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Effect of conservation agriculture on soil hydro-physical properties, total and particulate organic carbon and root morphology in wheat (*Triticum aestivum*) under rice (*Oryza sativa*)-wheat system

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ABSTRACT

Short-term (5 years) effect of conservation agriculture (CA) practice on soil hydro-physical characteristics, soil organic carbon status and root morphology in wheat (*triticum aestivum* L.) was monitored under rice (*Orgza sativa* L.)-wheat rotation in a clay loam soil at the Indian Agricultural Research Institute, New Delhi. A small improvement in soil water content and a marginal decrease in bulk density by CA contributed in significant reduction (30-37%) in sub-surface compaction. The CA improved soil structure in the plough layer (0-15 cm) with significant increase in soil organic carbon status (27-38%). A marginal change in pore size distribution was recorded in favour of larger volume of retention pores (11-12%), in expense of macro- or drainable pore space. Steady-state infiltration, which was essentially profile-controlled, was therefore lower in the CA plots. Decrease in sub-surface soil strength and better soil water retention facilitated root growth in wheat in the sub-surface layer under CA. Results implied that the CA practice in rice-wheat system, although with a shorter period, led to an overall physical improvement of the most active root zone. This had positive impact on root morphology, which contributed to increase in the crop yield.

Key words: Conservation agriculture, Organic C, Penetration resistance, Root morphology, Soil pores, Wheat

To face the challenge to feed the large global population with limited and depleting natural resources, agricultural practices must evolve to a better efficient and sustainable production environment. Rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping system of the Indo-Gangetic Plains plays a crucial role in the region's food security. At the same time, this cropping system is held responsible for the large-scale degradation of soil and natural resource base, and is a potential source of greenhouse gases. However, the demand of these two cereals is likely to grow by 2-2.5% per year until 2020, and therefore, continued efforts are required to ensure sustainability of this system.

Two of major issues with soil physical environment under rice-wheat system are the degradation of soil structural condition and depletion of soil carbon status, and the development of a sub-surface compact layer due to repeated puddling in rice over the years. The structural degradation through puddle-transplanting of rice has serious consequence to the following crop of wheat (Kukal and Aggarwal 2003). This accompanied with loss in soil carbon (Singh *et al.* 2014, Mondal *et al.* 2016) cause adverse impact on soil physical condition. Moreover, sub-surface soil compaction has been a major concern in rice-wheat system in Indo-Gangetic Plains (Aggarwal *et al.* 2006, Kumar *et al.* 2014) and elsewhere. European Union have acknowledged the compaction as a serious form of soil degradation and covering an area of 33 M ha in Europe (FAO 2015). Similar problems have been reported in India (Aggarwal *et al*. 2006, Ahmed *et al*. 2018), Australia (Hamza and Anderson 2005), Russia (Bondarev and Kuznetsova 1999), China (Ji *et al.* 2013), Japan (Ohtomo and Tan 2001) and New Zeeland (Russell *et al.* 2001). Soil compaction impairs the function of subsoil by impeding root growth and hindering water and gaseous exchange (McGarry and Sharp 2003). It also reduces macro-porosity and affect the crop yield adversely (Drewry *et al.* 2008). This may reduce root biomass by 50–68% in highly puddled soil (Kukal and Aggarwal 2003), and the crop yield as much as 60% (Sidhu and Duiker 2006).

Conservation agriculture (CA) is a suite of practices encompassing zero or reduced tillage, maintaining crop residue on the soil surface and introduction of legumes to the system. Rice-wheat rotation is a unique system

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due to its completely contrasting edaphic environment. It is understood that CA practice could help in reducing a majority of problems associated with the system including the soil puddling in rice, which destroys soil structure and limits the time available for seed bed preparation for sowing of succeeding wheat crop. Adoption of CA in rice-wheat system can be a logical and environment-friendly option to sustain or improve the productivity and economic viability of rice-wheat cropping system (Hobbs *et al.* 2008). Moreover, it can substantially improve soil properties through non-disturbance for a sufficiently longer period, and with retention of crop residue, physically protect the surface soil resulting in lesser run-off and higher water intake into the soil profile. Improved soil physical condition in CA might result in better root growth and efficient use of applied water and nutrients.

We hypothesize that the adoption of CA in rice-wheat system for a few uninterrupted years can substantially improves the soil hydro-physical condition and the carbon status, and reduce the sub-surface compaction and the modified soil environment may promote root growth in wheat. This study assessed the changes in soil physical properties, organic carbon and root characteristics in direct-seeded rice and no-till wheat system (NT-NT), in comparison to a conventional system, where rice was puddle-transplanted followed by conventionally tilled wheat (CT-CT). We have included a treatment of puddle-transplanted rice and no-till wheat system (CT-NT) to better understand the role of puddling in rice. The study also highlights the problems of subsurface compaction and its effects on crop yields.

MATERIALS AND METHODS

A field experiment titled 'Conservation agriculture practices for improving resource-use efficiency and productivity of rice (*Oryza sativa*)-based cropping system' has been continuing on rice (*kharif*)-wheat (*rabi*) rotation at the ICAR-Indian Agricultural Research Institute, New Delhi since 2010. The climate is semi-arid with dry hot summer and cold winter. Annual rainfall is 710 mm of which 80% is received during the southwest monsoon from July to September, and rest through the 'Western Disturbances' from December to February. During wheat 2015-16, mean monthly minimum and maximum temperatures were 6.1 and 33.9°C in December and April, respectively, and the rainfall was bare minimum (2.6 mm). Average daily bright sunshine hours was 4.8 and pan evaporation varied from 2.5 (January) to 8.2 mm/d (April). The soil texture of surface soil layer is clay loam while in deeper layers it is loam; oxidizable organic carbon content was 6.2 and 1.2-2.9 g/kg in surface and sub-surface layers, respectively.

The experiment was laid in a randomized block design with three replications. Five treatments were selected for the study: NT-NT$_1$: Direct-seeded rice (DSR) – No-tilled wheat (NTW), NT-NT$_2$: DSR + brown manuring – NTW, NT-NT$_3$: DSR + mung bean residue - NTW + rice residue – Relay mungbean, CT-NT: Puddle-transplanted rice (PTR) – NTW, CT-CT: PTR – Conventionally tilled wheat.

