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Changes in Soil Physical Properties and Available Micronutrients as Influenced by Tillage and Weed Management Strategies under Diversified Cropping System

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ABSTRACT: The degradation of the soil caused by intensive tillage operations is a considerable solicitude for the sustainable crop production in Southern Telangana Zone (STZ), India. The farmers have adopted cotton and maize production under conventional agricultural practices which is well-known to have a bearing on soil depletion. Thus, conservation agriculture (CA) practices are necessitated to monitor the changes on important soil physical properties *viz.*, soil particle size distribution (soil texture), soil bulk density (SBD), maximum water holding capacity (MWHC), total porosity (TP) and soil available DTPA extractable micronutrients *viz.*, manganese (Mn), iron (Fe), copper (Cu) and zinc (Zn) as influenced by tillage practices and weed management options after harvest of monsoon cotton and winter maize crops (after third year) with CA. Three tillages (main treatments); T_1: conventional (CT) – conventional (CT) – fallow, T_2: CT – zero tillage (ZT) – zero tillage (ZT) and T_3: triple ZT + residue retention (R) and weed management (sub-treatments): herbicides (W_1 and W_2), W_3: integrated weed management (IWM) and W_4: unweeded were laid in split-plot design. soil samples collected at 0 –15 cm, post-harvest of monsoon cotton and winter maize were analysed for soil physical properties and available micronutrients and SBD was determined in-field at 0 –15 and 15 – 30 cm soil depth by following the standard protocols. The salient findings were: higher availability of DTPA extractable micronutrients in the order; Fe > Mn > Zn > Cu in monsoon cotton than winter maize after harvest, greater MWHC (8.05% – 8.43%), SBD (5.38% – 11.51%) in 0 – 15 cm after maize, but reduced SBD (4.88%) in 15 – 30 cm soil depth after cotton, and a reduction in TP (3.66% – 6.68%) under conservation tillage (T_3) by both crops compared to the initial values and T_1. The soil textural class was sandy clay loam. Weed management treatments did not have any significant variation in general. These results indicate the advocacy of conservation tillage (T_3) as a win-win for restoring the degraded soils in STZ of India.

Keywords: Soil health, Soil quality, Conservation Agriculture, Soil degradation, Soil properties, Conservation tillage.

INTRODUCTION

Conservation agriculture (CA) is a sustainable production system that shield and preserve the soil resource besides improving sustainable crop production. The soil is degrading rapidly due to intensive use of tillage operations, shrinking away precious natural resources available for crop production and other agri-related endeavours. This situation necessitates the need for Conservation Agriculture (CA) practices to restore the soil quality, enrich soil organic carbon (SOC) and also to feed the population of India, projected to be about 1.48 billion by 2030 (Laxmi *et al.*, 2019). According to Food and Agricultural Organization (FAO, 2022), CA is a concept of resource saving agricultural crop production, based on enhancing the natural and biological processes above and below the ground on a long-term basis. CA involves minimum soil disturbance, permanent soil cover through crop residues or cover crops, and crop rotations for achieving higher productivity.

Cereal-based crop production is predominant in Southern Telangana State and contributes to approximately 40% of the total cereal production of the country. Maize is the second most important crop grown during the winter season, after rice in Telangana state, India. It was cultivated in 0.187 million hectares in 2020-21, with a production of 1.307 million tonnes and productivity of 7.01 tonnes per hectare (Agriculture action plan, 2021). Currently, a genetically modified cotton is widely cultivated by Indian farmers. In Telangana state, cotton crop was grown in 2.383 million hectares area with a total production of 10.113 million tonnes and productivity of 721 kilograms per hectare during monsoon, 2020-21 (Agriculture action plan, 2021).

However, these urbanization and industrial agricultural practices with over-use and excess chemical fertilizers have been associated with the depletion of available micronutrients and deterioration of overall soil quality (Nthebere *et al*., 2023). Soil micronutrients play a pivotal role in plant nutrition, food security and their availability in the soil determine crop yields, thus, the linkage between long-term specific soil management practices like Conservation agriculture (CA) through various tillage systems and weed control practices should be assessed in order to understand soil management practices which sustain the soil resources (Zulu *et al*., 2022). Several research studies have reported an improvement on some soil physical properties and soil micronutrients particularly on the soil surface under CA.

