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Soil Hydro-thermal Regimes as Affected by Different Tillage and Cropping Systems in a Rainfed Vertisol

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The present investigation was aimed to study the short-term effect of different tillage and cropping systems on soil hydro-thermal properties under conservation agriculture (CA) practices. The field experiment consists of three different tillage systems [*viz*., conventional tillage (CT), reduced tillage (RT) and no-tillage (NT)] and four cropping systems [*viz.,* soybean (*Glycine max*) + pigeon pea (*Cajanus cajan*) intercropping (2:1), soybean – wheat (*Triticum durum*), maize (*Zea mays*) + pigeonpea intercropping (1:1), and maize – gram (*Cicer arietinum*)]. Results indicated that the surface layer (0-5 cm depth) recorded higher moisture content that decreased with increasing soil depth. The data on soil moisture retention at field capacity (FC) was not significantly influenced by tillage and cropping systems. Among different tillage systems, NT (38.9%, v/v) and RT (38.2%, v/v) recorded higher water content at field capacity than CT (37.5%, v/v). Similar to field capacity, soil moisture retention at permanent wilting point (PWP) was not influenced either by tillage or by cropping systems. Tillage and cropping systems had no significant effect on soil temperature recorded during *rabi* season. It was observed that tillage system, depth and their interaction (tillage × depth) had a significant effect on volumetric heat capacity in dry and saturated soil. Results showed that reduced tillage (0.68%) and no-tillage (0.67%) registered significantly ($P < 0.05$) higher soil organic carbon (SOC) than CT (0.62%) in the 0-5 cm layer. Study results reinforce the significance of CA practices, which is not only affecting soil hydro-thermal properties (soil moisture, temperature and volumetric heat capacity) but also favourably influencing bulk density, porosity and SOC in a Vertisol of Central India.

Key words: Soil moisture, soil temperature, conservation tillage, cropping system, Vertisols

Soil hydrothermal properties are important factors that govern the various physical processes and also known to regulate several plant growth processes including seed germination, seedling emergence, root development, as well as soil microbial activity within rhizosphere (Hillel 1998). Residue mulches largely modify soil temperature that helps to conserve soil moisture, control weeds and enhance soil productivity (Hati *et al*. 2014). He *et al*. (2010) reported that reduce tillage (RT) and no-tillage (NT) recorded significantly higher mean soil temperature (by 0.7-2.4 °C) in the top layer (10 cm depth), compared with conventional tillage (CT) in the cold season during the spring maize. Shen *et al*. (2017) found that tillage had significant effects on soil temperature in black soil of Northeast China and weekly average soil temperature reported under NT was 0-1.5 °C lower than mouldboard plough. However, these results were not consistent over four years of experiment. Further, it is established fact that the soil hydro-physical properties varied with soil temperature fluctuation. For example, the coefficients of saturated hydraulic conductivity and unsaturated hydraulic conductivity of soils depend on the soil temperature (Arkhangel'skaya and Umarova 2008).

Vertisols in India is inherently productive and cover ~15% of total cultivable area. However, very scanty information is available on the soil hydrothermal properties in Vertisols under conservation agriculture practices. Therefore, there is a need to understand the dynamics of soil moisture and temperature regimes under different tillage and cropping systems in Vertisols. Thus, the hypothesis of the study was CA practices would positively affect soil hydrothermal regimes (soil water, temperature and

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Table 1. Tillage and cropping details in Vertisols of Central India

Treatment details	Sub-plot (Cropping System)	
Main plot	First year	Second year
1. Conventional tillage (CT)	1. Soybean + pigeon pea intercropping (2:1)	1. Soybean + pigeon pea intercropping (2:1)
2. Reduced tillage (RT) with residue retention	2. Soybean - wheat	2. Soybean - wheat
3. No tillage (NT) with residue retention	3. Maize + pigeon pea intercropping (1:1)	3. Maize + pigeon pea intercropping (1:1)
	4. Maize – gram	4. Maize – gram

volumetric heat capacity) compared to CT practices. Keeping this in view, the objective was to study soil hydro-thermal regimes under different tillage and cropping systems in a rainfed Vertisol of Central India.

