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Effect of contrasting tillage and cropping systems on soil aggregation, carbon pools and aggregate-associated carbon in rainfed Vertisols

J. Somasundaram[a], R. S. Chaudhary[a], D. Awanish Kumar[a], A. K. Biswas[a], N. K. Sinha[a], M. Mohanty[a], K. M. Hati[a], P. Jha[a], M. Sankar[b], A. K. Patra[a], R. Dalal[c] & S. K. Chaudhari[d]

[a]*ICAR- Indian Institute of Soil Science, Nabibagh, Berasia Road, Bhopal, 462038, India,* [b]*ICAR-Indian Institute of Soil and Water Conservation Research, Kaulagarh Road, Dehradun, 248195, India,* [c]*School of Agriculture and Food Sciences, The University of Queensland, St Lucia, QLD 4072, Australia, and* [d]*Indian Council of Agricultural Research, KAB-II, Pusa Campus, New Delhi, 110012, India*

Summary

Worldwide, conservation agriculture practices involving minimal soil disturbances and retention of crop residue (>30%) have been practised increasingly and recognized to enhance soil health by optimizing key soil attributes. However, little information is available on the short-term effects of conservation agriculture practices on soil properties under rainfed Vertisols of Central India. Thus, our aim was to study the short-term effects of contrasting tillage treatments and cropping systems on soil aggregation, aggregate-associated carbon (C), carbon pools and crop productivity. This study comprised three tillage systems (TS), reduced tillage (RT), no tillage (NT) with retention of crop residue and conventional tillage (CT), together with four cropping systems (CS), namely soya bean (*Glycine max* L.) + pigeon pea (*Cajanus cajan* L.) (2:1), soya bean–wheat (*Titricum durum* L.), maize (*Zea mays* L.) + pigeon pea (1:1), and maize–chickpea *Cicer arietinum* L.). The experiment was laid out in a split-plot design with three replicates. Soil samples were collected at four depths: 0–5, 5–15, 15–30 and 30–45 cm from the experimental field after completion of four crop cycles. Results indicated that at depths 0–5 and 5–15 cm, tillage and cropping system had a significant effect on aggregate mean weight diameter (MWD). The MWDs of 0.97 and 0.94 mm were larger for NT than CT (0.77 and 0.83 mm) at 0–5- and 5–15-cm depths, respectively. Water-stable aggregates (WSAs) were also larger for NT (70.74%) and RT (70.09%) than CT (59.50%) at 0–5 cm. Tillage practice, cropping system and their interaction had a greater effect ($P < 0.05$) on the content of aggregate-associated C for large macroaggregates (LM). There was more aggregate-associated C for NT and RT at 0–5-cm depth than for CT. Cropping system also had a significant effect ($P < 0.05$) on aggregate-associated C at 0–5-cm depth. Soil organic C (%) fractions were in the order of non-labile >very labile >less labile >labile for 0–5- and 5–15-cm depths after four crop cycles. Less labile and non-labile C fractions contributed >50% of TOC, indicating a more recalcitrant form of carbon present in the soil. Tillage had no significant effect ($P > 0.05$) on crop yields after four crop cycles. Conservation agriculture can have a positive effect on aggregate stability, aggregate-associated C and different carbon pools in a Vertisol.

Highlights

- Does conservation agriculture affect soil aggregation, aggregate stability and carbon pools more than conventional tillage?
- The SOC concentration increases with aggregate size and provides physical protection and stabilization of carbon (C).
- Aggregate-associated C content was significantly affected by tillage practices and cropping system.
- Less labile and non-labile C fractions contribute >50% TOC in the rainfed Vertisols of central India.

Correspondence: J. Somasundaram. E-mail: somajayaraman@gmail.com
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Introduction

Agriculture is the mainstay of the Indian economy, with about 60% of the population residing in rural areas either primarily or secondarily associated with farming for their sustenance and monetary support. With the dawn of the green revolution in the late 1970s, India has made major progress in food security, poverty reduction and per capita income. However, agricultural intensification in the form of intensive, inversion tillage-based production systems has led to an adverse effect on natural resources, namely soil, water, biodiversity and the associated ecosystem services provided by nature. Consequently, land degradation has resulted in decreased crop yields as well as total-factor productivity. A classic example has been the marked decline and degradation of soil organic carbon (SOC), mainly ascribed to changes in land use and management practices. Guo & Gifford (2002) reviewed 74 publications and inferred that SOC stocks declined markedly because of changes in land use (from pasture or native forest to plantations (−10 to −13%), and native forest or pasture to crop (−42 to −59%)), but increased from native forest to pasture (+8%), crop to pasture (+19%), crop to plantation or secondary plantation (+18 to +53%). Briedis *et al.* (2018) also observed that the reduction in C stocks of labile fractions at 0–5-cm depth by changing land use from natural vegetation (NV) to conventional tillage (CT) was about 72–89% of total C in the soil of subtropical Brazil. However, these labile fractions were restored by 12–89% at the same site with the adoption of no tillage (NT) compared with CT.

Tillage is a key factor that has a strong control on soil physical properties and biogeochemical cycles. Conventional tillage (CT) can affect physical, chemical and biological properties of soil, thus affecting soil productivity and sustainability (Palm *et al.*, 2014). Frequent disturbances of the soil through CT enhance oxidation of soil organic matter, weaken soil aggregate stability and increase soil erosion (Guo *et al.,* 2015). The above scenario has forced farmers, scientists and land managers to search for an alternative approach that is ecologically sustainable as well as economically profitable (Palm *et al.*, 2014).

The concept of conservation agriculture (CA) has emerged as a sustainable approach for greater agricultural production and profitability and for mitigating adverse effects of climate change. Conservation agriculture has often been regarded as a set of management principles to enhance efficiency of water and nutrient use, decrease soil erosion and conserve natural resources (i.e. a farmer's time and labour and fossils fuels) (Hobbs, 2007). Conservation agriculture has been encouraged to improve soil aggregation and increase infiltration, thereby reducing soil erosion, soil and water conservation, C sequestration and reduction in soil compaction (Govaerts *et al.*, 2009).

No tillage (NT), a component of CA, reduces carbon loss from soil by water erosion (Müller-Nedebock & Chaplot, 2015) and delays the decomposition of soil organic matter. In a meta-analysis of 41 research studies worldwide, Mhazo *et al.* (2016) showed that sediment concentration and soil losses were 56 and 60% smaller under NT than CT, respectively. Differences in sediment concentration and soil losses for NT and CT were greater in soil with little clay and under temperate climates. Moreover, NT decreased the runoff (R) coefficient by about 40% compared with CT in mulched soils under a cool climate, whereas crop residues did not reduce runoff.

There was a worldwide expansion of NT during the late 1990s, supported by the use of new herbicide molecules and better NT technologies (Derpsch *et al.*, 2010). The above suggests that all three key principles of CA should be applied simultaneously to get maximum benefits; if applied in isolation they might not help farmers to maintain crop yield and profitability (Pittelkow *et al.*, 2014).

The CA practices have been developed successfully for many different regions of the world (Palm *et al.,* 2014). In the Indian subcontinent CA is prevalent mainly under rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) management on 10.5 M ha in the Indo-Gangetic Plain. The large-scale adoption of CA might not only increase SOC in the soil, but also: (i) help to mitigate emissions of greenhouse gases that contribute to global warming and (ii) reduce SOC loss and decomposition, improve soil productivity and reduce environmental damage and degradation from the existing unsustainable inversion tillage systems. The latter, in general, adversely affect water quality, reduce soil biodiversity and increase soil erosion at the larger scale. Conservation agriculture can improve productivity in the long term. Guo *et al.* (2015) reported that short-term effects of NT increased microbial biomass C significantly (20%) compared with CT, but did not affect concentrations of total organic C (TOC), dissolved organic C (DOC), easily oxidizable C (EOC) and SOC of aggregates. Larger amounts of SOC in macroaggregates (2–1 mm) were related to changes in the composition of soil microbial groups, suggesting that these aggregate fractions were sensitive to changes in composition of the soil microbial community related to short-term conservation management practices. Moreover, Briedis *et al.* (2018) reported that apparently all C fractions were affected by different soil management systems, but the effect was greater for the labile than mineral-associated C fractions.