Chopped residue of rice crop was applied @5 t/ha in NT-NT$_3$. Similarly, residues of moong bean, grown as relay crop, were incorporated *in-situ* into the soil by rotavator before sowing of rice in the respective treatment. For puddle-transplanting of rice, tractor drawn puddler was used for puddling, and tractor drawn disc plough were used for conventional wheat followed by harrowing and planking. Seedlings from the nursery were transplanted manually, while in DSR, sowing was done by multi-crop planter with a row spacing of 20 cm and a seed rate of 40 kg/ha. A pre-sowing irrigation was given to ensure good germination in DSR. Sowing of wheat was done with happy seeder in residues of the rice crop in the respective treatments, at spacing of 20 cm (row-to-row) and 5 cm (plant-to-plant) with a seed rate of 100 kg/ha. At maturity, the crop was harvested and the yield was recorded.

Undisturbed soil cores were collected from 0-15, 15-30, 30-45 and 45-60 cm soil layer for measurement of soil bulk density following the method of Blake and Hartge (1986) in three replicates from each plot. Fresh soil cores were processed in the laboratory, weighed and oven-dried at 105°C for 48 h. Dry soil weight was then divided by core volume to get the bulk density (g/cm).

Soil penetration resistance, expressed as cone index (CI, kPa) was measured by using Rimik cone penetrometer (model no. CP20). The diameter of the base of cone, and the slant height was 1.2 and 2.4 cm, respectively and the angle of cone was 30°. The instrument records data automatically at 2 cm soil depth increment. The maximum depth of measurement was kept at 44 cm. The penetration resistance readings were taken from NT-NT$_3$, CT-NT and CT-CT treatments only, along with the soil water content at the time of PR readings. A total of seven readings were obtained from each plot and averaged to get one value, representative of the plot.

Soil samples were collected from 0-7.5, 7.5-15 and 15-30 cm soil layers from multiple locations in a plot for aggregation analysis. Large moist clods were gently broken by hand along the plane of weakness, without putting additional pressure. The broken samples were thoroughly mixed and passed through an 8 mm sieve and stored in plastic bags at 4°C till analysis. Aggregate stability was measured by Le Bissonnais (1996) method with two pre-treatments, viz. (a) fast wetting (FW) and (b) slow wetting (SW). Soil samples for aggregate analysis were kept overnight at 40°C in an oven to obtain uniform dryness prior to pre-treatment. In FW test, approximately 5 g of aggregates was gently immersed in 50 ml of deionized water for 10 min, while in slow wetting test, aggregates were capillary-wetted at -0.3 kPa suction on a tension table for 30 min, and then gently immersed in water (50 mL). After these pre-treatments, the samples were transferred onto a 0.053 mm sieve previously immersed in ethanol and the sieve was moved gently for 3 min. Aggregates on 0.053 mm sieve were collected, oven-dried at 105°C, and dry-sieved using a column of 6 sieves: 2, 1, 0.5, 0.2, 0.1 and 0.053 mm. Four replicates were performed for each pre-treatment. For each of these methods, aggregate mass on each sieve was recorded and aggregate stability was expressed as mean weight diameter (MWD) (Kemper and Rosenau 1986).

Soil samples (0-5, 5-15 and 15-30 cm layers) were analyzed for total organic carbon (TOC) using the elemental analyzer. The particulate organic matter fraction was isolated by following the method of Cambardella and Elliott (1993). Briefly here, 10 g of soil (<2 mm) was dispersed in 30 ml of sodium hexametaphosphate solution (5 g/l) and agitated in a reciprocating shaker for 18 h (180 rpm). The suspension was poured onto a 0.053 mm sieve and rinsed thoroughly with distilled water until the silt+clay fractions (<0.053 mm) were completely washed away. The retained fraction was transferred into a glass beaker and dried at 50°C. Carbon of the dried fraction (POM-C) was determined by the elemental analyzer.

To determine the relative distribution of macro- and micro-sized pores, water content of undisturbed samples obtained from 0-15, 15-30, 30-45 and 45-60 cm layers, was measured at -100 cm matric potential in hanging water column (Berliner *et al.* 1980). The boundary between macro- and micro-pore was taken as 30 μm equivalent to 100 cm water head (Marshall 1959). Additionally, soil water content at -10, -20, -50 cm suction (hanging water column), and -330 cm suction (pressure plate apparatus) were determined for 0-15 cm layer to evident the effect of tillage, if any (estimated for NT-NT_3, CT-NT and CT-CT treatments). The matric potential was converted to the effective pore size by using the following equation (Marshall *et al.* 1996):

$$r = \frac{2\gamma\cos\alpha}{\rho g h}$$

where r is the mean equivalent cylindrical radius of pores (m) at a given soil matric potential head, h (m) applied to drain the water from soil core; γ is the surface tension (72.7 mJ/m^2 at 20ºC); α is the contact angle between the water and pore wall, assumed to be zero; ρ is density of water (Mg/m^3) and g is acceleration due to gravity (m/s^2). The water content change was taken as the volume of the pores under specific size-class.

Soil infiltration rate was measured at ponding using a double ring infiltrometer (Bouwer 1986) in four replicates. The two concentric rings 20 and 30 cm in diameter, and 15 cm height were inserted up to 5 cm deep into the soil by hammering on the wooden piece, placed on the top of the rings. A fixed water level in the inner ring was maintained by adding measured quantity of water after a time interval. Data were fitted to Philip (1957) equation [$i=0.5*S*t^{-0.5} + A$, where i=infiltration rate, t=time. Parameters S is 'sorptivity' which relates the ability of soil to absorb water at very initial stage of infiltration when force of gravity can be neglected, and A is functionally related to saturated hydraulic conductivity of the soil], and the parameters were retrieved. All the above physical parameters were monitored at the harvest of wheat in 2016 (6 years after the initiation of the experiment)

Root sampling was done at five locations in each treatment at grain filling stage of wheat by using root auger having a diameter of 7 cm. After removing the above ground plant parts, the core of the auger was placed keeping the base of the stem at centre and the soil core was excavated from each 15 cm depth layer down to a 45 cm depth (0-15, 15-30 and 30-45 cm layers). Root samples were soaked overnight in water containing sodium hexametaphosphate and washed through a 0.5 mm sieve). Washed roots were collected and stored in butter paper bags in refrigerator to prevent degeneration until it was scanned.