Materials and Methods

Study details

A field experiment was initiated during 2011 (*rabi* season) at the research farm of ICAR-Indian Institute of Soil Science, Bhopal, Madhya Pradesh (23°18′ N, 77°24′ E; altitude 485 m above mean sea level) on deep clayey Vertisol (isohyperthermic Typic Haplustert) with 58% ± 2.2 clay, 22% ±1.8 silt, and 20% ± 1.1 sand in the upper 30 cm of soils. Initial soil fertility status of N, P and K were low (226 kg ha^{-1}), low to medium (16.5-22.5 kg ha^{-1}) and high (582 kg ha^{-1}) status at 0-15 cm depth, respectively. The climate of the area is characterized as hot sub-humid type, with mean of 15 years annual air temperature, mean annual rainfall and potential evapotranspiration are 25 °C, 1130 mm and 1400 mm, respectively. Study site recorded a mean maximum temperature of 40.7 °C during May and mean minimum temperature of 10.4 °C during January, with an average (of 15 years) rainfall of 1099 mm. The initial bulk density (BD), particle density (PD), porosity and per cent stable aggregates of soil (0-15 cm depth) reported as 1.34 Mg m^{-3}, 2.65 Mg m^{-3}, 49.5 and 58.0%, respectively. The experiment was laid out in a split-plot design with three replications (Table 1). Tillage system includes a) CT, which is similar to farmers' practice, and consists of 4 passes of duck foot cultivator including inverting of soil to a depth of ~15 cm followed by sowing in *kharif* (rainy season), and one pass tillage operation followed by sowing in *rabi* (winter season) crops, b) RT, consists of one pass of duck foot cultivator followed by sowing through no-till seed drill in *kharif* and direct sowing during *rabi* season with residue retained at >30% on the soil surface (half of the residue either slanting or laid off on the soil surface due to tillage), and c) NT, direct sowing during *kharif* and *rabi* season with residue retained at >30% on the soil surface. Crop residue under different treatments was measured systematically by line-transect method using a beaded or knotted line for estimating per cent residue cover. The annual addition of residue under soybean based cropping system was about 1.6-2.2 t ha^{-1}, whereas maize based cropping system was about 2.6-3.0 t ha^{-1}.

Soil moisture retention

Soil moisture retention was determined at field capacity (FC) and permanent wilting point (PWP) using a pressure plate apparatus (Soil moisture equipment Corp. Santa Barbara, CA, USA) after completion of four crop cycles. Soil water content was determined gravimetrically (Rayment and Lyons 2011).

Soil temperature and volumetric heat capacity

Soil temperature was measured in the experimental field at weekly interval in the 0 to 5 and 5 to 15 cm depths using a digital thermometer (digital thermometer, Model ETI 2001 Thermometer, UK) during 7.00 AM and 2.00 PM.

The heat flux in soils depends on the heat capacity and thermal conductivity of soils, which vary with soil composition, BD, and water content (Hillel 1998). The volumetric heat capacity (VHC) of a soil is defined as the change in heat content of a unit bulk volume of soil per unit change in temperature. It is expressed as calories per cubic centimetre per degree (Kelvin), or Joules m^{-3}. The value of VHC can be estimated by summing the heat capacities of the various constituents, weighted according to their volume fractions as given by de Vries (1975) and Hillel (1998).

$$VHC = \Sigma f_m C_m + f_o C_o + f_w C_w + f_a C_a$$

Here, f denotes the volume fraction of each phase. The solid phase includes a number of components such as various minerals (m) and organic matter (o), water (w), and air (a) and the symbol Σ indicates the summation of the products of their respective volume fractions and heat capacities. The heat capacity values of mineral, organic matter and water are 0.48, 0.6 and 1.0 cal cm^{-3} °K, respectively. Since, the air density is only about 1/1000 that of water, its contribution to the specific heat of the composite soil can generally be neglected.

Soil samples were collected at different depths and passed through a 0.25 mm sieve. These were used for soil organic carbon (SOC) analysis by adopting wet digestion method of Walkley and Black (1934).