Chen *et al.* (2009) indicated that carbon input can be enhanced and decomposition decreased by residue management and conservation tillage. Crop residues play crucial roles in enhancing organic C sequestration, moderating soil temperature and conserving soil moisture in CA. They protect the soil surface, enhance infiltration and reduce the rates of runoff and soil erosion (Mchunu *et al.,* 2011), reduce water loss by surface evaporation, and provide substrate for the activity of soil microorganisms and a source of SOC (Six *et al.,* 2000a). It is well known that TOC requires a long period (i.e. >5 years) to react to residue management because of its slower turnover rate and larger soil organic C pool (West & Post, 2002). Labile organic-C fractions, namely MBC and DOC contents, however, can respond more rapidly to soil management practices than TOC (Haynes, 2005; Guo *et al.*, 2015). These labile C fractions also play a crucial role in the priming effect in soil (Liu *et al.*, 2017). A larger labile-C pool has been observed under NT at 0–10-cm depth, which further plays a vital part in soil aggregation (Somasundaram *et al.*, 2017). Short- and medium-term conservation tillage have resulted in changes in SOC because of the large background C content and its temporal and spatial variation (Guo *et al.*, 2015). Long-term implementation of CA has been reported to increase organic matter and nutrient accumulations in topsoil (Somasundaram *et al.*, 2017). Retention of crop residues as a surface mulch increases soil aggregation more than if incorporated (Blanco-Canqui & Lal, 2009). He *et al.* (2009) concluded that NT with crop residue cover reduced bulk density (BD) at 0–30-cm depth, increased MWD, WSA and pore-size distribution, and enhanced the rate of infiltration. In CT frequent soil disturbance accelerates OM cycling, which reduces organic carbon, aggregation and mineral nitrogen (Lal, 2007). During the last six decades, the area under conservation agriculture, in particular reduced tillage (RT) and NT farming practices, has increased around the world (~156 M ha), whereas in the Indian subcontinent the spread of CA is <6.7 M ha of the arable land, especially in the rice–wheat belt (Parihar *et al.*, 2016).

Enhanced physical protection of C possibly provides ample time to reinforce the interaction between C fractions and soil minerals because it is considered a major pathway for C stabilization and accumulation in soil. Although there is much information on the long-term effects of conservation agriculture on soil aggregation, aggregate-associated C and carbon pools of the Indo Gangetic Plain (Bhattacharyya *et al.*, 2012; Parihar *et al.*, 2016) and temperate regions (Alvarez, 2005), there is little on the short-term effects of conservation tillage and retention of crop residues on soil properties and crop yields in Vertisols of central India. This present study aimed to provide information on the effects of short-term conservation management on SOC fractions. Long-term (>5 years) conservation agriculture is known to enhance SOC status and increase microbial biomass and activity (Govaerts *et al.*, 2007). Alvarez (2005) reported that the increase in SOC under RT and NT follows an S-shape time-dependent process, which reached a steady state after 25–30 years. The short-term effects of management on SOC fractions and composition of the microbial community are complex and depend on factors such as climate, soil type, crop rotation, crop residue additions and management practices.

Therefore, the present investigation aimed to (i) study the short-term effect of conservation agriculture on soil aggregation and water-stable aggregates compared with CT and (ii) study the aggregate-associated C, different C pools and crop yields under contrasting tillage and cropping systems in rainfed Vertisols of central India.

Materials and methods

Study site and soil sampling

The present investigation was on a Vertisol in central India at the Research Farm of ICAR-Indian Institute of Soil Science, Bhopal, India. The experimental site is at 23°18′N, 77°24′E and is 485 m above sea level. The climate of the area is a hot sub-humid type, with mean annual air temperature, mean annual rainfall and potential evapotranspiration of 25 °C, 1130 mm and 1400 mm, respectively. The soil of the experimental area is classified as a deep clayey Vertisol (Vertisol, Isohyperthermic Typic Haplustert) with 58% clay, 22% silt and 20% sand. The experimental soil had a pH of 8.17, electrical conductivity (EC) of 0.15 dS m^{-1}, organic carbon content of 0.59%, and available concentrations of nitrogen 257 kg ha^{-1}, phosphorus 19.5 kg ha^{-1} and potassium 576 kg ha^{-1} at 0–15-cm soil depth.

At the start of the experiment, the entire field was cross-ploughed with a duck foot cultivator and levelled using a laser land leveller for uniformity in the field with a gentle slope (<1%). The field experiment was started during August 2011 with three contrasting types of tillage, no tillage (NT), reduced tillage (RT) and conventional tillage (CT), in combination with four cropping systems to study their effect on soil properties and crop productivity under rainfed conditions. The experiment had a split-plot design with tillage system as the main plot (40-m long × 5-m wide) and cropping systems, soya bean (*Glycine max* L.) + pigeon pea (*Cajanus cajan* L.) (two rows of soya bean:one row of pigeon pea), soya bean (*Glycine max* L.)–wheat (*Titricum durum* L.), maize (*Zea mays* L.) + pigeon pea (*Cajanus cajan* L.) (one row of maize : one row of pigeon pea), and maize–chickpea (*Cicer arietinum* L.), as 10 m × 5 m subplots (Figure 1) and replicated three times. The CT consisted of deep summer ploughing after residue burning and three to four passes, including tine cultivation followed by sowing *kharif* (rainy season) and *rabi* (winter season) crops. The RT consisted of a one-pass tillage operation with a duck foot cultivator and sowing of *kharif* and *rabi* crops with a zero-till seed drill, and NT consisted of planting crops into undisturbed soil by opening a narrow slit of adequate width and depth to cover the seed. The detail of treatments is given in Table 1. The recommended doses of fertilizers (soya bean 30:26.4:24.9, pigeon pea 30:26.4:24.9, wheat 120:24.6:33.2, maize 120:24.6:33.2 and chickpea 40:26.4:24.9 of N: P: K kg ha^{-1}, respectively) were added to the soil during each cropping season.

Soil sampling and analysis

Soil samples were taken randomly from two to three locations of each treatment plot at the end of the fourth crop cycle at depths of 0–5, 5–15, 15–30 and 30–45 cm during April 2015 with a core sampler. At each depth there were 36 soil samples (3 tillage system × 4 cropping system × 3 replicates) and 144 in total. Sub-samples were taken separately from the bulk soil and passed through a 4-mm sieve. Soil retained on the 4-mm sieve was used to study aggregate stability and size distribution. The samples were air-dried, crushed and then passed through a 2-mm sieve after removing stones and large plant material for soil analysis. Aggregate-associated C was estimated from the soil retained by an array of sieves of different diameter after wet sieving and later dried at 45 °C in an oven. Oven-dried soil samples were grouped into large macroaggregates (>2000 μm), small macroaggregates (>125 μm), microaggregates (>53 μm) and silt + clay (<53 μm). After determining the size fractions, these samples were crushed to a uniform size of <250 μm for aggregate-C analysis.

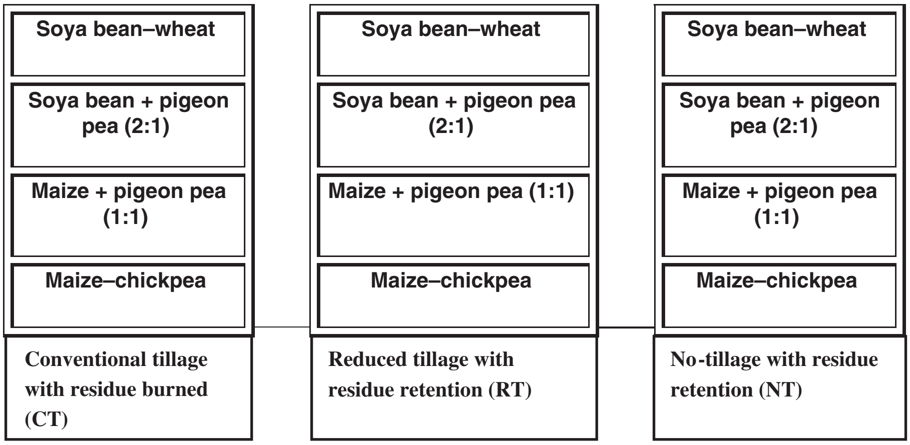

Figure 1 Layout of treatment details of one replication under different tillage systems.