Washed roots were spread with thin film of water on transparent plate for scanning by using a root scanner. Root morphological parameters (length, surface area, volume and dry weight) were computed by Win-RHIZO programme. Post scanning, roots were collected and oven-dried at 65°C for 48 h and weighed. Measured root length, surface area, volume and root dry weight was divided by the volume of the core to get respective densities for each depth.

The whole plots were harvested (leaving two border rows on each side and 0.5 m from each side of the length) and sun-dried for three days in the field and then the total biomass yield was recorded. After threshing, cleaning and drying, the grain yield (t/ha) was recorded and reported at 14% moisture content. Straw yield was obtained by subtracting grain yield from the total biomass yield.

The statistical analysis was performed using the randomized block design analysis in SAS 9.4 (Indian NARS Statistical Computing Portal). Means were compared using significant difference where the analysis of variance was significant at P<0.05 (Duncan LSD).

RESULTS AND DISCUSSION

Bulk density and soil resistance to penetration

The effect of conservation agriculture (CA) treatments on soil bulk density (BD) was non-significant at all depths (Fig 1). In plough layer (0-15 cm), the NT-NT systems had marginally lower BD values (2-5%) compared to CT-NT

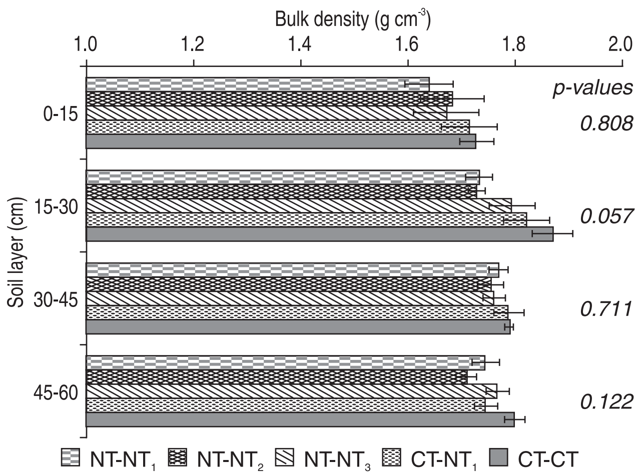

Fig 1 Bulk density of soil under conservation agriculture practices; horizontal bars indicate ±SE of mean; please refer to the text for treatment abbreviation

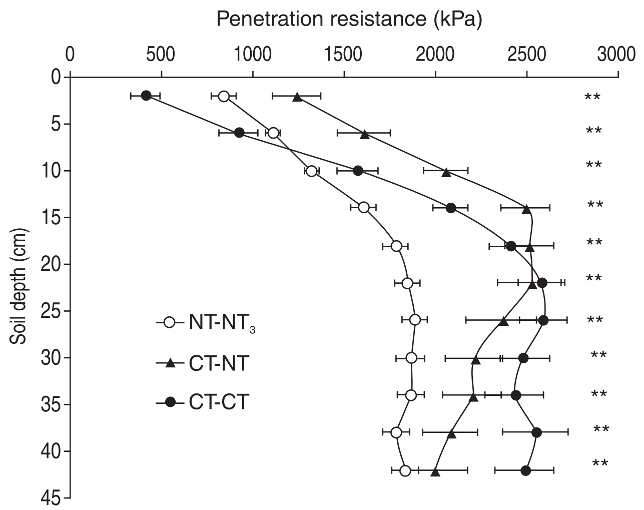

Fig 2 Soil resistance to penetration under conservation agriculture ($NT-NT_3$), conventional rice (puddle-transplanted) followed by no-till wheat (CT-NT), and both rice and wheat are conventionally grown (CT-CT); horizontal bars indicate ±SE of mean; ** means significant at $P<0.01$.

and CT-CT treatments, while at subsurface (15-30 cm) layer, CT-CT had marginally higher BD (1.87 g/cm) than the rest (1.82, 1.79 g/cm in CT-NT and $NT-NT_3$, respectively, and 1.73 g/cm in $NT-NT_1$ and $NT-NT_2$) ($P=0.057$). In 30-45 and 45-60 cm layers, BD varied between 1.75-1.79 and 1.71-1.80 g/cm, respectively; differences narrowed down compared to the layers above.

Unlike BD, penetration resistance (PR) of soil was significantly different among the treatments to a depth of ~40 cm (Fig 2). The PR increases steadily down the soil profile, and the compact sub-surface layer (~15-30 cm) is clearly distinguishable. At the same time, CT-CT resulted in a larger reduction in PR at this layer. In uppermost layers (0-4 and 0-8 cm), CT-CT had significantly ($p<0.01$) lower PR (2-3-times less than CT-NT and 1-1.5 times less than $NT-NT_3$). In other layers till 40 cm depth, $NT-NT_3$ recorded significantly ($P<0.01$) lower PR value than either of CT-NT and CT-CT. At most of these layers, CT-NT and CT-CT could not be differentiated, although $NT-NT_3$ showed consistently lower PR compared to both CT-NT (12-89% higher) and CT-CT (31-58% higher). The soil water content during PR measurement was similar at 0-15 cm (18±2%, v/v), but small differences were recorded at other layers, viz. 16±3% (v/v) in $NT-NT_3$ at 15-30 and 30-45 cm, compared to CT-NT (13±1% and 13±3%, v/v) and CT-CT (14±2 and 12±1%, v/v) in 15-30 and 30-45 cm layer, respectively.

