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ORIGINAL PAPER

Conservation Tillage, Residue Management, and Crop Rotation Effects on Soil Major and Micro-nutrients in Semi-arid Vertisols of India

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Abstract

Due to declining soil quality and increasing climate change, resource conservation technologies are often advocated for the food production system. Conservation agriculture (CA) is one of the technologies that increase soil nutrient status without jeopardizing the soil health and quality. The effects of conservation tillage, residue retention, and cropping systems on soil physical, chemical, and biological properties within the irrigated agricultural system are well established. However, scanty information is available on the combined impact of tillage, residue, and cropping system available on the major and micro-nutrient in the rainfed farming systems. Thus, a field experiment was conducted to measure the short-term effect of CA practices on soil properties and major (N, P, and K) and micro (Fe, Mn, Zn, and Cu)-nutrients in a Vertisol of Central India. The field experiment was laid out in a split-plot design consisting of two tillage systems (TS), conventional tillage (CT) and reduced tillage (RT), as the main plots and six cropping systems (CS) as subplots. A total of 144 soil samples were collected after four crop cycles to assess soil properties and nutrient (major and micro-nutrient) status. Results demonstrated that in the surface soil layer (0–5 cm), the major and micro-nutrient concentrations were higher than subsurface layers, regardless of TS and CS. In the surface soils, soil organic carbon (SOC) varied from 0.58 to 0.60% under CT and from 0.60 to 0.62% under RT. Tillage and cropping systems had a significant effect ($p < 0.05$) on major available nutrients (N, P, and K) at 0–5-cm depth. The DTPA extractable Fe, Mn, Cu, and Zn concentrations exhibited decreasing trends with increasing depth. At 0–5-cm depth, the DTPA-Fe, Mn, Cu, and Zn under CT varied from 7.56 to 9.58 mg kg^{-1}, 15.04 to 15.91 mg kg^{-1}, 1.37 to 1.80 mg kg^{-1}, and 0.57 to 0.62 mg kg^{-1} and under RT varied from 8.25 to 11.16 mg kg^{-1}, 15.65 to 17.73 mg kg^{-1}, 1.54 to 1.80 mg kg^{-1}, and 0.59 to 0.67 mg kg^{-1}, respectively. We concluded that RT practices, coupled with crop residue retention, positively affected major and micro-nutrient distribution and availability in this soil. Results highlight the importance of nutrient dynamics under different tillage and cropping systems and thus improve the nutrient recommendation in the semi-arid eco-region of Central India.

Keywords Conservation tillage · Crop residue retention · Cropping system · Major and micro-nutrient availability · Soil organic C · Sustainable soil management practices

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1 Introduction

Soil is a natural resource known for its vital ecosystem services such as buffering capacity, carbon storage, providing clean air and water, and climate change mitigation (Dalal et al. 2011). Tillage, which directly influences crop production and sustainability, is of great concern when inappropriately used (Kumar et al. 2019); if unattended, it may adversely affect soil conditions and jeopardize sustainable food production. Moreover, loss of fertile topsoil from the arable land through runoff and wind erosion adds to the issues found under conventional farming practices (Singh et al. 2020).

Agriculture production cannot be sustained to meet the ever-growing food demand without good fertile soil and best management practices. Conversion from conventional cultivation practices to conservation agriculture (CA) is often considered a better option for improving nutrient status and enhancing soil health and crop productivity (Saikia et al. 2020). The principles of CA involve; (i) minimum soil disturbance, (ii) maximum soil cover throughout the year through crop residue retention or cover crops, and (iii) diversified crop rotations for gaining higher productivity (Busari et al. 2015). The CA promotes soil health and quality by increasing soil organic carbon (SOC) and enhancing soil aggregation (Lal 2007; Dalal et al. 2011; Somasundaram et al. 2017, 2019), thus improving infiltration and reducing soil erosion losses (Govaerts et al. 2009).

Compared to the worldwide adoption of CA practices in around 11% of total world arable land (Kassam et al. 2015), India is still lagging behind a long way in adopting CA, covering only 5 million ha (3.52% of the total arable area). The probable reasons for non-adoption to new practices are the non-availability of machineries related to CA, lack of proper strategies in implementing CA, and small landholdings. Contrary to CA, conventional systems involve intensive inversion tillage practices coupled with crop residue burning, which accelerates SOC oxidation processes, that results in greater loss of SOC (Somasundaram et al. 2018a, 2018b), causing air pollution from crop residue burning (due to soot particles/black carbon and particulate matter), greenhouse gas emission, and loss of plant nutrients (Baker et al. 2007). It is estimated that about 500–550 million tonnes of crop residues is produced per year in India, of which 91–141 million tonnes of surplus residue is burnt (IARI 2012). Conventional tillage (CT) is aimed at reversing and mixing of a deep layer of soil; incorporating and destroying plant debris; exposing soil pathogen and pests to sunlight for control; and breaking of lump for getting proper tilth for better seed germination/crop establishment; however, these benefits shadowed over the long term in maintaining soil health as CT exposes the soil and hastens SOC losses. Further, intensive seedbed preparation under the conventional system leads to severe soil degradation in terms of soil and nutrient losses (Kaiser et al. 2014). Besides, the conventional system implies the use of farm machinery in multiple tillage operations, which increases the input cost of the farmers. Therefore, it has drawn worldwide attention to revert the land degradation processes through sustainable land management practices (Lal 2007; Somasundaram et al. 2020). The practice of CA has paramount importance in a climatic situation where high temperature stimulates the rapid oxidation of SOC. The CA practices may promote sustainable, efficient use of nutrients by improving nutrient balances and availability in the rhizosphere (Govaerts et al. 2009). However, nutrient management and application are always a challenging task under CA practices due to large quantities of crop residues, sometimes resulting in immobilization of nutrients. Further, understanding the effect of CA and crop residue retention on nutrient status will help strategize the nutrient management and recommendation, as these practices result in recycling nutrients through crop residue decomposition.

Similar to major nutrients, micro-nutrients such as Zn, Fe, Cu, and Mn tend to be present in higher concentrations under no tillage (NT) with residue retentions as compared to CT (Shiwakoti et al. 2019). In contrast, Govaerts et al. (2007) found a non-significant effect of different tillage practices on DTPA-extractable Fe, Mn, and Cu concentrations, although Zn concentration was significantly higher in the surface layer (0–5 cm) under permanent raised beds than CT soil. Du Preez et al. (2001) and Franzluebbers and Hons (1996) found similar effects, while Lopez-Fando and Pardo (2009) also reported higher Zn concentration in NT compared to other tillage systems.