Table 1 Contrasting tillage and cropping systems in Vertisols of central India

Tillage operations	Cropping system
Conventional tillage (CT): Farmers' practice: 3–4 tillage operations with duck foot or tine cultivator, residue removal during *kharif* (rainy season) and one-pass tillage with duck foot or tine cultivator followed by planting during *rabi* (winter season). Wheat straw burned under soya bean–wheat system, whereas for other cropping systems crops were harvested at 10–15 cm above ground level, which is similar to farmers' practice.	Soya bean + pigeon pea intercropping (2 rows of soya bean:1 row of pigeon pea) Soya bean–wheat Maize + pigeon pea intercropping (1 row of maize:1 row of pigeon pea) Maize–chickpea
Reduced tillage (RT): Is a form of conservation tillage; that is, tillage is reduced by half compared with CT during *kharif* (rainy season) (i.e. one-sweep tillage with duck foot cultivator followed by sowing or planting with a no-till planter), residue retained (>30% on soil surface), direct sowing during *rabi* (winter season) by no-till seed drill. Crops (maize, pigeon pea and wheat) were harvested leaving crop residue approximately 30–40 cm above the ground surface, simulating a combine harvester used in mechanized farming.	Soya bean + pigeon pea intercropping (2 rows of soya bean:1 row of pigeon pea) Soya bean–wheat Maize + pigeon pea intercropping (1:1) Maize–chickpea
No tillage (NT): Residue retention >30% on soil surface. Direct sowing by no-till seed drill during *kharif* and *rabi* seasons. Weeds are controlled by herbicide application. Crops (maize, pigeon pea and wheat) were harvested leaving crop residue approximately 30–40 cm above the ground surface, simulating a combine harvester used in mechanized farming.	Soya bean + pigeon pea intercropping (2 rows of soya bean:1 row of pigeon pea) Soya bean–wheat Maize + pigeon pea intercropping (1:1) Maize–chickpea

Soya bean (*Glycine max* L.), Pigeon pea (*Cajanus cajan* L.), Wheat (*Titricum durum* L.), Maize (*Zea mays* L.), Chickpea (*Cicer arietinum* L.)

The water-stable aggregates of the soil were determined by wet sieving (Kemper & Rosenau, 1986) and the MWD was calculated by the formula of van Bavel (1949). Water-stable aggregates >250 μm in diameter retained on sieves were expressed as percent water-stable aggregates (Kemper & Rosenau, 1986) taking a sand correction into consideration (Elliott, 1986). The organic carbon (OC) in bulk soil was analysed by the wet digestion method of Walkley & Black (1934). The fractions of organic carbon (i.e. different OC pools) were determined by a modified Walkley–Black method proposed by Chan *et al.* (2001). The analysis of oxidizable carbon was carried out with 5 and 10 ml of concentrated sulphuric acid (H_2SO_4, 18 M) instead of the 20 ml indicated by Walkley & Black (1934). The resulting three ratios of acid–aqueous solution, such as 0.5:1, 1:1 and 2:1 (which corresponded to 6 M, 9 M and 12 M H_2SO_4, respectively), were used to compare different amounts of oxidizable organic carbon extracted under an increasing oxidizing environment (Walkley, 1947). These four fractions represent various pools of organic carbon: (i) very labile carbon (Fraction 1), organic carbon oxidizible under 6 M H_2SO_4, (ii) labile carbon (Fraction 2), the difference in oxidizible organic carbon extracted between 9 M and 6 M H_2SO_4, (iii) less labile carbon (Fraction 3), oxidizible organic C analysed between 12 M and 9 M H_2SO_4 (12 M H_2SO_4 typically represents carbon analysed by the Walkley–Black method) and (iv) non-labile carbon (Fraction 4), residual organic carbon after reaction with 12 M H_2SO_4 compared with the total carbon estimated by the TOC analyser (Shimadzu 5000 VA, Kyoto, Japan).

Table 2 Mean weight diameter (MWD) and water-stable aggregates (WSA) in post-harvest soils after four crop cycles

		MWD / mm					WSA / %				
		Soil depths / cm									
Tillage (TS)	Cropping system	0–5	5–15	15–30	30–45	Mean	0–5	5–15	15–30	30–45	Mean
CT	Soya bean + pigeon pea (2:1)	0.78	0.81	0.67	0.73	0.75	60.37	57.79	55.83	57.22	57.80
	Soya bean–wheat	0.75	0.88	0.75	0.68	0.77	58.81	60.16	55.87	56.33	57.79
	Maize + pigeon pea (1:1)	0.84	0.88	0.75	0.68	0.79	59.86	58.14	56.80	58.74	58.39
	Maize–chickpea	0.71	0.74	0.84	0.76	0.76	58.97	58.10	56.47	54.79	57.08
	Mean	0.77	0.83	0.75	0.71	0.77	59.50	58.55	56.24	56.77	57.77
RT	Soya bean + pigeon pea (2:1)	0.85	0.85	0.66	0.70	0.77	67.97	62.87	56.38	57.16	61.10
	Soya bean–wheat	0.97	0.98	0.74	0.70	0.85	71.36	63.43	58.32	57.20	62.58
	Maize + pigeon pea (1:1)	0.97	0.79	0.73	0.65	0.79	69.96	64.88	57.76	52.69	61.32
	Maize–chickpea	0.98	1.05	0.84	0.70	0.89	71.06	66.14	61.53	57.65	64.10
	Mean	0.94	0.92	0.74	0.69	0.82	70.09	64.33	58.50	56.17	62.27
NT	Soya bean + pigeon pea (2:1)	1.03	0.95	0.73	0.65	0.84	69.70	66.84	55.17	59.34	62.76
	Soya bean–wheat	0.96	0.97	0.81	0.70	0.86	71.04	60.98	58.57	58.87	62.37
	Maize + pigeon pea (1:1)	0.87	0.90	0.78	0.76	0.83	70.06	63.56	58.03	56.08	61.93
	Maize–chickpea	1.03	0.95	0.82	0.72	0.88	72.14	67.16	60.94	54.12	63.59
	Mean	0.97	0.94	0.79	0.71	0.85	70.74	64.64	58.18	57.10	62.67
LSD $_{\text{Tillage (0.05)}}$					0.024						2.65
LSD $_{\text{Cropping system (0.05)}}$					0.030						1.33
LSD $_{\text{Depth (0.05)}}$					0.024						1.25

NT, no tillage; CT, conventional tillage; RT, reduced tillage; TS, tillage system.

Crop yield

Crops were harvested at maturity and yield properties were recorded at the end of four crop cycles. Crop yields were converted into soya bean grain equivalent yield (SGEY, $\mathrm{q\,ha^{-1}}$) by considering the minimum support price (MSP) of 2015–2016 of the Indian market (MSP in Indian Rupee Rate $\mathrm{quintal^{-1}}$): soya bean 2240 $\mathrm{quintal^{-1}}$, maize 1175 $\mathrm{quintal^{-1}}$, pigeon pea 3850 $\mathrm{quintal^{-1}}$, wheat 1525 $\mathrm{quintal^{-1}}$, chickpea 3425 $\mathrm{quintal^{-1}}$.

Statistical analysis

Soil aggregates, organic carbon pools and aggregate-associated carbon C were analysed with a split-plot design and yield data were analysed with a split-plot analysis of variance (ANOVA) using ssp.plot () of the agricolae package in the R statistical package. The assumptions of ANOVA (normal distribution of the residuals and equality of variances) were tested graphically. Means for the treatments were compared with Fisher's least significance difference (LSD) at $P < 0.05$. Pearson's correlation (r) analysis was carried out to determine the relations among the variables, such as SOC, MWD, WSA and aggregate-associated C.

Results

Effect of tillage and cropping systems on soil aggregation

Soil aggregation in terms of MWD decreased with increasing soil depth with little variation across the different tillage systems. Tillage, cropping system and soil depth had a significant effect ($P < 0.05$) on MWD. In addition, we observed that MWD was affected significantly by the interactive effect of tillage • cropping system • soil depth (Tables 2 and 3). Compared with CT, cropping systems under RT and NT had larger MWD at 0–5-cm depth and the largest MWD was for maize–chickpea and soya bean + pigeon pea (2:1) under no tillage (NT). The latter had significantly ($P < 0.05$) larger MWD of 0.97 and 0.94 mm than CT (0.77 and 0.83 mm) for the 0–5- and 5–15–cm depths, respectively. Similarly, RT had significantly ($P < 0.05$) larger MWD of 0.94 and 0.92 mm than for CT at 0–5- and 5–15-cm depths, respectively. The smallest MWD was recorded for CT (0.77 mm) at 0–5-cm depth. Similar trends were observed at lower depths (i.e. 15–30 and 30–45 cm).