Soil tillage is a crucial factor that alters the soil's physical properties. Among the crop production factors, tillage contributes up to 20% and affects the sustainable use of soil resources through its influence on soil physical properties (Alam *et al*., 2014). Important soil properties such as availability of nutrients and water to the plant, supporting capability, root penetration, the flow of air and heat *etc*., are closely associated with soil physical properties (Wartini *et al*., 2023). These in turn affect other soil properties (chemical and biological). Kharia *et al.* (2017) had indicated that soil available DTPA-extractable micronutrients (Zn, Fe, Cu and Mn) were significantly higher under Zero tillage with wheat residue retention compared to Zero tillage without wheat residue retention and conventional tillage with wheat residue retention plots in a sandy loam soil at Ludhiana, India. The increase in micronutrient availability was greater for Fe and Cu (12-14%) in comparison with the increase in the Zn and Mn (3-6%).

The lack of manual labour available for manual weeding brought about a significant increase in pre-emergence and post-emergence use of the herbicide in cotton and maize crops (Nthebere *et al*., 2023). Several research findings have substantiated the negative as well as the positive impact of agrochemicals on soil and crop productivity (Dhankar *et al*., 2021). However, overuse and excessive application of such herbicides tend to exude into the soil environment consequently bio-accumulating and producing of a large quantity of the residues which in turn result in micronutrient and macronutrient imbalance and quality-drop off in crop production. Hence, the current three years field study was conducted to monitor the changes on selected soil physical parameters (soil particle size distribution and soil textural class, soil bulk density, maximum water holding capacity and total porosity) and available micronutrients (manganese, iron, copper and zinc) as influenced by tillage practices and weed management options after third year (after harvest of cotton, 4th crop cycle and maize, 5th crop cycle) in cotton-maize-*sesbania* cropping systems.

MATERIALS AND METHODS

Site description

Location of the experimental site: The present on-going field experiment was conducted on the fixed plots at college farm, All India Coordinated Research Project on Weed Management, Professor Jayashankar Telangana Sate Agricultural University, Rajendranagar, South Telangana Zone, India in *Rabi* (Winter season) 2022-23 after third year in the 4th crop cycle (Monsoon cotton crop) and 5th crop cycle (Winter maize crop). The initiation of the study was during the year 2020 in *Kharif* (Monsoon), *Rabi* (Winter) and Summer seasons under cotton, maize, *sesbania* rotation respectively. Geographically, the experimental field is situated at 17^0 19' 18'' North latitude and 78^0 24' 37'' East.

Climate: The climate of the area is semi-arid tropical. The average annual rainfall of the region is 708 mm. The average annual temperature is 24.8˚C and the monthly mean maximum and minimum temperatures vary between 32.8 to 16.8 ˚C. Summers (March– June) are hot and humid, with average highs in the mid-to-high 30˚C. Maximum temperatures often exceed 40°C between April and May. The coolest temperatures occur in December and January when the lowest temperature occasionally drops to 10 °C. More than 75% of rainfall is due to the South-West monsoon and occurs between June to September.

(highlighted with red square line having 36 plots) at college farm, PJTSAU, Rajendranagar.

Fig. 1. Satellite view of the experimental field.

Weather during the crop growth period: The data on weather parameters during the crop growth period was recorded from the meteorological observatory located at Agricultural Research Institute, Rajendranagar, Hyderabad. During the experimental period in the year 2022-2023, total rainfall received was 1140 mm received in 65 rainy days. Late-onset of monsoon was observed with rainfall mostly received in August, September and October months. The monthly mean bright sunshine hours varied from 2.9 to 9.1 hours with an average of 6.0 hours, mean evaporation was 3.0 to 6.9 mm with an average of 5.0 mm and mean wind speed was in the range of 2.7 to 9.5 km hr^{-1} with an average of 6. 1 km hr^{-1}. These were similar to the normal sunshine hours, normal wind speed and normal evaporation in general. The monthly mean maximum temperature during the crop growth periods ranged from 28.7 to 35.4 °C with an average of 32. 1°C while the mean monthly minimum temperature varied from 13.7 °C to 22.9°C with an average of 18.3 °C, respectively. The average relative humidity during the crop growth season fluctuated from 86.1 % to 49.8 % with an average of 68 %.

Soil characteristics: The soil of the experimental field comes under the soil order *Inceptisols*. This soil is sandy clay loam in texture, red chalk in colour, slightly alkaline in soil reaction due to presence of lime concretion in the lower horizon. Details of some important physical, chemical and physico-chemical characteristics of the surface soil (0 – 15 cm) of the experimental site at initiation of experiment are depicted in Table 1.