None of the soil layers had significant change in BD, although the CA appeared to reduce the sub-surface compaction to a small extent. All of the NT-NT treatments recorded marginally lower (3-8%) soil BD in 15-30 cm layer, indicating possibility of reducing the subsurface compaction in the long run through adoption of CA. Sub-surface compaction has been a major concern in cultivated soils in many countries (FAO 2015, Ahmad *et al.* 2018). This has particular relevance to the rice-wheat system, where a highly compacted sub-soil layer has often been reported (Aggarwal *et al.* 2006, Gathala *et al.* 2011, Singh *et al.* 2014). The compact subsurface layer in CT-CT practice happened due to puddling in rice, which developed a hard layer below, and due to repeated tillage in wheat, which was mostly restricted to 0-15 cm layer. Penetration resistance corroborated the soil bulk density at sub-surface (1.73-1.87 g/cm^3), where CT-CT recorded as high as 2.5 MPa of soil-resistance-to-penetration. This is greater than the critical value of 2 MPa suggested for root growth and development (de Lima *et al.* 2012). A lower PR in CT in the layer up to 8 cm could be due to tilling, whereas omission of tillage caused increase in PR in NT-NT practice. The experimentation was in irrigated condition, and therefore, the soil water was comparable at surface, although a small change in soil water content at sub-surface could have added to the PR value in CT (14 and 33% less moisture in CT than NT in 15-30 and 30-45 cm soil depth, respectively). Considering 2 MPa as a threshold for better root growth (Silva *et al.* 2008, de Lima *et al.* 2012), higher PR in CT in the sub-surface layer could adversely affect the root growth (discussed later).

Soil aggregate stability

The effect of conservation practices on soil aggregate stability was clearly discernible (Table 1). In 0-7.5 cm layer under fast-wetting pre-treatment condition, soil macro-aggregate content was significantly higher in $NT-NT_3$ (56-287%, $P<0.01$) while CT-CT recorded the lowest content (22.7%). Similar trend could be found in the following 7.5-15 cm layer, where the highest and the lowest amount of macro-aggregates were recorded in $NT-NT_3$ (48.2%) and CT-NT (19.9%), respectively. In 15-30 cm soil layer, macro-aggregates content was higher in $NT-NT_3$ compared to CT-NT and CT-CT (50-68%, $P<0.05$) but was at par with $NT-NT_1$ and $NT-NT_2$. Amount of soil micro-aggregates followed the reverse; both CT-NT and CT-CT recorded 24-115% higher in micro-aggregates content compared to $NT-NT_2$ and $NT-NT_3$, but similar to $NT-NT_1$. Amount of stable macro-aggregates were nearly doubled with slow-wetting pre-treatment. $NT-NT_2$ recorded significantly higher content than CT-CT and CT-NT (42 and 22%, respectively, $P<0.05$), but it was at par with other treatments. Similar results were obtained in 7.5-15 cm layer. No significant difference was found at 15-30 cm layer. In slow-wetting, micro-aggregate contents were comparable among the treatments at all the layers. Greater macro-aggregates ensured larger mean weight diameter (MWD) in $NT-NT_3$ (0.59 mm), followed by $NT-NT_2$ (0.47 mm), $NT-NT_1$ (0.41 mm), CT-NT (0.36 mm) and CT-CT (0.29 mm) in 0-7.5 cm soil layer, when the fast-wetting pre-treatment was followed. In 7.5-15 cm layer, MWD was lower compared to the layer above, and $NT-NT_3$ could only have a significantly different (56-77% higher, $P<0.01$) MWD compared to the rest of the treatments. In 15-30 cm layer, treatments were at par. When aggregates were slow-wetted, MWD improved and was 2-3 times higher than the corresponding fast-wetting MWD. Here, MWD

Table 1 Soil aggregation as affected by conservation agriculture practices. Means are followed by SE of mean; values followed by similar letters within a soil layer are not different at P<0.05