Statistical analysis

Variation in soil properties such as soil moisture, temperature, BD, porosity, SOC and VHC of soil were analyzed using ssp.plot function of the agricolae package within R programming environment. The assumptions of ANOVA (normal distribution of the residuals and equality of variances) were also tested. Means for the treatments were compared with Fisher's least significance difference (LSD) at $P < 0.05$.

Results and Discussion

Effect of different tillage and cropping systems on soil moisture, bulk density and porosity

Mean data of soil moisture retention at FC in surface soil (0-5 cm) varied from 17.1 to 18.9 mm; 18.0-19.6 mm; 18.1-20.7 mm for CT, RT and NT, respectively, after four crop cycles (Fig. 1a, b). The surface soil recorded higher moisture retention and the value decreased with increasing depth with little variation. The data on soil moisture retention at FC was not significantly influenced by tillage system, cropping system and their interaction effect. However, soil depth had a significant effect on soil moisture content. Among different tillage practices, NT recorded relatively higher water retention (39.4%, v/v) than CT (37.4%, v/v) in the 0-5 cm and 5-15 cm depths. After completion of four crop cycles, tillage treatments showed favourable effect on soil moisture retention in the 0-5 cm and 5-15 cm depths. This was due to minimum soil disturbances coupled with residue retention that favoured retention of pores and inter-aggregate pores under RT and NT compared to CT. Despite cropping system did not show any significant effect in the 0-5 cm depth at the end of fourth crop cycle, soils under maize-gram and maize+pigeonpea (1:1) cropping system recorded relatively higher moisture retention at FC compared with other cropping systems, regardless of tillage practices. The interaction effects between tillage practices and cropping systems were not significant on soil moisture retention in all soil depths (Table 2).

Similar to FC data, soil moisture retention at PWP was not influenced either by tillage system or by cropping system (Fig. 1 a, b). The CA enhances soil-water retention more at lower suctions due to formation of intricate network of macro-pores and inter-aggregate pores. This is owing to higher activity of soil fauna *e.g.* earthworms and termites and enhanced soil organic matter content (Hati *et al.* 2014). At higher tensions close to the wilting point (1.5 M Pa), nearly all pores are filled with air, and the surface area and the thickness of water films on soil particle surfaces determine moisture retention. Our findings were corroborated by Thierfelder and Wall (2009), who reported that soil moisture was higher throughout the season in most CA treatments than in the CT plots. Similarly, Govaerts *et al.* (2009) also