Santiago et al. (2008) reported that Mn, Cu, and Zn concentrations in plants were higher under NT as compared to CT and minimum tillage systems. Higher micro-nutrient concentration in the NT system is attributed to higher SOM under NT systems in rainfed agriculture (Shiwakoti et al. 2019). However, under irrigated systems, the effect of CA is less known. The information regarding the effect of CA on soil properties under the irrigated ecosystem in Indo-Gangetic Plains (IGPs) is plenty (Das et al. 2014) but very scanty under rainfed regions. Although reports are available on most major nutrient status and SOC in CT soils (Srinivasarao et al. 2014; Kushwa et al. 2016), limited information is available on phosphorus and micro-nutrient status under the CA system in the rainfed Vertisols of Central India (Hati et al. 2015; Kushwa et al. 2016; Kushwah et al. 2016). Therefore, this study hypothesized that the adoption of CA practices, even for the short term (< 5 years), could enhance the availability of macro- and micro-nutrients than CT.

2 Materials and Methods

2.1 Description of Study

The field experiment was established at the beginning of the rainy (*Kharif*) season of 2010 at the research farm of ICAR–

Indian Institute of Soil Science, Bhopal, India. The geographical co-ordinate of the experimental site is 23° 18′ 21.91″ N and 77° 24′ 24.40″ E and is situated at 485 m a.s.l. The climate of the study site is characterized as a semi-arid eco-region. More particularly, the summer is hot and humid, and the winter is mild and dry with mean annual air temperature (25 °C), mean annual rainfall (1130 mm), and potential evapotranspiration (1400 mm). The length of the growing period varied from 90 to 150 days. The soil under the study site is a Vertisol (isohyperthermic, Typic Haplustert) with 58% clay, 22% silt, and 20% sand in the top 0–15-cm layer.

The field experiment was established in a split-plot design consisting of two tillage systems (reduced tillage (RT) and CT, farmers' practice) as the main plots and six cropping systems as the subplots, namely, CS1—soybean (*Glycine max*)-wheat (*Triticum durum*); CS2—soybean + cotton (*Gossypium hirsutum*) (2:1) intercropping; CS3—soybean-fallow; CS4—soybean + pigeon pea (*Cajanus cajan*) (2:1) intercropping; CS5—soybean-fallow, rotated with maize-gram/chickpea (*Cicer arietinum*); and CS6—maize-gram/chickpea, with three replications (Fig. 1a, b). The details of the cropping cycle and crop management practice are presented in Tables 1 and 2. The size of each plot was 10 m × 5 m. The CT consisted of summer plowing up to 15-cm depth after residue was removed and 3 to 4 pass tillage operations using tine cultivator, followed by the Kharif (June–October during the monsoon period) and *Rabi* (November–March during the winter period) season crops. The RT included one pass tillage operation (up to 5–10-cm depth) using duck foot cultivator, followed by sowing using zero-till planter for Kharif and Rabi crops.

2.2 Soil Sampling and Analysis

Soil samples were collected using a screw auger (5-cm dia.) at 0–5-, 5–15-, 15–30-, and 30–45-cm depths from all the three replications of each treatment at the end of the fourth crop cycle. The soil samples were collected from three random

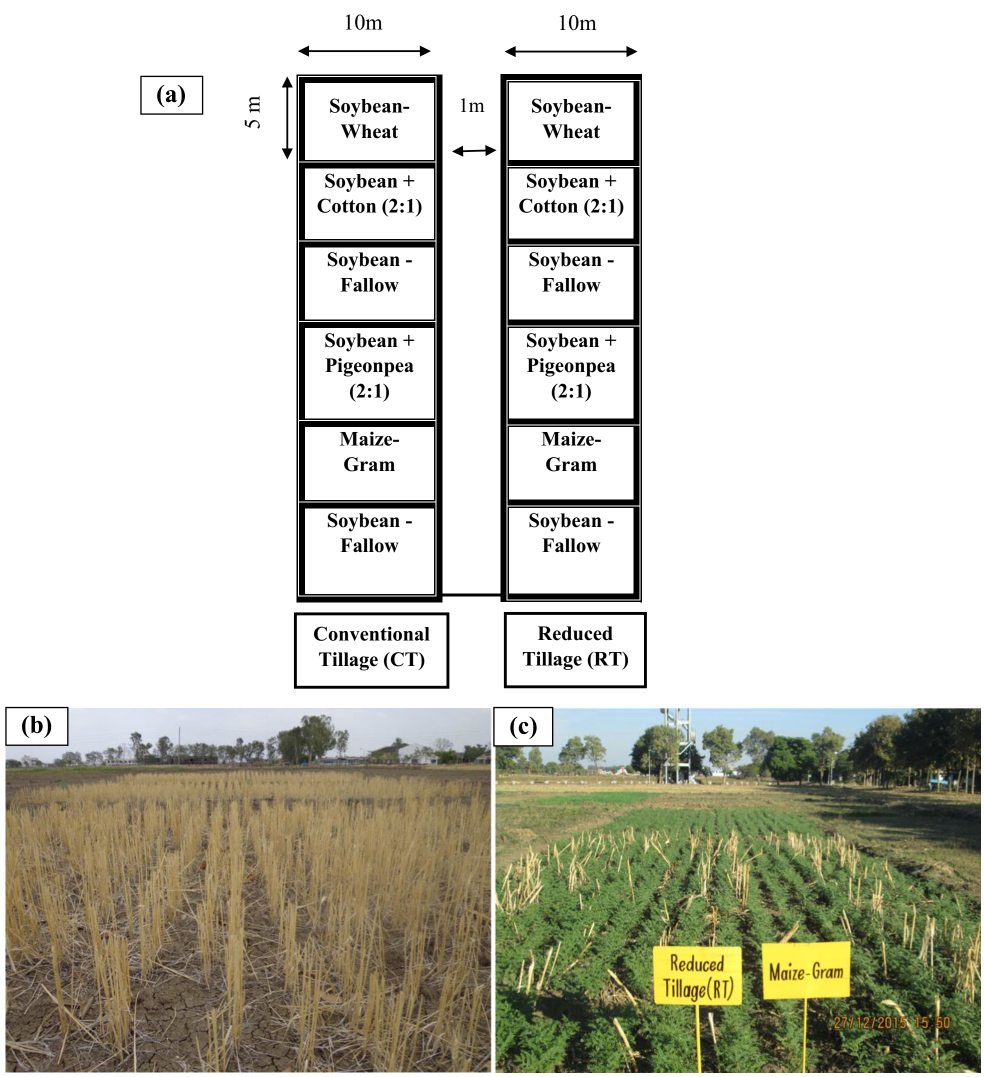

Fig. 1 **a, b, c** A view of layout of one replication (**a**) and crop residue retention (**b**, **c**) under conservation (reduced) tillage in a Vertisol

Table 1 Details of the tillage and cropping systems employed throughout the experimental period