Treatment	Macro-aggregates	Micro-aggregates	MWD (mm)
	------%-----		
	Fast-wetting pre-treatment		
	0-7.5 cm		
$NT\text{-}NT_1$	$32.6^{bc}\pm1.5$	$55.1^{ab}\pm1.0$	$0.41^{bc}\pm0.03$
$NT\text{-}NT_2$	$38.3^{b}\pm1.4$	$49.5^{b}\pm1.9$	$0.47^{b}\pm0.03$
$NT\text{-}NT_3$	$59.6^{a}\pm5.9$	$29.1^{c}\pm4.9$	$0.59^{a}\pm0.07$
CT-NT	$26.1^{cd}\pm0.5$	$62.7^{a}\pm1.1$	$0.36^{cd}\pm0.02$
CT-CT	$22.7^{d}\pm1.3$	$61.4^{a}\pm3.2$	$0.29^{d}\pm0.02$
P-value	<0.001	0<0.001	0.002
	7.5-15 cm		
$NT\text{-}NT_1$	$29.2^{bc}\pm1.2$	$60.3^{a}\pm1.1$	$0.23^{b}\pm0.01$
$NT\text{-}NT_2$	$31.5^{b}\pm2.4$	$57.6^{a}\pm1.2$	$0.24^{b}\pm0.01$
$NT\text{-}NT_3$	$48.1^{a}\pm3.8$	$36.3^{b}\pm6.5$	$0.39^{a}\pm0.04$
CT-NT	$19.9^{d}\pm2.2$	$67.2^{a}\pm3.6$	$0.22^{b}\pm0.03$
CT-CT	$22.3^{cd}\pm1.5$	$62.0^{a}\pm1.5$	$0.25^{b}\pm0.02$
P-value	<0.001	0.003	0.004
	15-30 cm		
$NT\text{-}NT_1$	$36.9^{ab}\pm3.6$	54.0 ± 4.9	0.27 ± 0.02
$NT\text{-}NT_2$	$34.2^{abc}\pm1.9$	56.5 ± 2.2	0.26 ± 0.02
$NT\text{-}NT_3$	$42.0^{a}\pm1.8$	47.6 ± 3.8	0.32 ± 0.01
CT-NT	$25.0^{c}\pm4.8$	64.8 ± 4.7	0.22 ± 0.03
CT-CT	$28.1^{bc}\pm2.3$	51.0 ± 2.9	0.27 ± 0.03
P-value	0.037	ns	ns
	Slow-wetting pre-treatment		
	0-7.5 cm		
$NT\text{-}NT_1$	$77.3^{ab}\pm4.7$	18.1 ± 4.4	$1.23^{bc}\pm0.30$
$NT\text{-}NT_2$	$81.7^{a}\pm4.0$	12.3 ± 2.3	$1.63^{ab}\pm0.12$
$NT\text{-}NT_3$	$75.4^{ab}\pm3.7$	17.7 ± 2.9	$1.77^{a}\pm0.05$
CT-NT	$67.1^{bc}\pm2.9$	25.8 ± 3.1	$0.73^{cd}\pm0.04$
CT-CT	$57.6^{c}\pm2.4$	25.5 ± 3.8	$0.60^{d}\pm0.05$
P-value	0.020	ns	0.002
	7.5-15 cm		
$NT\text{-}NT_1$	$78.4^{ab}\pm4.6$	15.9 ± 4.7	$1.51^{b}\pm0.05$
$NT\text{-}NT_2$	$82.3^{a}\pm5.9$	9.5 ± 1.5	$1.58^{ab}\pm0.15$
$NT\text{-}NT_3$	$81.4^{a}\pm2.0$	10.7 ± 1.0	$1.82^{a}\pm0.05$
CT-NT	$68.3^{bc}\pm4.1$	22.8 ± 6.1	$0.70^{c}\pm0.06$
CT-CT	$61.6^{c}\pm5.8$	25.7 ± 5.2	$0.72^{c}\pm0.09$
P-value	0.020	ns	<0.001
	15-30 cm		
$NT\text{-}NT_1$	72.5 ± 8.3	18.2 ± 9.0	$1.31^{b}\pm0.09$
$NT\text{-}NT_2$	78.9 ± 1.5	13.9 ± 1.2	$1.19^{b}\pm0.06$
$NT\text{-}NT_3$	81.0 ± 3.6	11.2 ± 3.0	$1.56^{a}\pm0.04$
CT-NT	67.3 ± 3.5	28.0 ± 2.3	$0.58^{c}\pm0.08$
CT-CT	63.3 ± 4.3	21.7 ± 5.6	$0.52^{c}\pm0.06$
P-value	ns	ns	<0.001

of aggregates significantly higher in $NT\text{-}NT_3$ (44-195%, P<0.01) than all other treatments except $NT\text{-}NT_2$. Similar results were obtained in other layers, and MWD in $NT\text{-}NT_3$ was higher compared to CT-NT and CT-CT treatments.

The effect of tillage and residue management on size distribution and stability of soil aggregates was clearly distinguishable. Irrespective of pre-treatment to the soil, NT-NT provided a better soil aggregation. Crop residues on the surface protects the soil for the diurnal and seasonal changes in temperature, water content and aeration, and this maintains a good soil structural condition (Salem *et al.* 2015, Mondal *et al.* 2018). A still larger impact in $NT\text{-}NT_3$ could be explained by the inclusion of legume (mung bean) in cropping system, making a higher amount of crop residue (rice+mung bean) addition. Among the two pre-treatments, slow wetting retained larger aggregates after wet sieving due to absence of slaking action of water, thereby resulting in higher MWD, compared to that through fast-wetting. The MWD of aggregates, an index of soil aggregation, was always higher in NT-NT. The organic matter through decomposition of crop residues further promoted the stable aggregates formation in NT-NT, while physical disturbance and absence of crop residue in CT limits the formation and stabilization of soil aggregates (Govaerts *et al.* 2009, Jat *et al.* 2013). Many authors have mentioned the beneficial role of crop residue, which is typically limited to the surface layer(s) (Mondal *et al.* 2013, Devine *et al.* 2014). However, we observed higher MWD and macro-aggregation in deeper layers also in NT which is in agreement with other authors (Abid and Lal 2008, Du *et al.* 2013, Xin *et al.* 2015).

Soil water retention and pore size distribution

The relative abundance of macro- or micro-pores as affected by CA was not distinguishable in any of the soil layers (Fig 3). However, micro-pores appear marginally higher at 0-15 and 15-30 cm in CA practices. Soil water retained at different matric potentials showed small variations, although a small increment in water retention was recorded in $NT\text{-}NT_3$ at higher potentials (0.1-5.2, 4.1-6.0 and 4.4-13.1% at -50, -100 and -330 cm water potential, respectively; Fig 4a). When the difference in water retained at small increments of matric potentials between $NT\text{-}NT_3$, CT-NT and CT-CT were computed, $NT\text{-}NT_3$ recorded significantly higher water content than CT-CT between -100 and -300 cm potentials (Fig 4b).

Pore size distribution was not affected by tillage. Marginally higher macro-pore volume in CT-CT or CT-NT, and marginally higher micro-pore volume in NT-NT could be suggestive of the tendency of rearrangement of pore sizes through the continuous no-tillage practice (Raczkowski *et al.* 2012, Jemai *et al.* 2013). Tilling the soil and not maintaining the surface residue cover led to formation of small cracks upon drying (visually observed; not recorded). Possibly, a little higher small pore volume in NT maintained a higher soil water status, preventing the development of cracks (Bandyopadhyay *et al.* 2003, Lopez-Bellido *et al.* 2016). The soil water retention at different