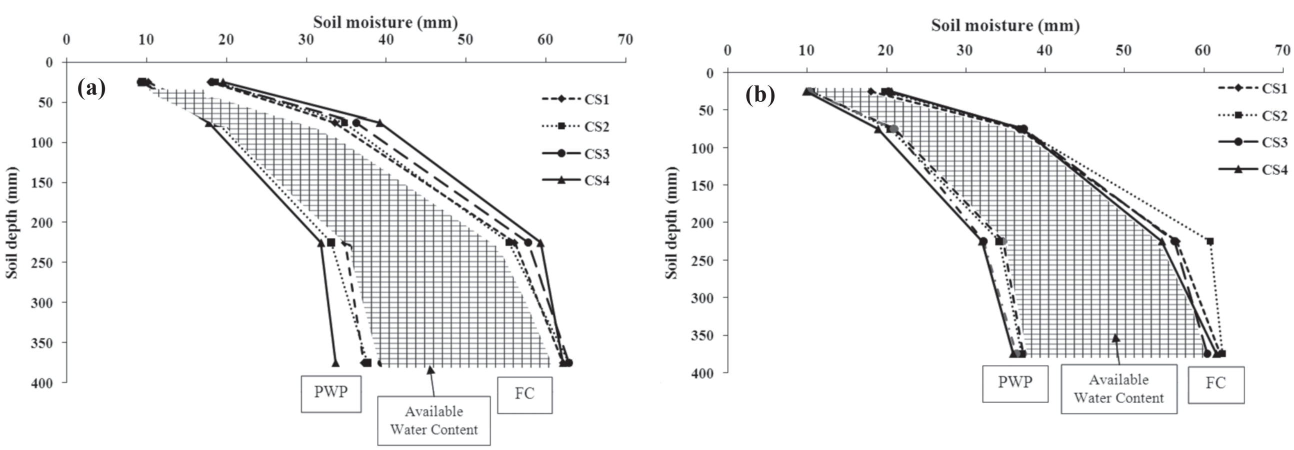

Fig. 1. Soil moisture content (mm) under different tillage system (a) reduced tillage and (b) no-tillage at field capacity (0.33 bar) and permanent wilting point (15 bar); shaded area shows available water content (AWC); CS1: soybean +pigeon pea (2:1), CS2: soybean-wheat, CS3: maize+pigeon pea (1:1), CS4: maize-gram

Table 2. Effect of different tillage and cropping system on bulk density, porosity, soil organic carbon and volumetric heat capacity of soil

	Bulk density ($Mg\ m^{-3}$)				Porosity (%)				Soil organic carbon (%)				Vol. heat capacity of dry soil ($J/\ m^3\ deg$) × 10^6				Vol. heat capacity of saturated soil ($J/\ m^3\ deg$) × 10^6			
	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4	D1	D2	D3	D4
CT																				
CS1	1.31	1.38	1.45	1.59	50.5	50.0	50.0	50.0	0.63	0.56	0.47	0.47	0.99	1.04	1.10	1.21	3.12	3.06	3.00	2.88
CS2	1.32	1.35	1.45	1.62	48.0	49.0	48.5	48.6	0.58	0.51	0.48	0.43	1.00	1.02	1.09	1.22	3.11	3.08	3.00	2.86
CS3	1.32	1.36	1.47	1.64	45.2	45.4	44.4	44.4	0.64	0.52	0.48	0.43	1.00	1.03	1.12	1.24	3.11	3.07	2.98	2.85
CS4	1.32	1.36	1.47	1.62	39.9	38.9	38.3	38.8	0.64	0.53	0.49	0.44	1.00	1.03	1.12	1.23	3.10	3.07	2.98	2.86
Mean	1.32	1.36	1.46	1.62	45.9	45.8	45.3	45.5	0.62	0.53	0.48	0.44	1.00	1.03	1.11	1.23	3.11	3.07	2.99	2.86
NT																				
CS1	1.27	1.31	1.41	1.58	52.0	52.2	51.9	51.4	0.67	0.61	0.52	0.48	0.96	0.99	1.07	1.20	3.15	3.12	3.03	2.89
CS2	1.27	1.29	1.48	1.6	50.5	51.4	51.4	50.3	0.67	0.57	0.53	0.49	0.96	0.97	1.12	1.21	3.15	3.13	2.98	2.88
CS3	1.27	1.29	1.41	1.56	46.7	44.3	46.8	46.3	0.65	0.58	0.51	0.48	0.96	0.98	1.06	1.18	3.15	3.13	3.04	2.91
CS4	1.29	1.32	1.42	1.61	40.2	39.6	41.2	39.1	0.69	0.59	0.53	0.47	0.98	1.00	1.08	1.22	3.13	3.11	3.02	2.87
Mean.	1.28	1.30	1.43	1.59	47.4	46.9	47.8	46.8	0.67	0.59	0.52	0.48	0.97	0.99	1.08	1.20	3.15	3.12	3.02	2.89
RT																				
CS1	1.23	1.26	1.44	1.64	53.5	52.4	45.8	38.0	0.68	0.59	0.55	0.46	0.93	0.95	1.09	1.24	3.18	3.16	3.01	2.84
CS2	1.21	1.25	1.40	1.61	54.3	52.8	47.1	39.4	0.67	0.55	0.55	0.46	0.92	0.95	1.06	1.21	3.20	3.17	3.04	2.87
CS3	1.21	1.24	1.43	1.65	54.4	53.3	46.1	37.7	0.68	0.62	0.56	0.46	0.91	0.94	1.08	1.25	3.20	3.17	3.02	2.84
CS4	1.22	1.24	1.44	1.63	54.0	53.0	45.5	38.7	0.69	0.58	0.52	0.49	0.92	0.94	1.09	1.23	3.19	3.17	3.01	2.86
Mean	1.22	1.25	1.43	1.63	54.1	52.9	46.1	38.5	0.68	0.59	0.55	0.47	0.92	0.95	1.08	1.23	3.19	3.17	3.02	2.85
LSD tillage (0.05)	0.013				0.46				0.02				0.008 × 10^6				0.0105 × 10^6			
LSD CS (0.05)	0.019				0.73				0.019				0.014 × 10^6				0.0160 × 10^6			
LSD depth (0.05)	0.013				0.5				0.015				0.010 × 10^6				0.011 × 10^6			