Experimental design and treatments: The experiment was laid out in split plot design with main plots and sub-plots treatments and replicated thrice. The treatments consist of combination of three tillage (s) as the main plots *viz*., T_1: conventional tillage (CT) – conventional tillage (CT) – fallow (no *Sesbania*), T_2: conventional tillage (CT) – zero tillage (ZT) – zero tillage (ZT) and T_3: triple zero tillage (ZT) + residue retention (R) for cotton, maize and *Sesbania*, respectively (Table 2a). In T_1: conventional tillage treatments, the field was ploughed twice followed by rotovator and sowing. For T_2: zero tillage treatments, there was no tillage operations done and in T_3: zero tillage (ZT) + residue retention (R), the previous crops (cotton and *sesbania*) were shredded and the residues were incorporated into the soil without any tillage operations (Table 2a). Four weed management options as sub-plots treatments included: W_1: chemical control, W_2: Herbicide rotation, W_3: IWM and W_4: Unweeded control and elucidated in table 2b. *Sesbania* in summer season was sown only for the purpose of incorporation into the soil and as a legume cover crop, hence there were no tillage operations and weed management treatment done during that period and treatment T_1 was fallowed (no *Sesbania*).

Sowing and fertilizer application: The monsoon cotton seeds of Sadan and cultivar were sown at the space of 90 cm in between the rows and 60 cm in between the crops in a net plot area of 41.4 m^2 with 9 rows per plot. The seed rate adopted was 450 g $acre^{-1}$. Before sowing, the field preparation was done with a plough twice followed by rotovator and levelling with the hand operated implements in T_1 and T_2: conventional tillage plots while sowing was done directly without any tillage operation in conservation tillage plots (T_3). The recommended dose of fertilizer followed was 120-60-60 kg ha^{-1} of N- P_2O_5 - K_2O. RDP in the form of DAP and MOP (500g + 100g/ line) as basal after crop emergence in T_1, T_2 and T_3. Urea + potash (2:1) applied at 30 DAS, flowering stage and square formation of cotton. For winter maize, the seeds of DHM 117 variety were sown at 60 cm × 25 cm in the same net plot size (fixed plots) with 10 rows per plot. The field preparations done in maize were similar to that of monsoon cotton in T_1 and T_3 plots except T_2 plots which were converted to zero tillage *i.e*., direct sowing of the seed without any tillage operation. A seed rate of 20 kg ha^{-1} was adopted. Thinning and gap filling were done 12 days after germination.

Table 1: Soil physico-chemical characteristics at initiation of the experiment (0-15 cm depth).

Sr. No.	Soil property	Value	Method
1.	Soil type	Red soil	Bouyoucos hydrometer (Piper, 1966)
2.	Mechanical separates (%)		
	Sand	66.00	
	Silt	12.50	
	Clay	21.50	
	Texture	Sandy clay loam	
3.	Bulk density (Mg/m^3)	1.23	Gravimetric method (Blake and Hartge 1986)
4.	Soil pH (1:2)	7.82	pH meter (Jackson, 1973)
5.	EC (dS/m) (1:2.5)	0.33	Conductivity meter (Jackson, 1973)
6.	Organic carbon (g/kg)	6.50	Wet digestion method (Walkley and Black 1934)
7.	Available nutrients (kg/ha)		
	Nitrogen	220.80	Alkaline permanganate method (Subbiah and Asija 1956)
	Phosphorus (P_2O_5)	52.10	Olsen's method (Olsen *et al*.,1954)
	Potassium (K_2O)	528.75	Neutral ammonium acetate method (Jackson, 1973)

The maize crop was principally raised with irrigation water with few rainfall amounts received during winter season. Recommended dose of 200:60:50 kg ha^{-1} of N: P_2O_5: K_2O through urea, di-ammonium phosphate and muriate of potash were applied, respectively. Nitrogen and potassium were applied in three equal splits *i.e*., as basal dose, at knee high and tasselling stage. The recommended dose of phosphorous was applied as a basal dose.

Soil sampling and standard methodology: Composite soil samples were collected after harvest of monsoon cotton in the 4th crop cycle and maize in the 5th crop cycle from each plot at a depth of 0 – 15 cm. These collected samples were passed through 2 mm sieve and analysed for soil available DTPA extractable micronutrients *viz*., manganese (Mn), iron (Fe), copper (Cu), zinc (Zn) and soil physical properties *viz*., soil particle size distribution (texture), maximum water holding capacity and total porosity.