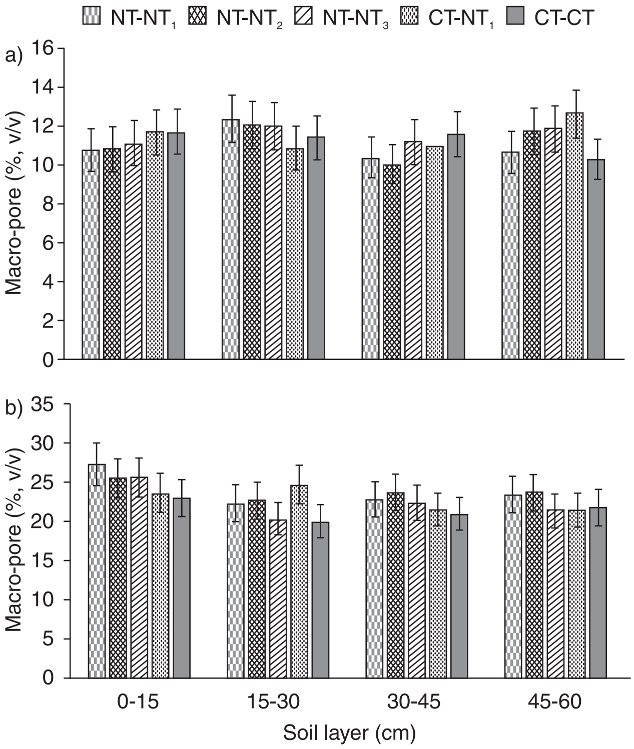

Fig 3 Distribution of macro- and micro-pore in various soil layers down the profile; vertical bars signify ±SE of mean.

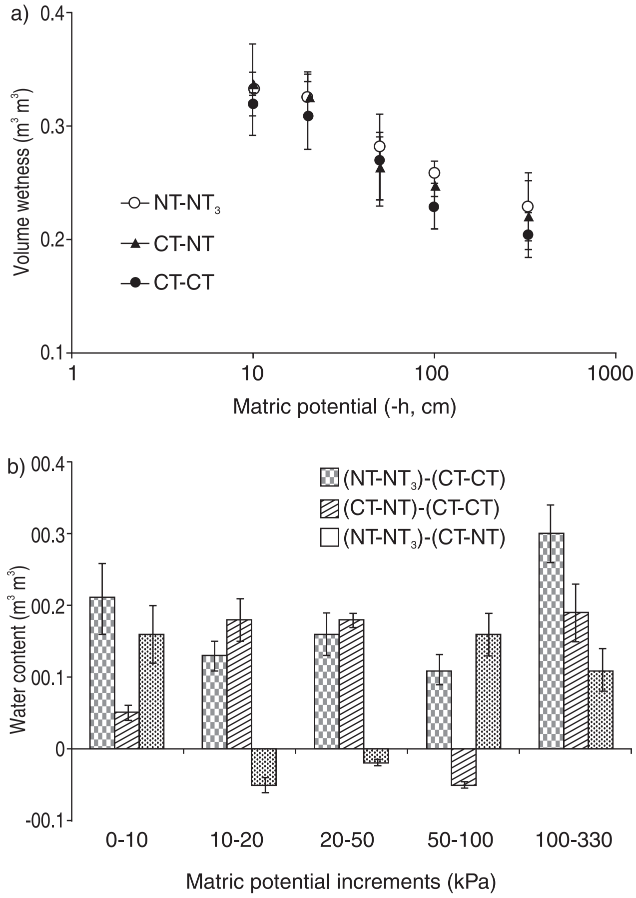

Fig 4 Soil water retention at different matric potentials (a) and difference in water retention between the treatments (b) at matric potential increments for 0-15 cm soil layer; vertical bars show ±SE of mean.

potentials also confirms the fact that higher water could be retained in no-tillage systems. Water held between 100-330 cm potential is likely to be more stable compared to the water held at lower potential. The water retained in soil at matric potential between 100 and 330 cm is 1.5 times higher in NT-NT than the CT-CT, and thrice as much higher compared to CT-NT system.

Infiltration characteristics

In CT-CT, initial rate of infiltration was very high (49-154%; p<0.01) compared to the NT-NT$_1$/NT-NT$_2$/NT-NT$_3$, but was at par with CT-NT (Table 2). The final or steady-state infiltration rate differed significantly (p<0.05) between any of NT-NT treatments (0.21-0.37 cm/h) and CT-NT (0.91 cm/h), but was comparable to CT-CT (0.57 cm/h). The CT-CT treatment recorded higher cumulative infiltration for 5 h (83-144%; P<0.05 than NT-NT$_1$ and NT-NT$_2$, respectively), but was similar to NT-NT$_2$ and CT-NT. The infiltration parameters, S and K of Philip's infiltration equation had significantly higher values (51 cm/s$^{1/2}$ and 4.64 cm/h) in CT-CT. The CT-NT had larger 'K' but similar 'S' compared to the NT-NT treatment. Higher initial, final and cumulative infiltration are indicative of a more

Table 2 Initial and final infiltration rates, cumulative infiltration and infiltration parameters under conservation agriculture in rice-wheat system; mean values are followed by ±SE of mean; values in the same column followed by similar letter are not different at P<0.05.

Treatment	Infiltration rate		Cumulative infiltration	Infiltration parameter*	
	Initial	Final		S	A
	cm/h		cm	cm s$^{-1/2}$	cm h^{-1}
NT-NT$_1$	4.7^c±0.3	0.24^b±0.06	2.8^{bc}±0.4	27.3^b±1.7	1.00^b±0.18
NT-NT$_2$	7.0^{bc}±1.1	0.37^b±0.09	4.5^{ab}±0.9	34.1^b±6.6	0.82^b±0.22
NT-NT$_3$	4.1^c±0.6	0.21^b±0.02	2.1^c±0.2	30.0^b±4.7	1.46^b±0.33
CT-NT	8.5^{ab}±1.3	0.91^a±0.32	4.6^{ab}±0.7	55.8^a±9.1	1.54^b±0.07
CT-CT	10.5^a±1.1	0.57^{ab}±0.10	5.2^a±1.0	51.0^a±5.1	4.64^a±1.26
P-value	*0.003*	*0.043*	*0.041*	*0.005*	0.005

*From Philip (1957)