Effect of tillage and cropping system on aggregate stability

Water stable aggregates (WSA, %) were significantly ($P < 0.01$) affected by tillage and soil depth and their interactions (Tables 2 and 3). The mean values for WSA across tillage systems showed that NT (70.74%) and RT (70.09%) had significantly larger ($P < 0.01$) WSA than under CT (59.50%) at 0–5-cm depth. Cropping systems had no significant effect on WSA at 0–5- and 5–15-cm depths. Across tillage and cropping systems, the largest WSA (%) was for maize–chickpea at 0–5- and 5–15-cm depths. For tillage, WSA (%) was in the order NT > RT > CT for all depths. The interactions of tillage system

Table 3 Summary of analysis of variance (ANOVA) for selected soil properties under contrasting tillage and cropping systems in a Vertisol

			Aggregate-associated C			
	MWD	WSA	LM-C	SM-C	M-C	S + C-C
Treatments	*P* value					
Tillage (T)	≤ 0.01	≤ 0.05	≤ 0.05	≤ 0.05	ns	ns
Cropping system (CS)	≤ 0.05	ns	≤ 0.001	≤ 0.05	ns	ns
Soil depth (D)	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001
T • CS	≤ 0.01	ns	≤ 0.05	≤ 0.05	ns	ns
T • D	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	ns	≤ 0.001
CS • D	≤ 0.05	ns	≤ 0.001	≤ 0.001	ns	ns
T • CS • D	≤ 0.001	ns	≤ 0.001	≤ 0.01	≤ 0.05	ns

LM-C, large macroaggregate carbon; SM-C, small macroaggregate carbon; M-C, microaggregate carbon; S + C-C, silt + clay carbon; C, carbon; ns, non-significant.

• cropping systems were not significant for WSA after four crop cycles.

Effect of tillage and cropping systems on aggregate-associated C in soil

The percentage of small macroaggregates (SM) was largest, followed by microaggregates (M), large macroaggregates (LM) and silt + clay (S + C) (Figure 2). At 0–5-cm depth, LM and M aggregates were significantly affected by tillage system. Small macroaggregates showed no significant effect among the tillage systems. At 5–15-cm depth, SM and M aggregates were significantly affected by tillage system, whereas LM and S + C were not. At depths 15–30 and 30–45 cm tillage had no significant effect on aggregate-size distribution.

The results showed that the aggregate-associated C content increased with aggregate size and it was in the following order of large macroaggregate (LM) > small macroaggregate (SM) > microaggregate (M) > silt + clay (S + C) in the soil samples. Overall, LM had the largest aggregate C and it decreased with decreasing size of aggregates. Tillage practices and cropping systems had a significant effect ($P < 0.05$) on aggregate-C for LM and SM, whereas soil depth had a significant effect on all aggregate-associated C. The interaction of tillage and depth was significant for LM-C and SM-C. We found that the interaction of tillage • cropping system • soil depth was significant for LM-, SM- and M-C. There was more LM aggregate-C for NT (0.65%) and RT (0.64%) at 0–5-cm depth than for CT (0.55%) (Tables 3 and 4).

Effect of tillage and cropping system on soil organic carbon pools

Differences between carbon fractions were larger at 0–5-cm depth. In general, trends of C fractions in Vertisols were in the order of non-labile (F4) > very labile (F1) > less labile (F3) > labile (F2) for 0–5- and 5–15-cm depths (Table 5; Figure 3). For lower

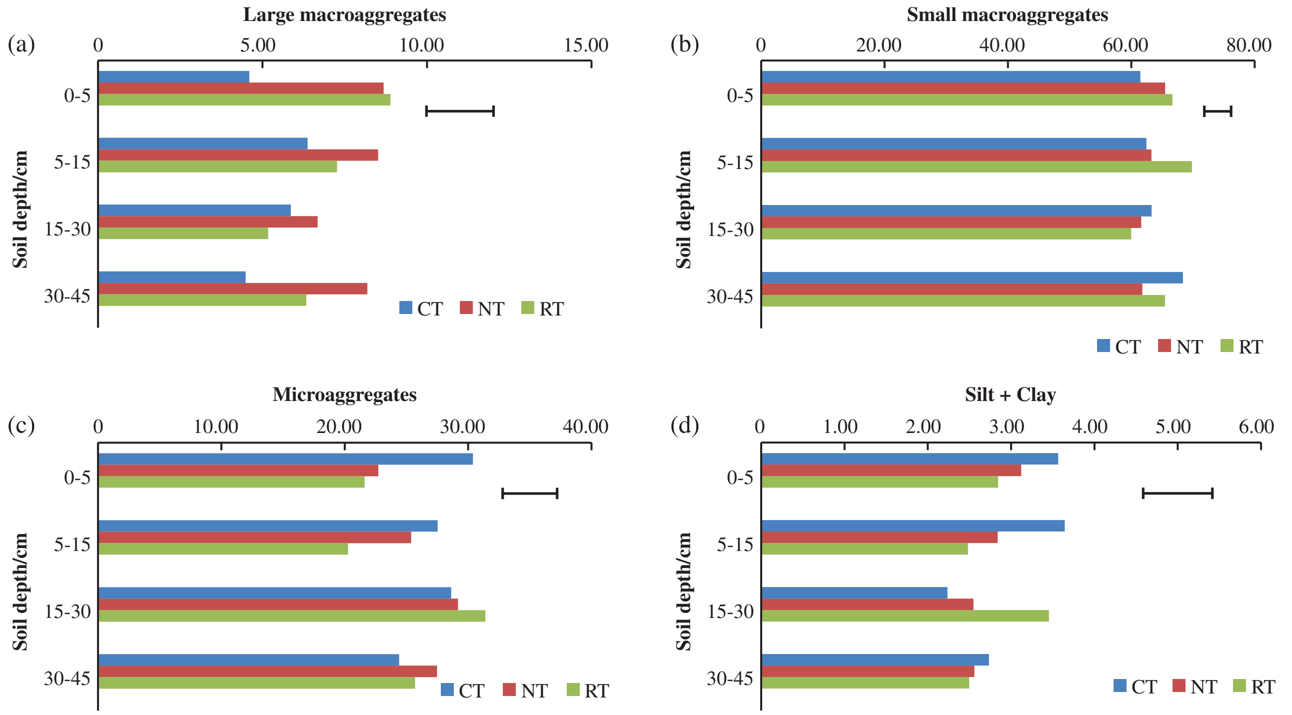

Figure 2 Aggregate-size distribution (%) for (a) large macroaggregates, (b) small macroaggregates, (c) microaggregates and (d) silt + clay at the depths examined under different tillage treatments. CT, conventional tillage; RT, reduced tillage; NT, no tillage (averaged over cropping system). Horizontal bar indicates $\text{LSD}_{\text{tillage.depth}}$ value at $P < 0.05$.

Table 4 Aggregate-associated C/% in soils under contrasting tillage and cropping systems after four crop cycles