CT: Conventional tillage, RT: Reduced tillage with residue retention, NT: No-tillage with residue retention, LSD: Bold face numbers are significantly different at $P < 0.05$; CS1: Soybean +Pigeon pea intercropping (2:1), CS2: Soybean-Wheat, CS3: Maize+Pigeon pea intercropping (1:1), CS4: Maize-Gram;
D1:0-7.5 cm, D2: 7-15 cm, D3:15-22.5 cm, D4: 22.5-30 cm

Table 3. Soil temperature recorded during residue burning

Particulars	Soil temperature
Before burning	34.8 - 35.7 °C
During burning	51 - 5 5 °C
5min after burning	40.0 - 41.3 °C

reported that soils under NT with residue retention had higher surface soil water contents compared with tilled soils in the high lands of Mexico.

Bulk density

In general, soil BD increased with increasing depth. Among different tillage systems, CT recorded higher BD than RT and NT (Table 2). The plots under RT registered lower BD (1.22 Mg m^{-3}) followed by NT (1.28 Mg m^{-3}) and CT plots (1.32 Mg m^{-3}). Soil BD data were not affected by cropping system. Lower BD under RT was possibly attributed to residue incorporation and minimum soil disturbances. Similar results were reported by Hati *et al*. (2014) in Vertisols of Central India. Parihar *et al*. (2016) reported that CA practices recorded lower BD under sandy loam soils (Typic Haplustept).

Porosity

Similar to soil BD values, porosity was significantly influenced by tillage practices, depth and their interaction effect (tillage × depth). The RT recorded higher porosity (52.9%) than CT (45.9%). Porosity values significantly decreased with increasing soil depth, regardless of tillage practices (Table 2). Porosity was not affected by cropping systems and its interaction effect with tillage. Our results were similar to the findings of Hati *et al*. (2014) who reported that CT practices improved soil physical environment in Vertisols. Verhulst *et al*. (2010) reported that there is some evidence that the porosity in the topsoil may be greater under NT. However, the extent of increase may be a function of the build-up of organic matter at this depth and enhanced macro-faunal activity.

Effect of conservation agriculture practices on soil temperature and volumetric heat capacity

Before burning of crop residues, soil temperature was around 34-36 °C, while burning of crop residue rose temperature to 51-55 °C (Table 3). Tillage treatments and cropping systems had no significant effect on soil temperature recorded during the *rabi* season (Fig. 2). Minimum soil temperature (0-5 cm) at 7.00 AM and maximum at 2.00 PM varied between 9-20 °C and 23-32 °C, respectively (Fig. 3). At 7.00 AM, soil temperature was higher under RT than CT throughout the growth period; while at 2.00 PM, the trend was reversed between the two treatments. We observed moderation in soil temperature due to presence of crop residue at the soil surface *i.e.* relatively higher soil temperature under RT in the morning hour (7.00 AM) and lower temperature in the afternoon (2.00 PM) (Fig. 2, 3). This result is corroborated with the findings of Cox *et al*. (1990), who reported that the difference between soil temperatures at surface soil was due to residue accumulation. Presence of crop residues regulates the soil temperature depending upon its amount and type. In fact, crop residues usually have reflective as well as conductive properties that bring changes in the