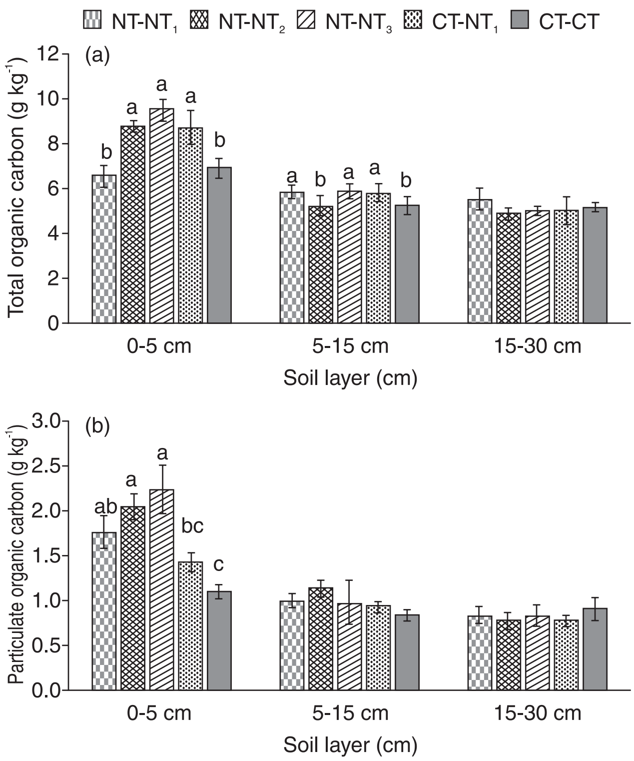

Fig 5 Total organic carbon (TOC) (A) and particulate organic carbon (POC) (B) in 0-5, 5-15 and 15-30 cm soil; vertical bars represent ±SE of mean; treatments followed by same letters within a soil layer are not statistically significant at P<0.05.

open soil structure (greater volume of larger pores) and cracks at surface in CT. Sorptivity was also higher in CT, which tells about the greater affinity of soil for water, when the effect of gravity is minimum (Philip 1957). It could be that soil had developed a mild hydrophobicity due to the presence of crop residue and higher soil organic matter on the surface in NT over the years, which slowed the process of intake of water. The 'A' parameter of the Philip equation, which is functionally similar to saturated hydraulic conductivity (Dunin 1976) was also higher in CT system.

Total organic carbon (TOC) and particulate organic carbon (POM-C)

TOC and POM-C of soil differed significantly among the treatments in the 0-5 cm layer (Fig 5). The highest value of TOC was recorded in NT-NT_3 (9.58 g/kg), which was significantly higher (38-46%, P<0.01) than NT-NT_1 (6.54 g/kg) and CT-CT (6.92 g/kg), but was comparable to NT-NT_2 (8.78 g/kg) and CT-NT (8.70 g/kg). In the below layer (5-15 cm), variation in TOC content reduced (5.23-5.86 g/kg), and both NT-NT_1 and NT-NT_3 had significantly higher (11-12%, P<0.05) TOC content than the CT-CT. In 15-30 cm layer, no significant difference in TOC content was recorded. The POM-C content significantly varied only in 0-5 cm layer, where NT-NT_3 and NT-NT_2 had significantly higher (16-103%, P<0.05) POM-C content. In other layers,

Table 3 Grain and straw yield of wheat under conservation and conventional agriculture practices; means are followed by ±SE of mean; values with same small letters in a column are not significantly different at P<0.05

Treatment	Grain yield	Straw yield
	--------t/ha--------	
NT-NT_1	$4.00^{c}\pm0.18$	$5.95^{c}\pm0.25$
NT-NT_2	$4.40b^{c}\pm0.20$	$6.54^{bc}\pm0.32$
NT-NT_3	$5.02^{a}\pm0.15$	$7.52^{a}\pm0.22$
CT-NT	$4.64^{ab}\pm0.15$	$6.89^{ab}\pm0.21$
CT-CT	$4.22^{bc}\pm0.07$	$6.27^{c}\pm0.10$b
P-value	0.015	0.012

POM-C content varies between 0.77 to 1.13 g/kg; treatment difference was non-significant.

Mean values of TOC was higher by 34% in NT. This highlights the favourable condition of soil organic carbon accumulation through no-tillage practice. Addition of crop residue and incorporation of legume in crop rotation in NT-NT_3 treatment could be the possible cause of higher TOC content in the soil. Residues get slowly decomposed and the resultant organic matter is added to the soil which helps in aggregate formation, water retention and improves overall soil physical health. In subsurface layers, TOC content was almost comparable between CT and NT, which implies that the role of tillage and crop residue is restricted to the surface layer (Ussiri and Lal 2009, Meurer *et al.* 2017). Identical result in POM-C proves the close association of TOC and POM-C. Absence of crop residue left over the surface caused lower POM-C content in CT, moreover, tillage destroyed the stable aggregates, and exposed the aggregate-protected organic C which undergoes decomposition (Six *et al.* 2002, Tan *et al.* 2007).

Root characteristics

Both the length and surface area densities of roots in 0-15 cm layer were higher in CT-CT treatment (28-93%, P<0.01) than the rest (Fig 6). The NT-NT recorded 2.0-3.1 cm/cm^3 of root length density (RLD), which was comparable to one another. It was marginally higher in NT-NT_3 at 15-30 cm (1.36 cm/cm^3), but was significantly higher at 30- to 45-cm depth increment than CT-CT. A large surface area density (SAD) of roots at 0-15 cm layer was recorded in CT-CT (twice the values in other treatments). In 15-30 cm layer, SAD reduced sharply, but NT-NT_3 recorded the highest value (higher by 44-160%, P<0.05). In 30-45 cm layer, difference was non-significant. The root volume density (RVD) did not differ significantly among the treatments, although in the plough layer, CT-CT resulted in apparently higher values (62-193%, P=0.08). The root dry weight density was also comparable among the treatments.