Table 2a: Main plots – Tillage.

Treatments	*Kharif* (Monsoon)	*Rabi* (Winter)	Summer
T_1	CT (Cotton)	CT (Maize)	Fallow (no *Sesbania*)
T_2	CT (Cotton)	ZT (Maize)	ZT (*Sesbania*)
T_3	ZT +R (Cotton)	ZT+R (Maize)	ZT+R (*Sesbania*)

CT-Conventional Tillage ZT-Zero Tillage R-Residue retention

For soil bulk density (SBD) sampling, core sampler method Blake and Hartge (1986) was used to determine SBD. Intact core samples (5 cm diameter and 5.5 cm length) were obtained in triplicate for 0-15 cm and15-30 cm soil depth from all plots at the end of the three years after harvest of cotton (4th crop cycle) and maize (5th crop cycle) using stainless steel core samplers. The samples were oven dried at 105ºC for 24 hrs and the ρb was calculated based on oven dry weight (Eq (1))

$$\rho b = M_s/V_t \quad (1)$$

where, M_s is the mass of oven dry soil (Mg), and V_t is the total volume of soil core (m^3).

Soil texture and particle size distribution: Soil texture was analysed using international pipette method (Piper, 1966).

Maximum water holding capacity: A clean and dry keen's cup was taken and a filter paper was fixed which was cut to fit the size of the cup in a circular shape at the bottom. The weights of dry keen box along with the filter paper in it were taken. Then the soil sample passed through 0.2 mm sieve were transferred into the box giving small tappings and the box was completely filled up with soil. The excess soil in the keen's cup was removed with a glass rod or spatulas and kept in a trough of water. The water level was adjusted in such a way that it was 2 cm from the bottom of the keen's cup in water, followed by 24 hrs saturation. After 24 hrs of saturation, the excess amount of water due to swelling was removed with a sharp knife.

The next day the box from the trough was taken out and excess amount of water was allowed to drain out for 30 mins. Thereafter, the weights of the Keen's cup along with wet soil in it, were noted down and the samples were kept for drying along with the box in an oven at 105°C for 24 hrs till a constant weight was obtained. The weights of the boxes with oven- dried soil and the inner diameter and height of the Keen's cups with Vernier calipers were noted down. The maximum water holding capacity was calculated as per Keen Roezkowski (1905) using the equation (2)

Maximum water holding capacity (MWHC)

$$= \frac{(W_{bds} - W_b)}{(W_{bds} - W_b)} \times 100 \quad (2)$$

Weight of the Keen cup + filter paper = W_b (g)

Weight of the Keen cup + filter paper + oven- dried soil = W_{bds} (g)

Total porosity: The Keen Roezkowski cup method was employed to determine the total porosity (TP) (Piper, 1966) using the equation (3);

$$\text{Total porosity} = \frac{(W_{bws} - W_{bds})}{V} \times 100$$

Weight of the Keen cup + filter paper + wet soil = W_{bws} (g)

Weight of the Keen cup + filter paper + oven- dried soil = W_{bds} (g)

Volume of the Keen's cup, V = $\pi r^2 h$ (cm^3)

Available DTPA extractable micronutrients: Micronutrient content of the soil was determined by DTPA extract (1:2 soil: DTPA). The extract consists of 0.005M DTPA, 0.1M Triethanolamine and 0.01M $CaCl_2$ adjusted to pH of 7.3. Ten grams of soil was taken in an Erlenmeyer flask to which 20 ml of DTPA extractant was added. The contents were shaken for two hours and filtered using Whatman No. 1 filter paper. Fe, Cu, Zn and Mn were determined by using ICP (Lindsay and Norvell, 1978).

RESULTS AND DISCUSSION

Soil physical properties

Soil textural class (soil particle size distribution): The particles that make up the soil are categorized into three groups based on the sized- sand, silt and clay. Sand particles are the largest and clay the smallest ones. Soils are combined into three in all cases. The relative percentage of sand, silt and clay are what give soil its texture. Despite the fact that texture is an intrinsic property of the soil, management techniques may indirectly contribute to changes in particle size distribution, especially in the surface layers as a result of tillage (Fentie *et al*., 2020). The soil particle size distribution was influenced by tillage practices and weed management options. After harvest of monsoon cotton and winter maize crops, the percentage of sand, silt and clay particles ranged from 64.32 – 65.53, 12.51 – 12.84 and 21.90 – 22.98 respectively (Table 3).