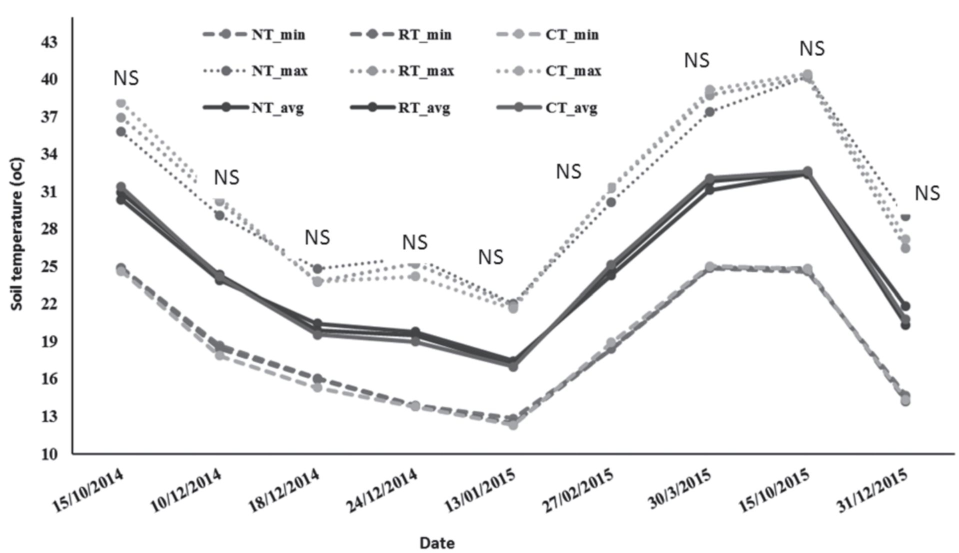

Fig. 2. Effect of conservation agriculture on soil temperature (°C) at the surface layer (0-5cm)

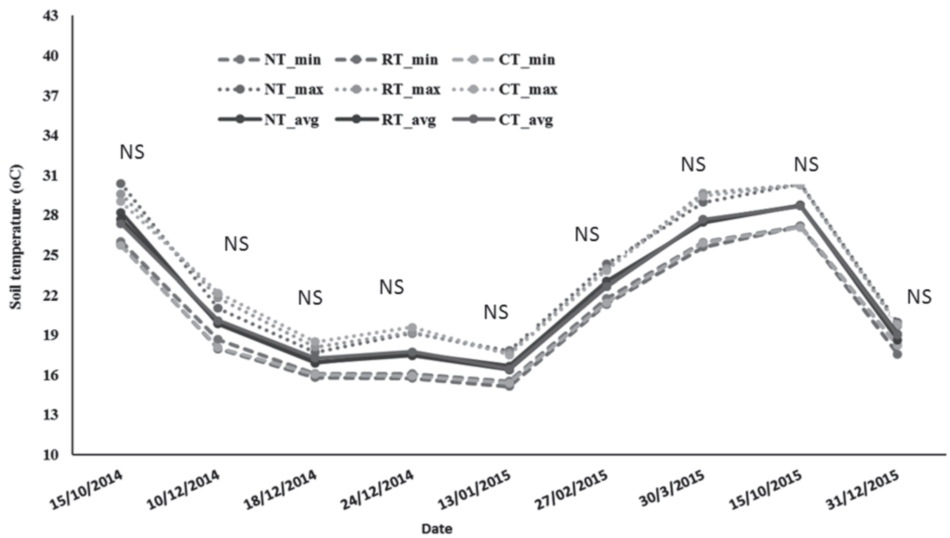

Fig. 3 Effect of conservation agriculture on soil temperature (°C) in sub-surface layer (5-15cm) (NS, Non-significant)

Table 4. Summary of analysis of variance (ANOVA) for selected soil properties under different tillage and cropping systems in a Vertisol

Particulars	BD	Porosity	OC	Vol. heat capacity of dry soil	Vol. heat capacity of saturated soil	Moisture content at field capacity	Moisture content at PWP
Tillage	***	***	**	***	***	NS	NS
Cropping system	NS	NS	NS	NS	NS	NS	NS
Depth	***	***	***	***	***	***	***
Tillage × depth	***	***	NS	***	***	NS	NS
Cropping system × depth	NS	NS	NS	NS	NS	NS	NS
Tillage ×cropping system × depth	NS	NS	NS	NS	NS	NS	NS