		Aggregate associated C / %																			
	Cropping system	LM					SM					M					S + C				
		Depth / cm					Depth / cm					Depth / cm					Depth / cm				
Tillage (TS)		0–5	5–15	15–30	30–45	Mean	0–5	5–15	15–30	30–45	Mean	0–5	5–15	15–30	30–45	Mean	0–5	5–15	15–30	30–45	Mean
CT	Soya bean + pigeon pea (2:1)	0.52	0.46	0.44	0.36	0.45	0.48	0.42	0.35	0.31	0.39	0.49	0.39	0.39	0.34	0.40	0.44	0.37	0.34	0.30	0.36
	Soya bean–wheat	0.58	0.52	0.49	0.41	0.50	0.49	0.46	0.37	0.32	0.41	0.44	0.43	0.39	0.34	0.40	0.44	0.41	0.38	0.33	0.39
	Maize + pigeon pea (1:1)	0.56	0.51	0.46	0.37	0.48	0.52	0.48	0.41	0.37	0.45	0.44	0.42	0.38	0.35	0.40	0.44	0.38	0.35	0.30	0.37
	Maize–chickpea	0.54	0.46	0.44	0.40	0.46	0.56	0.46	0.38	0.34	0.44	0.44	0.37	0.34	0.29	0.36	0.41	0.36	0.35	0.31	0.36
	Mean	0.55	0.49	0.46	0.38	0.47	0.51	0.45	0.38	0.33	0.42	0.46	0.40	0.37	0.33	0.39	0.44	0.38	0.35	0.31	0.37
RT	Soya bean + pigeon pea (2:1)	0.61	0.49	0.46	0.40	0.49	0.60	0.43	0.38	0.36	0.44	0.50	0.39	0.34	0.29	0.38	0.48	0.38	0.34	0.32	0.38
	Soya bean–wheat	0.61	0.50	0.45	0.40	0.49	0.54	0.46	0.41	0.33	0.44	0.44	0.41	0.33	0.32	0.38	0.45	0.37	0.33	0.27	0.36
	Maize + pigeon pea (1:1)	0.62	0.57	0.36	0.32	0.47	0.49	0.40	0.38	0.33	0.40	0.42	0.41	0.38	0.33	0.39	0.46	0.40	0.37	0.28	0.38
	Maize–chickpea	0.70	0.55	0.45	0.42	0.53	0.59	0.50	0.45	0.37	0.48	0.50	0.43	0.40	0.36	0.42	0.45	0.38	0.30	0.27	0.35
	Mean	0.64	0.53	0.43	0.39	0.50	0.55	0.45	0.41	0.35	0.44	0.47	0.41	0.36	0.32	0.39	0.46	0.38	0.34	0.28	0.37
NT	Soya bean + pigeon pea (2:1)	0.60	0.52	0.45	0.39	0.49	0.55	0.42	0.38	0.34	0.42	0.42	0.37	0.37	0.32	0.37	0.47	0.40	0.33	0.31	0.38
	Soya bean–wheat	0.72	0.63	0.53	0.32	0.55	0.63	0.52	0.40	0.33	0.47	0.53	0.41	0.36	0.35	0.41	0.45	0.43	0.36	0.31	0.39
	Maize + pigeon pea (1:1)	0.62	0.48	0.42	0.38	0.48	0.58	0.52	0.47	0.33	0.48	0.46	0.42	0.39	0.35	0.41	0.44	0.39	0.33	0.29	0.36
	Maize–chickpea	0.68	0.58	0.43	0.36	0.51	0.60	0.58	0.39	0.33	0.48	0.45	0.43	0.39	0.35	0.41	0.43	0.39	0.34	0.32	0.37
	Mean	0.65	0.55	0.46	0.36	0.51	0.59	0.51	0.41	0.33	0.46	0.47	0.41	0.38	0.34	0.40	0.45	0.4	0.34	0.31	0.38
	LSD aggregate-C (*P* 0.05)	LM					SM					M					S + C				
	LSD $_{\text{Tillage (0.05)}}$	0.0266					0.0220					0.0356					0.0449				
	LSD $_{\text{Cropping system (0.05)}}$	0.02013					0.0250					0.0280					0.2010				
	LSD $_{\text{Depth (0.05)}}$	0.0117					0.0133					0.0150					0.0120				

NT, no tillage; CT, conventional tillage; RT, reduced tillage; TS, tillage system; LM, large macroaggregate; SM, small macroaggregate; M, microaggregate; S + C, Silt + clay; C, carbon.

depths, namely 15–30 and 30–45 cm, the carbon pools followed a similar trend to that of the surface layer. Significant effects of tillage, cropping system and their interactions followed a similar trend at 0–5- and 5–15-cm depths with few exceptions. At lower depths, treatment effects were not significant for the various carbon fractions (Figure 3).

At the end of the fourth crop cycle, contributions of different fractions of C to the total organic carbon (TOC) at 0–5-cm depth varied from 26.2 to 38.1%, 9.6 to 15.0%, 9.9 to 24.1% and 29.9 to 47.2% for very labile, labile, less labile and non-labile, respectively. For the 5–15-cm depth, contributions of the different fractions to TOC varied from 28.9 to 41.6%, 8.6 to 13.2%, 11.7 to 18.0% and 31.2 to 50.4% for very labile, labile, less labile and non-labile, respectively. Carbon contents decreased with increasing soil depth, mainly for the very labile faction (F1), which contributed >40% at 0–5- and 5–15-cm depths compared with that at 15–30- and 30–45-cm depths. Moreover, less labile and non-labile fractions contributed >50% of TOC, indicating that a more recalcitrant form of carbon exists in the Vertisols of central India. This was also evident from the proportion of the recalcitrant pool compared to more oxidizable pools (Table 6).

Effect of tillage and cropping system on crop yields

Tillage had no significant effect ($P > 0.05$) on the soya bean grain equivalent (SGE) after four crop cycles (Figure 4), whereas cropping system had a greater effect on SGE yields. Among the cropping systems studied, maize–chickpea had a significantly ($P < 0.05$) larger yield (5.6 t ha^{-1}) than maize + pigeon pea (1:1) (4.5 t ha^{-1}), soya bean + pigeon pea (2:1) (2.8 t ha^{-1}) and soya bean–wheat (2.7 t ha^{-1}). The interaction effect of tillage and cropping systems showed no significant effect on crop yields. The overall performance of the crop under different tillage and cropping systems in terms of grain yield was in the order NT > RT > CT.

Discussion

Effect of different tillage and cropping systems on mean weight diameter and water stable aggregates

Soil aggregation improved under RT and NT, coupled with retention of crop residue compared with CT. This was possibly because minimum soil disturbance with residue retention under these treatments has favoured soil aggregation. Recurrent additions of residue under NT and RT is a source of C for microbial activity and nucleation centres for aggregation; therefore, increased microbial activity probably induced the gluing of residue and soil particles into macroaggregates (Beare *et al.,* 1994; Somasundaram *et al.*, 2017). Chen *et al.* (2009) also reported that returning crop residues enhanced microbial activity and soil organic C content, which favoured the binding of residue and soil particles into macroaggregates. Cereal-based cropping systems (maize–chickpea and soya bean–wheat) had positive effects on MWD. Furthermore, the interactive effect of tillage, cropping system and soil depth promoted soil aggregation (MWD) in this study. The smallest MWD was for CT because of frequent soil disturbance through intensive tillage operations coupled with less residue added (Hati *et al.*, 2015). Several studies have reported improved soil aggregation under NT at 10-cm depth compared with CT, which was supported by our findings (Sheehy *et al.*, 2015; Somasundaram *et al.*, 2017). Improved aggregation under conservation agriculture helped to safeguard labile C from microbial attack (Six *et al.*, 2002). Labile carbon (C) plays a significant role in aggregate formation and stabilization, and it also helps to encourage microbial biomass to improve soil aggregation (Haynes, 2005; Guo *et al.*, 2015). Similarly, the disruption of macroaggregates had adverse effects on labile C and decreased its physical protection, which in turn results in the loss of SOC (Beare *et al.*, 1994; Bronick & Lal, 2005). We observed a significant positive correlation of SOC with MWD ($r = 0.68$) and WSA ($r = 0.76$) at 0–5-cm depth (Table 6). This suggests that SOC promotes aggregation and increases the stability of aggregates under conservation agriculture, such as RT and NT coupled with residue retention. Similarly, many researchers have indicated that the quantity of labile organic C and bulk SOC in the soil were correlated significantly with MWD and the stability of aggregates (Tisdall & Oades, 1982; Cambardella & Elliott, 1993; Chen *et al.*, 2009).

The larger percentage of WSA at 0–5-cm depth under RT and NT was mainly ascribed to minimum soil disturbance and addition of crop residues. However, cropping system did not have a significant effect on WSA. Similarly, many other researchers found more WSA under RT and NT (Sheehy *et al.*, 2015) than CT. Mchunu *et al.* (2011) also observed that no tillage (NT) effectively reduced soil loss and runoff, and enhanced aggregate stability compared with CT in the highlands of South Africa. Similar results were reported by Sun *et al.* (2015) and Müller-Nedebock & Chaplot (2015). Mhazo *et al.* (2016) showed that sediment concentration and soil loss were 56 and 60% less under NT than CT, respectively.

