice–maize (RM)	1.47 ± 0.047 ^a	1.56 ± 0.022 ^a	1.51 ± 0.020 ^a	1.52 ± 0.022 ^a
Rice–lentil (RL)	1.48 ± 0.037 ^a	1.55 ± 0.029 ^a	1.52 ± 0.023 ^a	1.52 ± 0.018 ^a

Within a column means followed by the same letter are not significantly different at $p \leq 0.05$ by Duncan multiple range test

Fig. 3 Interaction effect of tillage practices and cropping systems on bulk density of soil. Error bars indicate ± standard error. Bars followed by different small letters in a particular depth are significantly different at $p \leq 0.05$



The noticeable differences in BD values under different treatments were due to different tillage and cropping management practices. In the surface layer, lower BD values in treatments receiving CT was due to seasonal disturbance of soil by conventional tillage, while RT (reduced and zero tillage during rice and winter crop cultivation, respectively) resulted in compaction of surface layer and higher BD values in treatments where conservation agricultural practices were followed (RT and RT30). A similar observation was reported by several researchers (Alvarez and Steinbach 2009; Mondal et al. 2013). Except surface layer, no significant differences among the treatments could be attributed to insensitivity of BD toward soil management like tillage (Mondal et al. 2019) and higher replication variation due to heterogeneity of soil.

Soil infiltration rate

The soil infiltration rate in tillage and cropping systems management followed a nonlinear (power function) relationship against time. The rate showed a sharp decrease initially followed by a gradual change and attained the final steady state value which differed significantly among the treatments (Fig. 4). The initial intake rate was significantly higher (58%, $p < 0.05$) in RL cropping system (34.37 mm h^{-1}) in comparison with RW system (21.71 mm h^{-1}) but was nonsignificant with RM system (33.39 mm h^{-1}). The final infiltration rate in RL (4.86 mm h^{-1}) was as high as 2.74 times higher compared to RM (1.77 mm h^{-1}) and 3.33 times higher compared to RW (1.46 mm h^{-1}). The tillage practices RT30 registered significantly higher initial (41.56 mm h^{-1}) and final (2.28 mm h^{-1}) infiltration rate over CT but was nonsignificant with RT. The interaction of cropping systems and tillage practices on initial and final infiltration rates was nonsignificant (data not presented).

The large difference in initial infiltration rate in RL cropping system and RT30 was possibly attributed to a more open structure on surface soil caused by no irrigation in lentil and less structural destruction due to residue retention, respectively. However, the final infiltration rate, which is certainly profile controlled, was also high in reduced tillage plots. This might be attributed to abundance of macro-pores as well as the continuity of pores due to less disturbance of soil in no tillage. These open and continuous macro-pores are the major conduits of water flow. The breakdown of pore continuity, as well as larger proportion of micro-pores in conventional tillage practices, could significantly decrease the infiltration rate. Nevertheless, the standing crop stubble remaining in RT and RT30 field induced a vertical mulching effect, resulting in greater water infiltration than CT (Govaerts et al. 2007). As a cumulative effect, infiltration is improved, and the risk of run-off and soil erosion is controlled (Blanco-Canqui and Lal 2008).

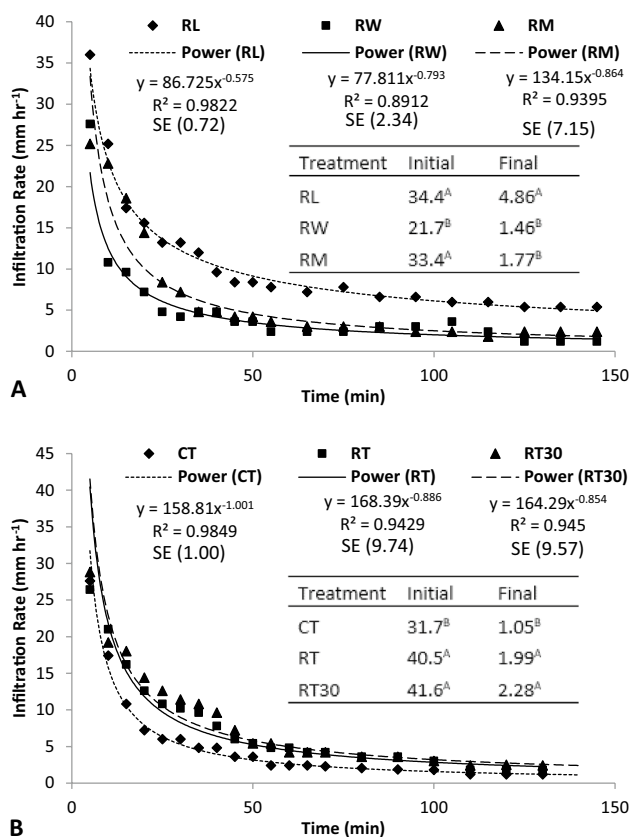


Fig. 4 Soil infiltration rate as affected by **a** cropping systems (averaged over tillage practices) and **b** tillage practices (averaged over cropping systems)

Conclusions

Conservation agriculture is gaining importance day by day due to its beneficial effect on soil health and sustainability of productivity besides environmental benefits. Our results showed that the retention of crop residues and reduced tillage could significantly improve the soil physical health and organic carbon status. It also reveals that macroaggregate contains maximum amount of organic carbon and plays major role in carbon sequestration. Physical properties of soil, viz. bulk density, soil aggregation, infiltration rate, have changed in a direction that was consistent with soil fertility. The short-term effect of different tillage and cropping systems was mostly limited to upper soil layer only. Long-term experiments needed to be carried out to observe the changes in organic carbon and soil physical properties due to tillage and cropping systems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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