Treatment details	Subplot (crop sequences/rotations)	
Main plot	First year	Second year
1. Conventional tillage (CT)/farmers' practice: 3–4 tillage operations using duck foot cultivator or tine cultivator, residue removal during Kharif (rainy season), and one sweep tillage followed by planting during Rabi (winter) season	CS 1—soybean-wheat	Soybean-wheat
	CS 2—soybean + cotton (2:1) intercropping	Soybean + cotton (2:1) intercropping
	CS 3—soybean-fallow	Soybean-fallow
	CS 4—soybean + P. pea (2:1) intercropping	Soybean + P. pea (2:1) intercropping
	CS 5—soybean-fallow	Maize-gram
	CS 6—maize-gram	Maize-gram
2. Reduced tillage (RT): one sweep tillage during Kharif (rainy season) using duck foot cultivator followed by sowing/planting using no-till planter, residue retained on the field, direct sowing during Rabi (winter) season	CS 1—soybean-wheat	Soybean-wheat
	CS 2—soybean + cotton (2:1) intercropping	Soybean + cotton (2:1) intercropping
	CS 3—soybean-fallow	Soybean-fallow
	CS 4—soybean + P. pea (2:1) intercropping	Soybean + P. pea (2:1) intercropping
	CS 5—soybean-fallow	Maize-gram
	CS 6—maize-gram	Maize-gram

locations in each plot to overcome the heterogeneity within the plot and to obtain sufficient volume for soil analysis. After collection, these samples were composited and sieved through a 2-mm sieve before analysis. Soil pH (1:2.5 soil to water ratio) was determined, as described by Jackson (1973). The SOC was estimated through wet oxidation with potassium dichromate (Walkley and Black 1934). The available (mineralizable) N was determined by distilling the soil sample with alkaline $KMnO_4$ and determining the N trapped in boric acid as NH_3 (Subbiah and Asija 1956). The available P was determined by Olsen's method (Watanabe and Olsen 1965), using 0.5 M sodium bicarbonate (pH 8.5) as extractant. Darco G-60 (Merck, India) was used to absorb the dispersed organic matter and make the filtrate colorless. The available K was determined by flame photometry using neutral ammonium acetate (1 M NH_4OAc pH 7.0), as described by Hanway and Heidel (1952). The available form of Cu, Fe, Mn, and Zn were analyzed by extracting 10-g soil with 20 ml of 0.005 M DTPA, 0.01 M $CaCl_2$, and 0.1 M triethanolamine at pH 7.3 (Lindsay and Norvell 1978). Atomic absorption spectrophotometer (Model Varian Z240 2008, Australia) was used for determining the micro-nutrient concentrations in the extracts.

The crops were harvested manually at maturity and grain yield recorded at the end of four crop cycles. Yields were converted into soybean grain equivalent SGEY (t ha^{-1}) by considering minimum support price (MSP) of 2013–2014 as fixed by the Indian government.

2.3 Statistical Analysis

The effects of tillage practices and cropping systems on soil nutrient concentrations were assessed using ANOVA, considering tillage as the main plot and cropping system as the subplot. Further, we explored the cropping system effect on soil properties under CT and RT. The significant effects were established at $p < 0.05$. The normality and homogeneity of variances were tested using the Shapiro-Wilk normality test and Levene test, respectively. Correlation analysis and principal component analysis (PCA) of studied soil properties were also examined. In this study, PCA was performed considering soil properties under different tillage and cropping systems at 0–45-cm depth. PCA results in uncorrelated variables called principal components (PCs) that are linear combinations of the original variables. All the statistical analyses were performed

Table 2 Experimental crops, fertilizer rates, and row spacing used throughout the experiment

S. No.	Name of crops	Cultivars	Fertilizer rate (N:P:K in kg ha^{-1})	Row spacing (cm)	Season
1	Wheat (*Triticum aestivum* L.)	Malwa Shakti (HI 84–98)	120:26.4:33.2	22.5	Rabi
2	Soybean (*Glycine max* L.)	JS 335	30:26.4:24.9	30	Kharif
3	Cotton (*Gossypium hirsutum* L.)	Bt cotton	90:19.8:37.4	90	Kharif
4	Pigeon pea (*Cajanus cajan* L.)	*Aasha* (local)	30:26.4:49.8	90	Kharif
5	Maize (*Zea mays* L.)	Kanchan 101	120:26.4:33.2	60	Kharif
6	Gram/Chickpea (*Cicer arietinum* L)	JG 130	40:26.4:24.9	30	Rabi

in R statistical software v 4.02. The ANOVA and the normality assumption were performed using the "doebioresearch" package, while the Levene test was conducted using the "car" package. The correlation was performed through the "corrplot" package, while PCA was performed using the "FactoMineR" and "factoextra" package.

3 Results

3.1 Tillage and Cropping System Effect on Soil pH and SOC

In the surface layer (0–5 cm), soil pH values varied from 7.64 to 7.83 (Table 1) under CT and 7.63 to 7.77 under RT (Table S2). Soil pH increased with depth, although it was not affected either by tillage or by cropping system or their interactions; however, it tended to be lower under RT than CT (Fig. 2a; Table 1, S2).

SOC concentrations in the surface soils (0–5-cm depth) varied from 0.58 to 0.60% under CT (Table 1) and 0.60 to 0.62% under RT (Table S2). However, the C stratification ratio did not show any significant differences between RT and CT (data not presented). The SOC concentration decreased with depth, regardless of tillage practices (Fig. 2b; Table 1, S2). At all the depths, SOC concentration was higher in RT as compared to CT. Under RT, soybean-fallow rotated with a maize-chickpea system (CS5) had relatively higher SOC (0.62%) at the 0–5-cm soil layer. However, within the RT, at 5–15-cm soil layer, there was a significant improvement in SOC (0.58%) in CS2 and CS5 (Fig. 2b; Table 1, S2). Further, there was no significant improvement in SOC at 15–30-cm and 30–45-cm depths. The interaction effect between tillage × cropping system × depth on SOC was not significant (Table 3).