NS, non-significant; BD, Bulk density; OC, organic carbon; *** indicates significant at *P<0.01*; PWP, permanent wilting point

surface net-radiation and soil heat-flux density. Several researchers reported that crop residue and other surface mulches modify mineral-soil temperature (Singh *et al*. 2006; Saha *et al*. 2010) by changing the soil thermal properties (volumetric heat capacity, thermal conductivity, and thermal diffusivity).

Results revealed that during the winter month, minimum temperatures (T_{min}) were similar in the NT, RT and CT plots at both soil depths (Fig. 2, 3). However, in the summer month, CT had higher soil temperature than NT. Similarly, when we compared maximum temperature (T_{max}) among all the studied tillage systems, relatively higher Tmax was observed under NT and RT than CT in the winter month, and the opposite trend was found in the summer month. Furthermore, results indicated the similar trend of average temperature (T_{avg}) in all tillage systems (Fig. 2). Shen *et al*. (2018) have also reported that soil temperature was affected by both tillage and residue type. They recorded 0.5-0.9 °C lower soil temperature in NT than moulboard plough during the four year period (2004-2007) in a black soil of Northeast China.

Volumetric heat capacity (VHC)

It was observed that tillage system, depth and their interaction (tillage × depth) had significant effects on VHC in dry as well as saturated soils (Table 2, 4). Lower VHC in dry soil was observed, regardless of tillage practices. This was mainly due to higher porosity and lower BD, whereas opposite trend was observed under saturated soil. Moreover, surface layer (0-5 cm) recorded higher VHC (saturated soil). This was mainly due to higher water content and these values of VHC decreased with increasing depth. Our results corroborated with the findings of Abu-Hamdah (2003), who have reported that water content plays a major role in soil heat capacity, but it is the most difficult to manage. However, soil management practices may significantly affect the VHC as some adverse practices result in soil compaction that will enhance the BD and decrease the soil porosity (Pramanik *et al*. 2015).

Effect of tillage and cropping system on soil organic carbon

Overall, higher SOC was recorded at topsoil after four crop cycles and its concentration decreased with increasing soil depth. Among different tillage systems, RT (0.68%) and NT (0.67%) registered significantly ($P < 0.05$) higher SOC than CT (0.62%) at 0-5 cm. Similarly, in the 5-15 cm depth, RT (0.59%) and NT (0.59%) registered significantly ($P < 0.05$) higher SOC than CT (0.53%). Overall, tillage had significant effect ($P < 0.05$) on SOC after four crop cycles regardless of soil depths. However, cropping systems and tillage system × cropping system interaction did not have significant effect ($P > 0.05$) on SOC (Table 2, 4). Increased SOC in the 0-5 cm depth under RT and NT than CT was possibly attributed to minimum soil disturbances and crop residue retention, which helps in increasing SOC in the surface layers. The present results corroborated with the findings of McCarty *et al*. (1998) and Hati *et al*. (2014). They reported that conservation tillage, particularly NT, leads to a higher SOC concentration in the top soil and alters its distribution within the soil profile. The differences in SOC concentration between tillage treatment were highest in the upper most soil layer where they were in the order as follows: RT > NT > CT. It is manifestation of different interacting factors, such as minimum soil disturbances, increased residue retention/addition, reduced surface soil temperature, higher soil moisture content and decreased risk of erosion.

Conclusions

Short-term effect (4 years) of different tillage and cropping system on soil hydrothermal properties of Vertisols of Central India were examined. Soil moisture retention data at field capacity and permanet wilting point were not significantly influenced by tillage system and cropping system after completion of four crop cycles. Tillage treatments and cropping systems had no significant effect on soil temperature. Results of the study highlight the importance of continuous adoption of conservation tillage practices (NT and RT) coupled with residue retention for a long-term period. This could have positive impact on soil hydro-thermal regimes and other soil properties in a Vertisol of Central India.

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