Effect of different tillage and cropping systems on aggregate-associated C

We observed more small macroaggregates than other size fractions, which indicates that the aggregate hierarchy is still at an early stage in this soil. It is evident that SOC content increases with increasing aggregate size (Tisdall & Oades, 1982; Six *et al.*, 2000a). Tillage and cropping systems favoured aggregate-associated C under LM and SM aggregates. Our results accorded with those of Bhattacharyya *et al.* (2012), who reported that plots under NT had considerably more C across all aggregate sizes than under CT and CT–NT at 0–5-cm depth after 6 years of study. Puget *et al.* (1995) also recorded that C content increased with the size of aggregates; the larger SOC content in macroaggregates was because SOM was less decomposable in microaggregates protected in the macroaggregates. Regardless of tillage treatments, LM had more aggregate-C and aggregate-N than other size fractions (Six *et al.*, 2000a; Sheehy *et al.*, 2015). In contrast to NT and RT, CT had less aggregate-C because of frequent tillage, which breaks down

Table 5 Contribution of different oxidizable carbon fractions (%) to total organic carbon (TOC) and its ratio*

		0–5-cm depth					5–15-cm depth				
Tillage system	Cropping system	Very labile C (F1)	Labile C (F2)	Less labile C (F3)	Non-labile C (F4)	Ratio (F3 + F4/F1 + F2)	Very labile C (F1)	Labile C (F2)	Less labile C (F3)	Non-labile C (F4)	Ratio (F3 + F4/F1 + F2)
		/ %					/ %				
CT	Soya bean + pigeon pea (2:1)	33.33	12.61	9.91	42.34	1.14	41.57	8.99	17.98	38.20	1.11
	Soya bean–wheat	38.10	10.71	17.86	30.95	1.00	41.56	9.09	29.87	33.77	1.00
	Maize + pigeon pea (1:1)	31.19	12.84	15.60	41.28	1.29	40.00	9.41	17.65	38.82	1.14
	Maize–chickpea	35.63	10.34	24.14	29.89	1.18	40.26	11.69	15.58	31.17	0.90
	Mean	34.56	11.63	16.88	36.12	1.15	40.24	9.76	19.51	35.37	1.04
RT	Soya bean + pigeon pea (2:1)	31.36	11.02	19.49	42.37	1.60	31.90	6.90	9.48	49.14	1.53
	Soya bean–wheat	26.19	10.32	13.49	46.83	1.65	30.28	10.09	11.93	48.62	1.55
	Maize + pigeon pea (1:1)	32.76	12.07	19.83	43.10	1.54	33.33	8.77	12.28	45.61	1.25
	Maize–chickpea	27.83	9.57	20.87	40.00	1.63	31.07	12.62	11.65	43.69	1.27
	Mean	29.53	10.74	18.42	43.08	1.60	31.53	9.91	10.81	46.85	1.40
NT	Soya bean + pigeon pea (2:1)	32.50	11.67	15.00	44.17	1.34	37.86	6.80	22.33	39.81	1.16
	Soya bean–wheat	29.13	12.60	11.02	47.24	1.32	33.04	7.14	15.18	49.11	1.50
	Maize + pigeon pea (1:1)	31.78	14.95	17.76	41.12	1.26	34.69	9.18	16.33	40.82	1.30
	Maize–chickpea	28.00	11.20	18.40	44.80	1.61	28.93	10.74	9.09	50.41	1.58
	Mean	30.35	12.60	15.55	44.33	1.38	33.03	8.26	15.60	44.95	1.39

NT, no tillage; CT, conventional tillage; RT, reduced tillage; TS, tillage system; F1, very labile C; F2, labile C; F3, less labile C; F4, non-labile C. *Ratio was worked out based on mean values of different carbon fractions to TOC.

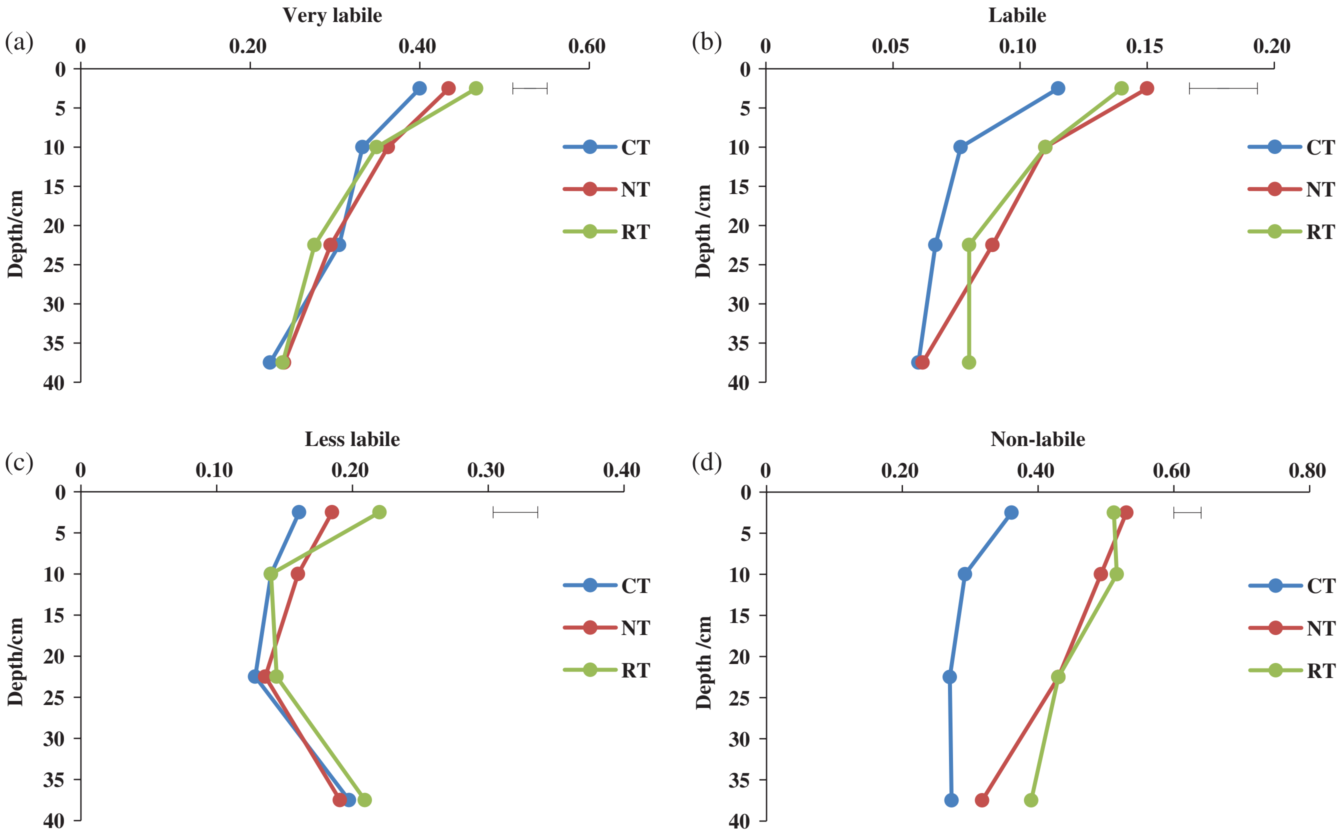

Figure 3 Organic carbon pools (%): (a) very labile C, (b) labile C, (c) less labile C and (d) non-labile C under different tillage systems after the fourth crop cycle. CT, conventional tillage; RT, reduced tillage; NT, no tillage; Fraction 1, very labile C; Fraction 2, labile C; Fraction 3, less labile C; Fraction 4, non-labile C. Horizontal bar indicates $\mathrm{LSD}_{\mathrm{tillage.depth}}$ value at $P < 0.05$.

aggregates, resulting in a loss of labile C from the system. Pinheiro *et al.* (2004) also reported that aggregate size decreased with continuous CT, probably because of mechanical disturbance of macroaggregates, which could have exposed SOM that had been protected against oxidation. Soil aggregation improved under NT compared with CT. Larger SOC contents in macroaggregates indicated that addition of crop residues and root biomass promotes microbial biomass, especially fungal hyphae within macroaggregates, which not only enhances C contents but also improves physical stabilization of aggregates (Zhang *et al.*, 2012). This was evident from the strong positive correlation between MWD and LM-C ($r = 0.73$) and the moderate one with SM-C ($r = 0.40$) at 0–5-cm depth (Table 6). Larger C contents occurred in large and small macroaggregates with changes in soil microbial composition and community resulting from short-term conservation management (Haynes *et al.*, 2005; Guo *et al.*, 2015). On the other hand, larger contents of large and small macroaggregate-C indicate slower turnover rates of macroaggregates resulting from minimum soil disruption under NT (Six *et al.*, 2000a, 2000b). The amount of residue addition coupled with minimum soil disturbance could play a crucial role in the physical protection of C through soil aggregation in a semi-arid region.