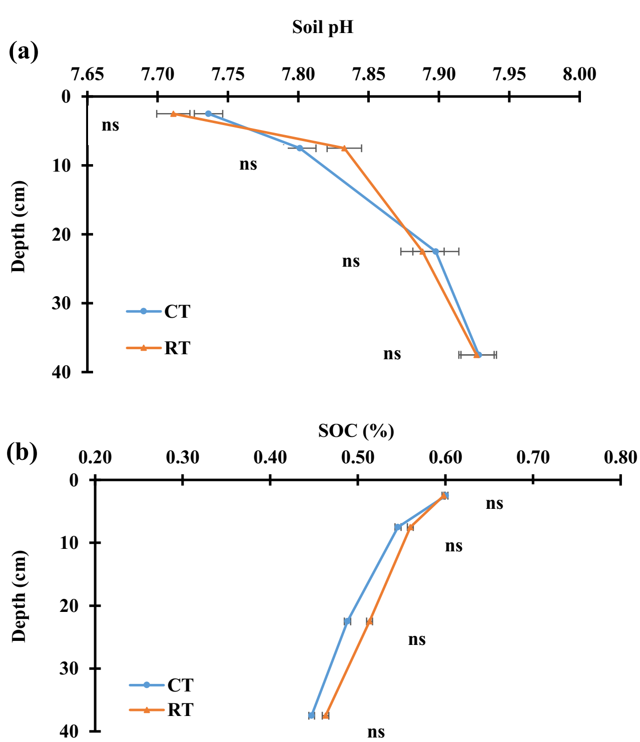

Fig. 2 Effect of tillage and cropping system on **a** soil pH and **b** soil organic carbon after four crop cycles; horizontal bar indicates significantly different at LSD at $p \leq 0.05$; CT conventional tillage, RT reduced tillage

3.2 Tillage and Cropping System Effect on Major Available Nutrients (N, P, and K)

Available N Its concentration in the surface soils (0–5-cm depth) varied from 207 to 228 kg ha^{-1} under CT (Fig. 3a; Table 1) and from 220 to 241 kg ha^{-1} under RT (Table S2). Tillage and cropping systems significantly affected N at 0–5-cm depth (RT > CT). In both tillage systems, the soybean-fallow (CS5) system had higher available N than other cropping systems. Both tillage and cropping systems had a significant effect on top layers (0–5 cm and 5–15 cm) only (Fig. 3a; Table 1, S2). The interaction between tillage × cropping system × depth had a non-significant effect on available N (Table 3).

Available P Its concentration in the surface soils (0–5-cm depth) varied from 20.0 to 22.5 kg ha^{-1} under CT (Table 1) and from 20.7 to 26.4 kg ha^{-1} under RT (Table S2). Overall, the available P concentration decreased with depth (Fig. 3b; Table 1, S2). The tillage system had a positive effect ($p < 0.05$) on available P under RT at 0–5-cm depth only as compared to CT. Under RT, available P was affected ($p < 0.05$) by the cropping system in the surface layer (0–5 cm) only. In particular, compared to other cropping systems (Fig. 3b), soybean + cotton (2:1) and soybean-fallow rotated with maize-chickpea (CS5) have, respectively, the highest (26.4 kg ha^{-1}) and the lowest (20. 7 kg ha^{-1}) available P. Under CT, cropping systems had a non-significant effect on available P. The interaction between tillage × cropping system × depth had a non-significant effect on available P (Table 3).

Available K Its concentration followed a similar trend to available P (Fig. 3c Table 1, S2). Its concentration in the surface soils (0–5-cm depth) varied from 311 to 375 kg ha^{-1} under CT (Table 1) and from 324 to 388 kg ha^{-1} under RT (Fig. 3c; Table S2). The cropping systems under both CT and RT showed a significant effect ($p < 0.05$) on the availability of K at 0–5-cm and 5–15-cm depth. Soybean-fallow (CS3) and soybean + pigeon pea (2:1) (CS4) had higher available K concentrations ($p < 0.05$) as compared to other cropping systems. A similar trend was also observed under RT (Fig. 3c; Table S2). Available K concentrations at 15–30- and 30–45-cm depths were not affected either by tillage or cropping systems. The interaction between tillage ×

Table 3 Significance values (*p* value) of effect of tillage, cropping system, and soil depth and their interaction on soil macro- and micro-nutrients in a Vertisol (pooled analysis)

Source of variation	pH	SOC	AV-N	AV-P	AV-K	AV-Fe	AV-Mn	AV-Zn	AV-Cu
Tillage	0.9525	0.0005	< 0.0001	0.0004	0.0521	0.0001	< 0.0001	< 0.0001	0.1537
Cropping system	0.0980	0.0052	0.108	0.0537	< 0.0001	0.0853	0.0044	0.1411	0.0064
Soil depth	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Tillage × cropping system	0.7528	0.4804	0.033	0.1716	0.9494	0.6380	0.5542	0.5540	0.5262
Tillage × soil depth	0.7439	0.0826	0.880	0.6008	0.3259	0.0760	0.7558	0.9076	0.6887
Cropping system × soil depth	0.9965	0.0101	0.613	0.6453	0.8531	< 0.0001	0.6002	< 0.0001	0.0215
Tillage × cropping system × soil depth	0.9963	0.8604	0.553	0.6077	0.8916	0.7361	0.9972	0.9621	0.8532

AV-N available nitrogen, *AV-P* available phosphorus, *AV-K* available potassium, *SOC* soil organic carbon, *pH* Power of hydrogen; *AV-Fe* available iron, *AV-Zn* available zinc, *AV-Cu* available copper, *AV-Mn* available manganese