Tillage significantly improved root length and surface area density in wheat at the surface layer, although the root volume density is only marginally higher in CT-CT system. The NT-NT (except NT-NT_2) had an intermediate impact,

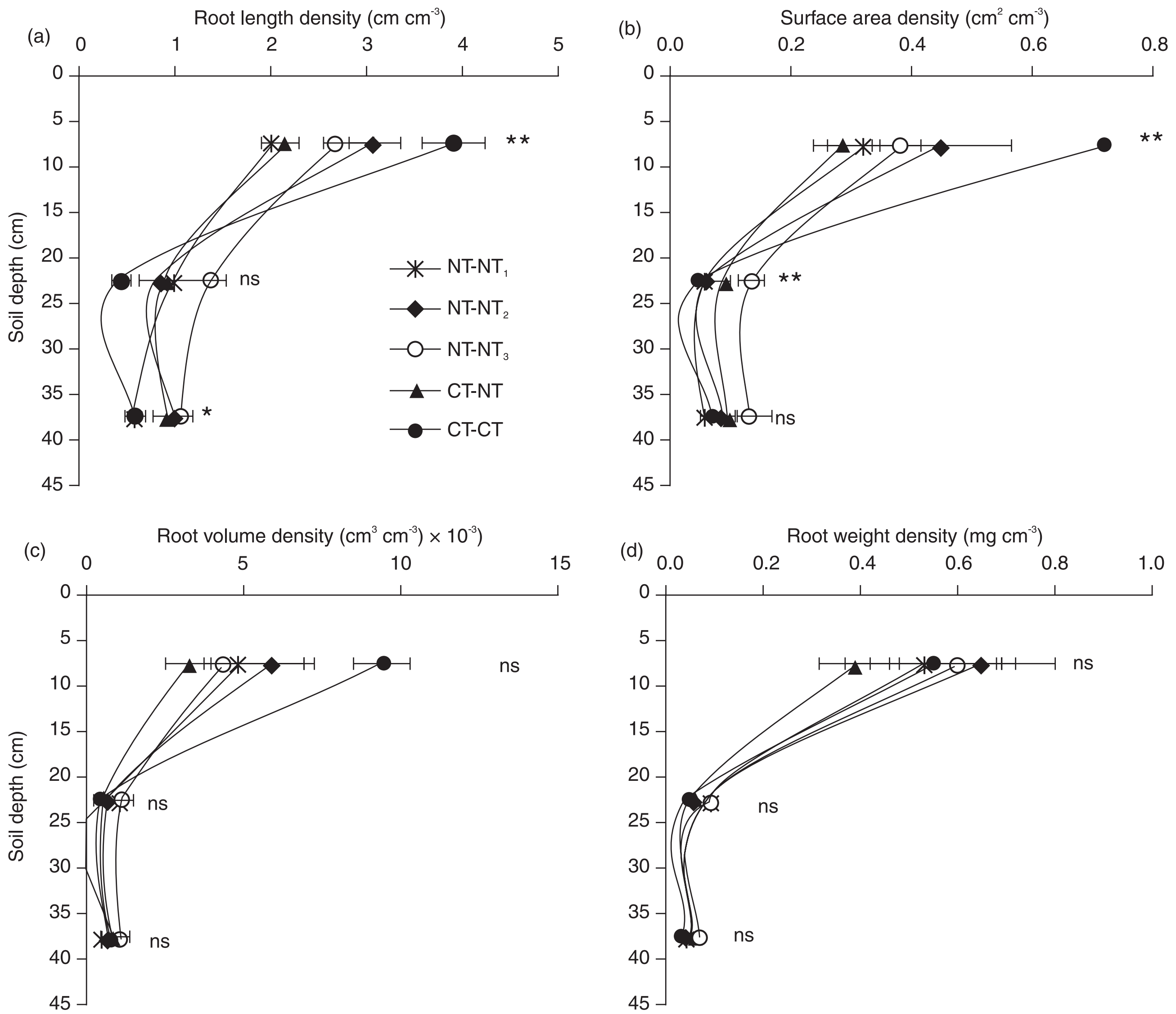

Fig 6 Root morphology in wheat as affected by conservation agriculture vis-a-vis conventional system; horizontal bars are ±SE of mean; *, ** and ns denote significant at $P<0.05$, $P<0.01$ and non-significant, respectively.

and was better than CT-NT in terms of root length density. Therefore, loosening the surface soil proved beneficial, while absence of tillage caused higher soil strength and constraints for root growth. Penetration which simulates the soil resistance to the penetration of roots confirms the surface compaction under the NT-NT practice. In contrast, NT-NT produced higher surface area density in the sub-surface layer. There was also a small marginal increase in root length density at sub-surface under the NT-NT system (Costa *et al.* 2010, Dusserre *et al.* 2012). Results suggests that residue retention as surface mulch coupled with inclusion of legume crop in rotation (NT-NT_3) or use of brown manuring (NT-NT_2) created a better soil subsurface condition for root growth. Addition of no residue (NT-NT_1) did not prove beneficial. Effect of tillage could not be differentiated in root volume and weight densities. However, average of RWD in the soil profile (0-45 cm) also validates the better root growth condition in NT (NT-NT_2 and NT-NT_3, 17-51% higher root volume density than both CT).

Grain and biomass yield of wheat

Tillage and residue treatments significantly influenced the grain and straw yields of wheat. Grain yield in NT-NT_3 recorded similar yield with CT-NT but was higher (8-26%; $P<0.05$) than the rest. The grain yield followed the order: NT-NT_3=CT-NT>NT-NT_2>CT-CT>NT-NT_1. Similar trends were obtained in straw yield also and values varied between 5.95-7.52 t/ha. Adoption of no-tillage and residue retention on soil surface promoted the grain and straw yield of wheat through improving soil physical properties, organic carbon and providing a better environment for root growth, especially in subsurface. Better root and shoot growth (as evident from straw yield) caused more efficient utilization of available resourced and ultimately grain yield was more. Several authors have reported similar result (Gupta *et al.* 2016, You *et al.* 2017).

Conclusion

The present study narrates the potential role of conservation agriculture in rice-wheat system in improving soil physical condition, especially in reducing the sub-surface compaction, even in a shorter period. Although the BD changed marginally, the soil penetration resistance was significantly less in the 15-30 cm layer under the CA. As a consequence, roots in wheat had a better distribution, and contributed improving the yield of the crop. Inclusion of mung bean in the cropping system and retention of its residues had the most visible impact. No-tillage only in wheat did not result in appreciable changes in comparison to other CA or the conventional rice-wheat system.

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