Effect of different tillage and cropping systems on soil organic carbon pools

We observed larger differences in the most readily oxidizable carbon fraction (i.e. very labile form (F1)), which was very sensitive to management practices (Guo *et al.*, 2015). This fraction depends largely on the amount of organic residues added to the soil (Chan *et al.*, 2001; Chan *et al.*, 2002), which explains why larger values were recorded in the surface layer and there was also more variation in this fraction with increasing soil depth. The labile carbon fraction is important for soil fertility (nutrition). Plant material including above- and below-ground biomass and living organisms contribute mainly to this fraction. In addition, very labile C often positively affects crop yields, whereas the non-labile fraction (recalcitrant C) improves soil properties such as cation exchange capacity (CEC), water-holding capacity and carbon stabilization for a longer time. Rangel *et al.* (2008) also observed a marked decrease in the very labile fraction (F1) with increasing soil depth. There were also small differences in the fractions, F2, F3 and F4, with increasing soil depth, which suggests that they are relatively insensitive to management practices, regardless of soil depth. Similar results were reported by Chan *et al.* (2001); they also observed more variation in the very labile fractions (more easily oxidizable C)

Table 6 Pearson correlation coefficients (*r*) between different soil properties after four crop cycles

	SOC	MWD	WSA	LM-C	SM-C	M-C	S + C-C
Surface layer (0–5 cm)							
SOC	1.00						
MWD	**0.68**	1.00					
WSA	**0.76**	**0.90**	1.00				
LM-C	**0.54**	**0.73**	**0.80**	1.00			
SM-C	**0.53**	**0.40**	**0.59**	**0.73**	1.00		
M-C	**0.26**	−0.01	0.18	**0.45**	**0.56**	1.00	
S + C-C	**0.42**	**0.46**	**0.46**	0.25	0.09	0.16	1.00
Subsurface layer (5–15 cm)							
SOC	1						
MWD	0.19	1.00					
WSA	**0.77**	**0.59**	1.00				
LM-C	**0.35**	**0.50**	**0.44**	1.00			
SM-C	−0.10	**0.51**	0.23	**0.42**	1.00		
M-C	−0.16	**0.49**	0.21	**0.45**	**0.59**	1.00	
S + C-C	0.22	**0.32**	0.23	**0.77**	0.19	0.31	1.00

SOC, soil organic carbon; MWD, mean weight diameter; WSA, water-stable aggregates; LM-C, large macroaggregate carbon; SM-C, small macroaggregate carbon; M-C, microaggregate carbon; S + C-C, silt + clay carbon. Bold face numbers indicate correlations are significant at 5% level (*n* = 36).

among pastures, and only little variation in other fractions. The ratio of fractions (F3 + F4):(F1 + F2) was more than 1 across tillage systems, indicating that more recalcitrant carbon exists in Vertisols than labile or oxidizable C fractions. There was more variation in SOC fractions in the soils studied; however, consistent effects of tillage or cropping systems on SOC fractions are likely to be observed as the duration of the experiment progresses.

Our results were supported by earlier findings, suggesting that the greater variation in very labile fractions would act as a reliable indicator and also monitor variation in soil quality under different management practices (Barreto *et al.*, 2010). Dolan *et al.* (2006) reported that crop residues are a prerequisite for the SOC pool, and SOC content will increase with the addition of more crop residues to the soil. The effects of conservation tillage on SOC accumulation possibly differs with the quantity and quality of residues added to soil. Furthermore, during tillage soil organic matter might be redistributed in soil. A slight change in SOC content can greatly affect the stability of macroaggregates. Correlation analysis indicated that SOC had a moderate positive ($r = 0.68$) correlation with aggregate MWD. Carter (1992) also reported a close linear relation between soil organic carbon and MWD. Understanding different carbon fractions under conservation agricultural practices is important for discerning the mechanisms of C protection and stabilization.

Effects of different tillage on crop yield

There was a small increase in crop yield under RT and NT compared with CT after four crop cycles. The benefits of conservation agriculture for crop yields might increase with time as a result of better soil health (i.e. from short to long term). In addition, other benefits, such as improvement in soil aggregation, aggregate stability and labile C fractions, eventually help to enhance soil health. Our results corroborated the findings of Tomar (2008), who reported that after 10 years of NT there were small increases in yield compared with CT plots under a rice–wheat system on Vertisols. Araya *et al.* (2016) reported that crop yields under resource conservation technologies such as *derdero* + (DER, a bed and furrow planting system, beds remain unploughed, furrows are tilled once at planting time and 30% of crop residue retained) and *terwah* + (TER, ploughed once at planting, furrows are made at 1.5-m intervals, creating fresh broad beds and 30% crop residue retained) increased by 30 and 16%, respectively, compared with CT. Adopting NT not only helps to improve crop yields, but production costs are also less and energy saving is greater. With the adoption of NT, the beneficial effects are likely to increase over time because of enhancement in soil quality (Tomar, 2008). Results of a long-term tillage experiment from 2000 to 2010 in the Bhopal region showed that yields with NT and RT in a soya bean–wheat system were similar with CT, but with a saving of energy and labour under the former on Vertisols of central India. Conservation agriculture practices such as no tillage and reduced tillage coupled with residue retention or incorporation were as effective as conventional tillage in terms of crop productivity (Hati *et al.*, 2015).

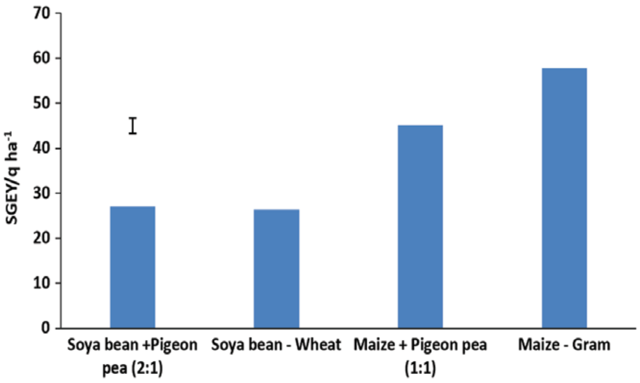

Figure 4 Effect of conservation agriculture on soya bean grain equivalent yield (SGEY, q ha^{-1}) under different cropping systems. Soya bean equivalent yields were calculated using the minimum support price of 2015–2016 of the Indian Market (MSP in Indian rupee rate quintal^{-1}; soya bean 2240 quintal^{-1}; maize 1175 quintal^{-1}; pigeon pea 3850 quintal^{-1}; wheat 1525 quintal^{-1}; chickpea 3425 quintal^{-1}; 1 INR = 0.02USD as on 27 April, 2017). Vertical bar indicates LSD$_{\text{cropping system}}$ value at $P < 0.05$.

Conclusions

We found that conservation agriculture management had a positive effect on soil aggregation and aggregate stability and also increased soil organic carbon content. Tillage practices had a significant effect on aggregate-associated C for large macroaggregates (LM) at 0–5- and 5–5-cm depths. Larger aggregate C in large and small macroaggregates favoured better aggregation under NT and RT than with CT. This suggests that these aggregates are sensitive to changes in the soil microbial community associated with short-term conservation management practices. Our results indicated further that Vertisols in central India had a larger proportion of non-labile organic carbon fractions, followed by the very labile fraction, than the other fractions at 0–5- and 5–15-cm depths after four crop cycles. In addition, CA practices not only improved soil aggregation and maintenance of soil C, but also increased crop yields after a few years of the practice. The outcomes of this study will help to improve soil health and crop productivity in rainfed Vertisols of central India and also in similar agroecological regions worldwide.

Supporting Information

The following supporting information is available in the online version of this article:

Table S1 Full analysis of variance (ANOVA) of mean weight diameter under conservation agriculture

Figure S1 Validity of ANOVA assumptions for mean weight diameter (MWD)

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References

Alvarez, R. 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use and Management*, **21**, 38–52.

Araya, T., Nyssenc, J., Govaerts, B., Deckerse, J., Sommer, R., Bauer, H. *et al.* 2016. Seven years resource-conserving agriculture effect on soil quality and crop productivity in the Ethiopian drylands. *Soil & Tillage Research*, **163**, 99–109.

Barreto, A.B.P., Gama-Rodrigues, E.F., Gama-Rodrigues, A.C., Fontes, A.G., Polidoro, J.C., Moco, M.K.S. *et al.* 2010. Distribution of oxidizable organic C fractions in soils under cacao agroforestry systems in Southern Bahia, Brazil. *Agroforestry Systems*, **81**, 213–220.

van Bavel, C.H.M. 1949. Mean weight-diameter of soil aggregates as a statistical index of aggregation. *Soil Science Society of America Journal*, **14**, 20–23.

Beare, M.H., Cabrera, M.L., Hendrix, P.F. & Coleman, D.C. 1994. Aggregate protected and unprotected organic matter pools in conventional and no-tillage soils. *Soil Science Society of America Journal*, **58**, 787–795.