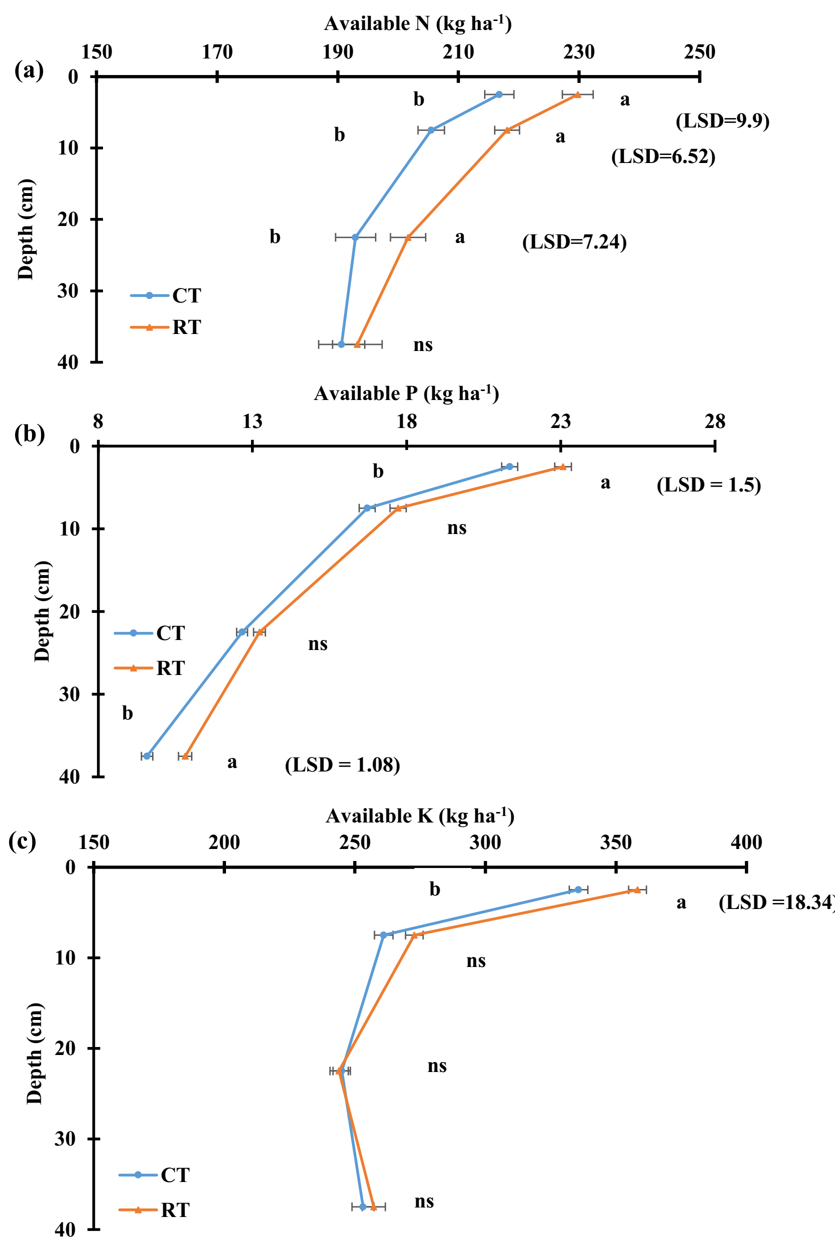

Fig. 3 Effect of tillage and cropping system on major nutrients **a** available N, **b** available P, and **c** available K after four crop cycles; horizontal bar indicates significantly different at LSD at $p \leq 0.05$; CT conventional tillage, RT reduced tillage

cropping system × depth had a non-significant effect on available K (Table 3).

3.3 Tillage and Cropping System Effect on Available Fe, Mn, Zn, and Cu

The available Fe concentration in the surface soils (0–5-cm depth) varied from 7.6 to 9.6 mg kg^{-1} under CT (Table S3; Fig. 4a) and from 8.3 to 11.2 mg kg^{-1} under RT (Table S4, Fig. 4a). The available Fe concentration decreased with depths under both the tillage systems. RT had a significant positive effect on available at 0**–**5- and 5**–**15-cm depths (Fig. 4a). Among various cropping systems, maize-chickpea (CS6) and soybean + pigeon pea (2:1) (CS4) had higher available Fe concentration as compared to other cropping systems under CT at 0–5-cm depth. In RT, soybean + pigeon pea (2:1) showed higher available Fe concentration at all the depths than other cropping systems. Similarly, maize-chickpea (CS6) and soybean-wheat (CS1) had higher available Fe concentrations under RT than CT. However, available Fe concentrations at 5–15-, 15–30-, and 30–45-cm depths were not significantly affected either by tillage or cropping systems. The interactions of tillage × cropping system × depth have a non-significant effect on available Fe (Table 3). The stratification ratio indicates that barring Fe; other micro-nutrients did not differ significantly under different tillage systems (data not presented).

The available Mn concentration varied from 15.0 to 15.9 mg kg^{-1} at 0–5-cm depth under CT (Table S3; Fig. 4b) and from 15.7 to 17.7 mg kg^{-1} under RT (Table S4; Fig.4b). The available Mn concentration decreased with depths under both the tillage practices (Fig. 4b). Higher available Mn concentration was found in the soybean-wheat (CS1) system compared to other cropping systems under RT at 0–5-cm depth. Available Mn concentrations at 15–30- and 30–45-cm depths were not influenced either by tillage or by cropping system. The interactive effects of tillage × cropping system × depth had a non-significant effect on available Mn concentration (Table 3).

The available Zn concentration in the surface soils (0–5-cm depth) varied from 0.57 to 0.62 mg kg^{-1} under CT (Table S3; Fig. 4c) and from 0.59 to 0.67 mg kg^{-1} under RT (Table S4; Fig. 4c). Like Mn, the available Zn concentration decreased gradually with depths under both the tillage practices, which significantly affected the available Zn levels (Fig. 4c). Among the cropping systems, soybean + cotton (2:1) (CS 2) and soybean-wheat (CS 1) system had the higher available Zn concentrations compared to other cropping systems under RT at 0–5-cm depth. Similar to available Fe and Mn, available Zn concentrations were not affected by either tillage or cropping system > 5-cm depth. Interactive effects of tillage × cropping system × depth had a non-significant effect on available Zn concentration (Table 3).

The available Cu concentrations at 0–5-cm depth varied from 1.37 to 1.80 mg kg^{-1} under CT (Table S3; Fig. 4d) and from 1.54 to 1.80 mg kg^{-1} under RT (Table S4; Fig. 4d). Similar to available Mn and Zn, available Cu concentration decreased with depths under both the tillage practices. Unlike the available Mn and Zn, tillage practices did not significantly affect available Cu (Fig. 4d). However, the cropping system had a significant effect on available Cu at 0–5-cm depth under both the tillage systems.

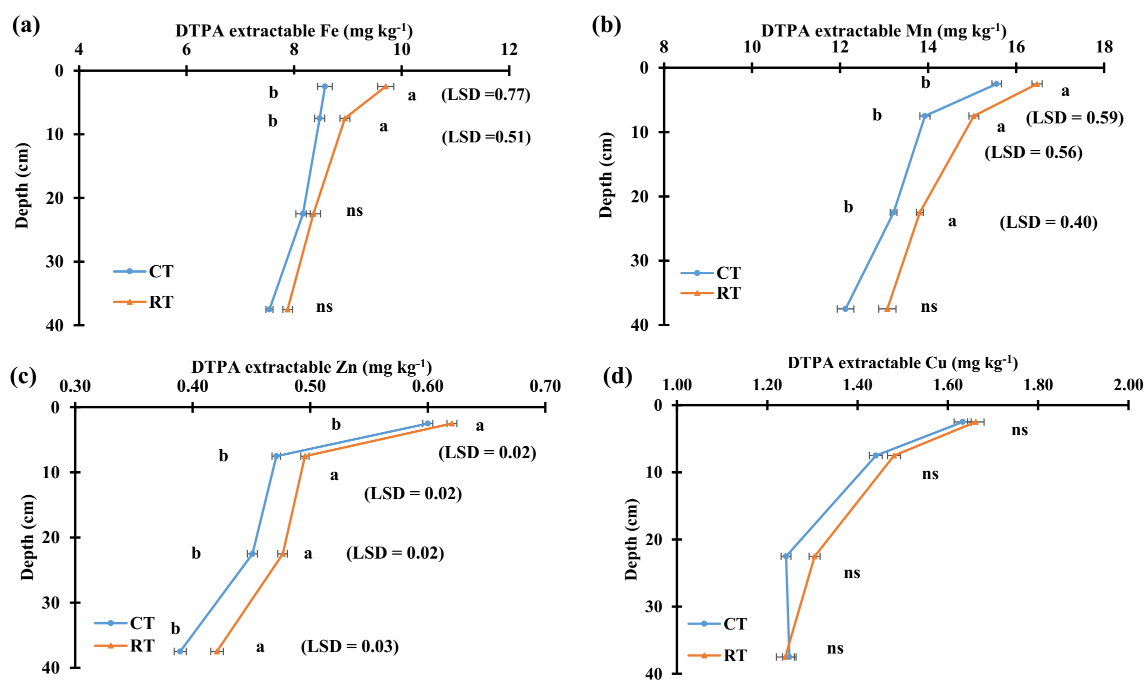

Fig. 4 Effect of tillage and cropping system on micro-nutrients **a** available Fe, **b** available Mn, **c** available Zn, and **d** available Cu after four crop cycles; horizontal bar indicates significantly different at LSD at $p \leq 0.05$; CT conventional tillage, RT reduced tillage

Among the cropping systems, soybean + pigeon pea (CS4) had higher available Cu concentration (1.80 mg kg^{-1}) followed by soybean-fallow (CS3) (1.78 mg kg^{-1}) and soybean-cotton (CS 2) (1.72 mg kg^{-1}) under CT at 0–5-cm depth. A similar trend was also observed under the soybean-fallow and soybean + cotton (2:1) RT system. Both tillage and cropping system did not significantly affect available Cu concentrations below 0–5-cm depth. Interactive effects of tillage × cropping system × depth had a non-significant effect on available Cu concentration (Table 3).

Crop yields were relatively higher under RT possibly due to improved soil properties after four crop cycles (Fig. 6). However, tillage practice had no effect on SGEY after four crop cycles. The effect of tillage will become more visible after a few more years of continuous adoption of conservation agriculture in this region. Based on the PCA of soil properties, PC1 and PC2 accounted for 58.8% and 11.3% of the total variance, respectively (Fig. 7). Except for available N and available Fe concentrations, all the properties were represented by the PC1. Further, PCA biplots were constructed using PC1 and PC2 to determining the separation between the tillage treatments based on soil major and micro-nutrients (Fig. 7; Table S5).

4 Discussion

Both soil pH and SOC (or SOM) affect the availability of major and micro-nutrients. Knowledge of the vertical distribution of available major and micro-nutrients in different tillage practices and cropping systems is crucial in understanding the inherent capacity of the soil to supply major and micro-nutrients and the extent of the modification of this nutrient-supplying capacity with tillage and different crop rotations. It will provide optimum fertilizer recommendations for crops for realizing sustainable crop productivity and ensuring food security in this region.

Soil pH was not significantly influenced either by tillage practices or by cropping system, although it tended to be lower in RT than CT. Lower pH in NT than CT and mouldboard plow (MP) was due to the acidifying effect from mineralization of organic matter, nitrification of surface-applied N fertilizer, root exudation (Neugschwandtner et al. 2014), and ammonium-based fertilizers (Dalal et al. 1991). The decrease in soil pH is a short-term effect owing to two main reasons: the production of organic acids during decomposition of crop residues and microbial respiration (Hulugalle and Weaver 2005) and the high buffering capacity of the clayey soil (> 55% clay content) containing smectitic clay minerals (Somasundaram et al. 2018a, 2018b). We have also observed a significant negative correlation between pH and SOC ($r = -0.54^{**}$) in the surface layer (0–5 cm), indicating the acidifying effect due to relatively higher SOC (although not significant) under RT. Similar findings have previously reported by Franzluebbers and Hons (1996) and Limousin and Tessier (2007). Indeed, we observed the effect of tillage practices on SOC at 0–5- and 5–15-cm depth. The trend of higher SOC concentration in RT than CT was due to surface placement of crop residues and subsurface contribution through root biomass decomposition. The slow residue decomposition is due to the placement of crop residue on the soil surface with less contact with soil microorganisms (Schomberg and Steiner 1999) and the reduction in mineralization rate of SOM due to physical protection of SOM within the soil aggregates making it less available for decomposition by soil microorganisms under NT (Khorami et al. 2018). Hati et al. (2015) reported that NT leads to a higher SOC concentration in the topsoil (0–5 cm) and alters the distribution of SOC within the soil profile. Bhattacharyya et al. (2012) also reported that reduction in tillage intensity led to a significantly higher SOC accumulation in the surface soil layer (0–5 cm) after 6 years of cropping in a sandy clay loam soil (Typic Haplaquept) in the western Himalayas. Many other researchers have reported that SOC concentration in the surface soil was higher under long-term NT and RT systems than CT (Dalal et al. 2011; Somasundaram et al. 2017). Our results corroborated the findings of Kushwah et al. (2016). They reported that wheat residue incorporation/retention on soil surface coupled with supplementary nutrient inputs increased SOC levels in a Vertisol of Central India. It is evident that the SOC concentration under CA increases due to differential interacting factors on C inputs and decomposition, such as minimum soil disturbance, increased residue retention/addition, changed soil hydrothermal regimes, and reduced erosion (Blevins and Frye 1993). The results of higher SOC in the RT system emphasize the importance of regular addition of crop residues and minimum soil disturbance to maintain SOC levels in Vertisols, especially under prevailing high temperature (~40–45 °C) and low rainfall situations in the semi-arid region.

According to Franzluebbers and Hons (1996), tillage, residue management, and crop rotation greatly impacted nutrient distribution, movement, and transformation in soils. Increased stratification of nutrients under NT is often recorded, with higher conservation and availability in the surface layer (Franzluebbers and Hons 1996; Shiwakoti et al. 2019) due to the surface placement of crop residues that favors higher root density near the soil surface under NT than CT (Qin et al. 2004). Similarly, Mackay et al. (1987) reported that a significantly higher proportion of nutrients was taken up from the top layer (0–7.5 cm) under NT than CT.

The availability of mineral soil N for plant uptake relies on the rate of C mineralization. NT is often associated with a lower N availability due to greater immobilization by the crop residue retention on the soil surface (Bradford and Peterson 2000) although the net immobilization period may be transient. Moreover, in the long run, the temporary immobilization of N under NT minimizes the losses of mineral N by leaching and denitrification (Follet and Schimel 1989). According to Schoenau and Campbell (1996), a higher immobilization under CA can increase the conservation of soil and fertilizer N in the long run, with initial higher N fertilizer application decreasing over time owing to decreased losses by soil erosion and the accumulation of a greater portion of easily mineralizable organic N.