Bhattacharyya, R., Tuti, M.D., Kundu, S., Bisht, J.K. & Bhatt, J.C. 2012. Conservation tillage impacts on soil aggregation and carbon pools in a sandy clay loam soil of the Indian Himalayas. *Soil Science Society of America Journal*, **76**, 1–11.

Blanco-Canqui, H. & Lal, R. 2009. Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Sciences*, **28**, 139–163.

Briedis, C., de Moraes Sá, J.C., Lal, R., Tivet, F., Franchini, J.C., de Oliveira Ferreira, A. *et al.* 2018. How does no-till deliver carbon stabilization and saturation in highly weathered soils? *Catena*, **163**, 13–23.

Bronick, C.J. & Lal, R. 2005. Soil structure and management: a review. *Geoderma*, **124**, 3–22.

Cambardella, C.A. & Elliott, E.T. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. *Soil Science Society of America Journal*, **58**, 123–130.

Carter, M.R. 1992. Influence of reduced tillage systems on organic-matter, microbial biomass, macro-aggregate distribution and structural stability of the surface soil in a humid climate. *Soil & Tillage Research*, **23**, 361–372.

Chan, K.Y., Bowman, A. & Oates, A. 2001. Oxidizible organic carbon fractions and soil quality changes in an Oxic Paleustalf under different pasture leys. *Soil Science*, **166**, 61–67.

Chan, K.Y., Heenan, D.P. & Oates, A. 2002. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. *Soil &Tillage Research*, **63**, 133–139.

Chen, H., Hou, R., Gong, Y., Li, H., Fan, M. & Kuzyakov, Y. 2009. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. *Soil & Tillage Research*, **106**, 85–94.

Derpsch, R., Friedrich, T., Kassam, A. & Li, H.W. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering*, **3**, 1–25.

Dolan, M.S., Clapp, C.E., Allmaras, R.R., Baker, J.M. & Molina, J.A.E. 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. *Soil & Tillage Research*, **89**, 221–231.

Elliott, E.T. 1986. Aggregate structure and carbon nitrogen, and phosphorus in native and cultivated soils. *Soil Science Society of America Journal*, **50**, 627–633.

Govaerts, B., Mezzalama, M., Unno, Y., Sayre, K.D., Luna-Guido, M., Vanherck, K. *et al.* 2007. Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. *Applied Soil Ecology*, **37**, 18–30.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J. & Dendooven, L. 2009. Conservation agriculture and soil carbon sequestration; between myth and farmer reality. *Critical Reviews in Plant Science*, **28**, 97–122.

Guo, L.B. & Gifford, R.M. 2002. Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, **8**, 345–360.

Guo, L.J., Zhang, Z.S., Wang, D.D., Li, C.F. & Cao, C.G. 2015. Effects of short-term conservation management practices on soil organic carbon fractions and microbial community composition under a rice-wheat rotation system. *Biology and Fertility of Soils*, **51**, 65–75.

Hati, K.M., Chaudhary, R.S., Mandal, K.G., Bandyopadhyay, K.K., Singh, R.K., Sinha, N.K. *et al.* 2015. Effects of tillage, residue and fertilizer nitrogen on crop yields, and soil physical properties under soybean–wheat rotation in Vertisols of Central India. *Agriculture Research*, **4**, 48–56.

Haynes, R.J. 2005. Labile organic matter fractions as central components of the quality of agricultural soils: an overview. *Advances in Agronomy*, **85**, 221–268.

He, J., Wang, Q.J., Li, H.W., Tullberg, J.N., McHugh, A.D., Bai, Y.H. *et al.* 2009. Soil physical properties and infiltration after long-term no-tillage and ploughing on the Chinese Loess Plateau. *New Zealand Journal of Crop and Horticulture Science*, **37**, 157–166.

Hobbs, P.R. 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? *The Journal of Agricultural Science*, **145**, 127–137.

Kemper, W.D. & Rosenau, R.C. 1986. Aggregate stability and size distribution. In: *Methods of Soil Analysis, Part I. Physical and Mineralogical Methods*, Agronomy Monographs No 9, Second edn (ed. A. Klute), pp. 425–442. American Society of Agronomy and Soil Science Society of America, Madison, WI.

Lal, R. 2007. Anthropogenic influences on world soils and implications for global food security. *Advances in Agronomy*, **93**, 69–93.

Liu, X.J.A., Sun, J., Mau, R.L., Finley, B.K., Compson, Z.G., van Gestel, N. *et al.* 2017. Labile carbon input determines the direction and magnitude of the priming effect. *Applied Soil Ecology*, **109**, 7–13.

Mchunu, C.N., Lorentz, S., Jewitt, G., Manson, A. & Chaplot, V. 2011. No-till impact on soil and soil organic carbon erosion under crop residue scarcity in Africa. *Soil Science Society of America Journal*, **75**, 1503–1512.

Mhazo, N., Chivenge, P. & Chaplot, V. 2016. Tillage impact on soil erosion by water: discrepancies due to climate and soil characteristics. *Agriculture Ecosystems & Environment*, **230**, 231–241.

Müller-Nedebock, D. & Chaplot, V. 2015. Soil carbon losses by sheet erosion: a potentially critical contribution to the global carbon cycle. *Earth Surface Processes and Landforms*, **40**, 1803–1813.

Palm, C., Blanco-Canqui, H., De Clerck, F. & Gatere, L. 2014. Conservation agriculture and ecosystem services: an overview. *Agriculture Ecosystem & Environment*, **187**, 87–105.

Parihar, C.M., Yadav, M.R., Jat, S.L., Singh, A.K., Kumar, B., Pradhan, S. *et al.* 2016. Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains. *Soil & Tillage Research*, **161**, 116–128.

Pinheiro, E.F.M., Pereira, M.G. & Anjos, L.H.C. 2004. Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a red latosol from Brazil. *Soil & Tillage Research*, **77**, 79–84.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E. *et al.* 2014. Productivity limits and potentials of the principles of conservation agriculture. *Nature*, **517**, 365–368.

Puget, P., Chenu, C. & Balesdent, J. 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. *European Journal Soil Science*, **46**, 449–459.

Rangel, O.J.P., Silva, C.A., Guimaraes, P.T.G. & Guimaraes, R.G. 2008. Fraçoesoxidaveis do carbon organico de Latossolocultivado com cafeeiroemdiferentesespacamentos de plantio. *Ciencia e Agrotecnologia*, **32**, 429–437.

Sheehy, J., Regina, K., Alakukku, L. & Six, J. 2015. Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in Northern European agroecosystems. *Soil & Tillage Research*, **150**, 107–113.

Six, J., Elliott, E.T. & Paustian, K. 2000a. Soil macro-aggregate turnover and micro-aggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology & Biochemistry*, **32**, 2099–2103.

Six, J., Paustian, K., Elliott, E.T. & Combrink, C. 2000b. Soil structure and soil organic matter: I. Distribution of aggregate size classes and aggregate associated carbon. *Soil Science Society of America Journal*, **64**, 681–689.

Six, J., Conant, R.T., Paul, E.A. & Paustian, K. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and Soil*, **241**, 155–176.

Somasundaram, J., Reeves, S., Wang, W., Heenan, M. & Dalal, R. 2017. Impact of 47 years of no-tillage and stubble retention on soil aggregation and carbon distribution in a vertisol. *Land Degradation & Development*, **25**, 1589–1602.

Sun, Y., Zeng, Y., Shi, Q., Pan, X. & Huang, S. 2015. No-tillage controls on runoff: a meta-analysis. *Soil & Tillage Research*, **153**, 1–6.

Tisdall, J.M. & Oades, J.M. 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, **33**, 141–163.

Tomar, S.S. 2008. Conservation agriculture for rice wheat cropping systems. *Journal of the Indian Society of Soil Science*, **56**, 358–356.

Walkley, A. 1947. A critical examination of a rapid method for determining organic carbon in soils: effect of variations in digestion conditions and inorganic soil constituents. *Soil Science*, **63**, 251–263.

Walkley, A. & Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*, **37**, 29–38.

West, T.O. & Post, W.M. 2002. Soil organic carbon sequestration rates for crops with reduced tillage and enhanced rotation. *Soil Science Society of America Journal*, **66**, 1930–1946.

Zhang, S., Li, Q., Zhang, X., Wei, K., Chen, L. & Liang, W. 2012. Effects of conservation tillage on soil aggregation and aggregate binding agents in black soil of Northeast China. *Soil & Tillage Research*, **124**, 196–202.