The higher available P in the 0–5-cm layer, we observed under RT, coupled with crop residue retention, is congruent with the findings of Duiker and Beegle (2006), who reported greater extractable P levels under NT than in CT, mainly due to the minimum mixing of the fertilizer P with the soil, resulting in lower P-fixation. This trend is beneficial when P is a limiting nutrient, but it may pose environmental problems because of the great possibility of soluble P losses in runoff water and subsequent contamination of groundwater (Duiker and Beegle 2006). In surface layers, P concentrations were higher across all tillage systems as compared to subsurface layers, but most distinctly under CT (Duiker and Beegle 2006). While a portion of P would be directly fixed by soil particles when P fertilizer is applied on the soil surface, when P is banded (in this study) as a basal application beneath the soil surface, there was a likely chance of higher P stratification partly owing to recycling by plants (Duiker and Beegle 2006). Thus, there is a possibility of a lower P starter fertilizer requirement under NT in the long term due to high available P levels in the surface layer. However, the subsurface application of P under NT may be beneficial if the surface soil dries out regularly during the crop growing season as it happens in the semi-arid regions (Mackay et al. 1987). Similar to our results, Kushwah et al. (2016) found an increased availability of P at 0–5- and 5–15-cm depths under CA with wheat residue retention.

Available K concentrations were considerably influenced by tillage and cropping system at 0–5-cm depth. K fertility enhancement is frequently reported in crop management practices of organic addition and residue recycling, as 90% K remains in crop residue (Srinivasarao et al. 1999). It was possibly due to surface retention of crop residue and application of K fertilizer with minimum mixing with soil and higher root density in the RT as compared to the CT. Similarly, Franzluebbers and Hons (1996) reported that NT practices conserve and enhance the availability of nutrients such as K in the top layer, where crop roots proliferate and utilize it. Govaerts et al. (2007) reported that concentrations of K, with residue retention, were 1.43 to 1.65 times higher under permanent raised beds than under CT raised beds at 0–20-cm depth. Other studies have found higher extractable K levels near the soil surface as tillage intensity decreases (Lal et al. 1990). Du Preez et al. (2001) reported enhanced levels of K under NT than CT, but this effect decreased with depth. On the other hand, Follett and Peterson (1988) indicated a higher or similar level of extractable K under NT compared to mouldboard tillage. However, Roldan et al. (2007) observed a non-significant effect of tillage or depth on available K.

Available Fe, Mn, and Zn concentrations were considerably higher under RT than CT at 0–5-cm depth after four crop cycles. However, available Cu concentration was not significantly influenced by tillage practice, although it was significantly affected by the cropping system at 0–5-cm depth under both the tillage systems. Overall, the RT, coupled with residue retention/residue recycling, has favored the micro-nutrient availability in this Vertisol in Central India. Similarly, Franzluebbers and Hons (1996) reported that available Zn, Fe, Cu, and Mn concentrations were relatively higher under NT than CT, especially available Zn and Mn being higher near the soil surface due to surface placement of crop residues. Our results corroborated those of Jat et al. (2018), who reported that available Zn and Mn concentrations were significantly higher under CA than under CT in sodic soils of Karnal, north-western India.

Irrespective of the tillage practice, the soil in this study had a high available Fe concentration according to the critical limits identified by Katyal and Sharma (1991), contrasting with the low to the medium status of available Fe concentrations in other cultivated Vertisols in India (Somasundaram et al. 2009). However, with continual cropping and Fe removal with the exported biomass, the available Fe concentrations will likely to decrease in the future. Therefore, it is essential to monitor the available Fe concentrations with changes in tillage and cropping systems so that appropriate remedial action can be taken before the crop yields are adversely affected by Fe

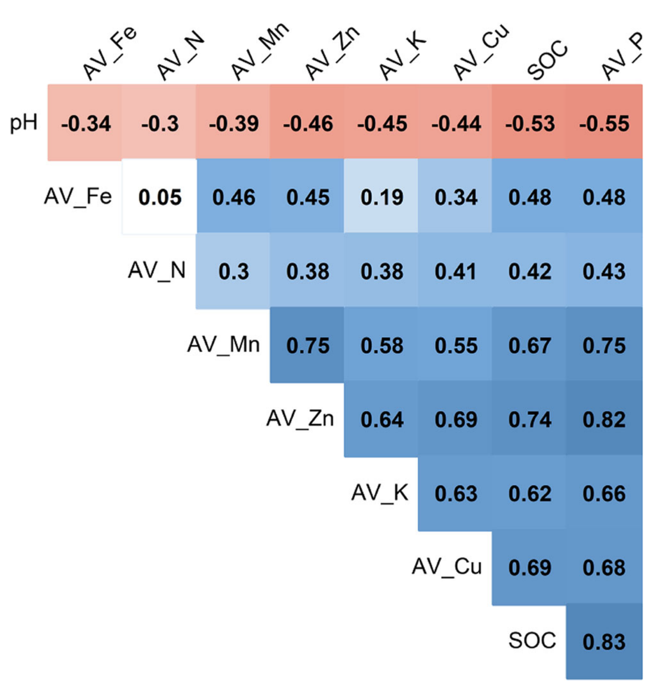

Fig. 5 Correlation matrix for different soil properties. Value in unshaded box indicates significance at $p < 0.05$; CT conventional tillage, RT reduced tillage

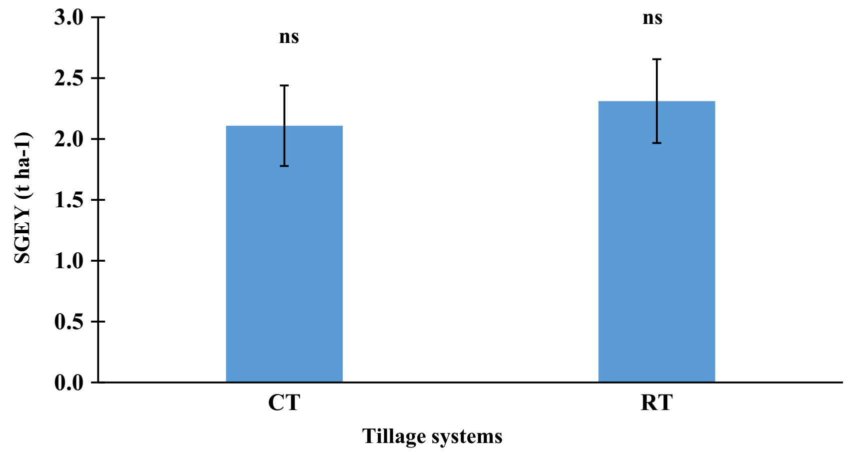

Fig. 6 Soybean grain equivalent yield (SGEY, t ha^{-1}) under different tillage systems (averaged over six cropping systems); CT conventional tillage, RT reduced tillage, ns non-significant

deficiency. The available Mn concentrations in this soil were under the sufficiency range (11–16 mg kg^{-1}) in both the surface and subsurface soils, similar to other Vertisols in India (Katyal and Sharma 1991). Critical limits for available Zn concentrations, identified for Indian soils by Takkar and Mann (1975), are < 0.6, 0.6 to 1.2, and > 1.2 mg kg^{-1} for deficient, medium, and high, respectively. Generally, the Zn level below 0.6 mg kg^{-1} is considered a critical limit, which may affect crop growth and productivity. Except for the surface soil (0–5 cm), available Zn concentrations were in the deficiency range (< 0.6 mg kg^{-1}). Somasundaram et al. (2009, 2011) also indicated that the cultivated Vertisols had marginal levels of Zn.

Compared to the critical level given by Katyal and Sharma (1991), our soils presented high available Cu concentrations, contrasting with the medium to the high status of Cu in Vertisols of the region (Somasundaram et al. 2009). However, with continual cropping and Cu removal with the crop, the available Cu concentrations will likely to decrease in the future. Therefore, it is essential to monitor the available Cu concentrations so that appropriate remedial action can be taken before the crop yields are adversely affected by Cu deficiency.

Among soil properties, soil pH has been primarily identified as the vital factor governing the availability of both major and micro-nutrients in soil. Changes in soil pH influence the electrical charge on the soil particles, which greatly affect the trace metals availability (Shiwakoti et al. 2019). Besides, all the micro-nutrients, namely, Mn, Zn, Fe, and Cu, are typically influenced by the soil environment (Brady 1984). In the studied soils, SOC and pH have strong and opposite correlations (positive and negative, respectively) with N, P, K, Fe, Mn, Zn, and Cu concentrations (Fig. 5). Both Fe and Mn are affected

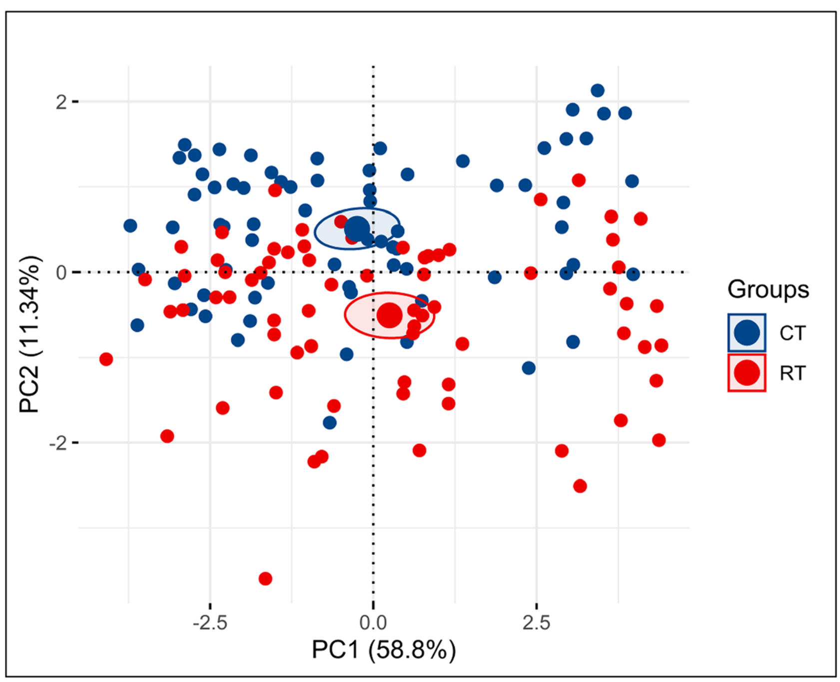

Fig. 7 Biplot indicating tillage effect on the first and second principal component at 0–45-cm depth (number shows PC score of each observation); CT conventional tillage, RT reduced tillage

by oxidation-reduction reactions and soil pH. The enhanced availability of micro-nutrients (Fe, Mn, Zn, and Cu) with an increase in SOM might be attributed to the greater availability of chelating agents (Shiwakoti et al. 2019). A slight variation in pH could alter the stability of both soluble and insoluble organic complexes and thus Zn availability (Shiwakoti et al. 2019). Under alkaline pH range (> pH 7.5), the formation of ZnO_2 ions resulted in a reduced availability of Zn (Kanwar 1976). It indicates that tillage practices influence the soil major and micro-nutrients after the 4-year tillage and cropping systems. Mloza-Banda et al. (2016) also used PCA to separate the influence of treatment effect under CA in Southern Malawi.

4.1 Practical Applications and Future Research Prospective

Improving SOC in the rainfed semi-arid region of India remains a challenging task due to high temperature (~45-50 °C) during the summer season. The CA provides better physical protection of soil from wind and water erosion due to its in-built components of crop residue retention and minimum soil disturbance. From this study, we could infer that the crop residue retention/addition plays a crucial role in improving not only SOC but also available major and micro-nutrients. It may also improve soil hydrothermal properties such as moderation of soil temperature and higher soil water retention due to less evaporation when crop residues are retained on the surface in the semi-arid region (Somasundaram et al. 2018a, 2018b). Therefore, an optimum level of residue retention (quantity of residue) and tillage operations (reduced intensity and number of tillage operations) greatly influences the soil health, crop productivity, and conservation of energy and labour cost in the semi-arid region. One of the possible strategies to increase the adoption of CA technologies in the rainfed region is by providing incentives to farmers, based on carbon footprint/storage and other ecosystem services through residue retention (Lal 2013; Somasundaram et al. 2020).

5 Conclusions

We investigated the short-term effect of conservation agriculture practices on the soil organic carbon and major and micro-nutrient status in a rainfed Vertisol of Central India. Soil pH was not influenced either by tillage or by cropping system although it tended to be lower in reduced tillage than conventional tillage. We found a relative improvement in soil organic carbon under reduced tillage compared to conventional tillage at 0–5-cm depth. Since soil organic carbon was positively related to available nitrogen, phosphorous, potassium, iron, manganese, zinc, and copper concentrations and negatively with soil pH, even small changes in these properties under reduced tillage lead to higher concentrations of these plant nutrients than conventional tillage. Multivariate analysis using principal component analysis indicated significant impact of tillage treatment on the surface layer (0–5-cm depth) only. Therefore, conservation agriculture, residue retention, and crop rotation have a positive impact on major and micro-nutrient distribution in Vertisols of Central India. Thus, conservation agriculture is often recognized as sustainable land management practices for enhancing soil health in the semi-arid region of Central India. Results of this study will assist in strategizing nutrient recommendation and management of soils under conservation agriculture in semi-arid eco-region of India and also useful in a similar agro-ecological region for managing Vertisols for better soil health and crop productivity.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that there is no conflict of interest.

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