After harvest of monsoon cotton, percentage of sand, silt and clay particles was not significantly affected by tillage and weed management. Similar trend was observed after harvest of winter maize (Table 3). However, percentage of sand was below the initial value (66.0%), silt was above the initial value (12.50%) and clay was also above the initial value (21.50 %) across tillage and weed management treatments after harvest of both crops (Table 3). Numerically, conservation tillage (T_3) recorded higher proportion of clay compared to T_1 and T_2. The soil textural class was categorized into sandy clay loam as per USDA soil classification system which was similar to the initial textural class (Table 3). Conservation tillage (T_3) had slightly increased clay particle size though the treatment-based comparison was not significant in terms of tillage probably due to retention of the previous crop residues which were decomposed, resulting in the addition more organic matter (OM) into the soil, and also the deep rooting systems of cotton and maize crops which offered good root penetration, permeability of aeration and water. These present results are in congruence with that of Eyayu *et al*. (2009) who had reported higher proportion of clay in the sandy clay loam textural class in conservation tillage with deep rooting cropping system contributing to high amount organic matter drawn from the crop residue retained into the soil. Similarly, Reichert *et al*. (2022) observed a consistent decline of sand and silt fractions whereas the clay content was relatively higher under conservation tillage. This is attributed to pedoturbation following intensive weathering, accelerated by continuous tillage (Birhanu *et al*., 2016).

Soil bulk density: Soil bulk density (SBD) is the dynamic attribute which changes with the soil aggregate conditions and increases with increase in soil depth as a result of soil organic matter concentration, porosity and compaction (Chaudhari *et al*., 2013). The soil management practices which involves tillage, permanent soil cover and diversified crop species may alter the SBD. Soil bulk density (SBD) was highly impacted by tillage and weed management practices at 0 –15 and 15–30 cm depths. After harvest of monsoon cotton, SBD ranged from 1.12 – 1.20 and 1.17 – 1.34 at 0 –15 and 15–30 cm depths respectively across all the treatments. After harvest of winter maize, SBD ranged from 1.30 – 1.40 and 1.28 – 1.44 Mg m^3 at 0 –15 and 15–30 cm soil depths respectively in all the treatments (Table 4). After harvest of monsoon cotton, the farmers practice (T_1) reduced SBD (1.12 Mg m^3) at 0 –15 and conservation tillage (T_3) reduced SBD (1.17 Mg m^3) at 15–30 cm in comparison with T_3 (1.20 Mg m^3) at 0 –15 cm and T_1 (1.34 Mg m^3) at 15–30 cm respectively (Table 4). Similar trend was observed for winter maize after harvest (Table 4).

Among weed management practices, SBD recorded after harvest of cotton was significantly lower in W_4: unweeded control (1.13 Mg m^3), W_3: IWM (1.13 Mg m^3) and W_2: herbicide rotation (1.14 Mg m^3) at 0 –15 cm compared to W_1: chemical weed control at 0 –15 cm with increased values at 15–30 cm. The trend was also similar for winter maize though no significant difference was observed at 15–30 cm. However, the SBD recorded after harvest of cotton at the end of third year in both depths across all the treatments was lower than the initial value (1.23 Mg m^3) and higher than the initial value for maize (1.23 Mg m^3). However, the overall SBD values were higher in winter maize than monsoon cotton probably due to less or no amount of rainfall received during winter season which resulted in dryness of the soil, hence more compaction, while in monsoon there was higher rainfall, and more deep rooting system of cotton than maize which have the potential to extend deeper within the soil profile, thereby breaking the compacted soil layers and drawing more soil organic matter, resulting in lower SBD.

The significantly lower SBD obtained at the top layer of the soil under T_1 and T_2 as compared to conservation tillage might be due to intensive tillage implements which breaks the hard layer thereby creating the conditions conducive for the plant root concentration. In accordance with the results of this study, Busari and Salako (2015); Al-Hamed *et al*. (2018) obtained the lower SBD under CT than any other tillage systems due to tillage operations disintegrating the soil surface, making it to become loose. Similarly, Abagandura *et al*. (2017) had found that SBD for the upper soil layers from 0 – 20 cm was the greatest for Zero tillage (ZT) accompanied by reduced tillage (RT) and the lowest for conventional tillage (CT), indicating that less soil disturbance results in a rise in SBD at the top layer of the soil.

The overall increase in SBD with increase in soil depth under T_1 and T_2 compared to T_3 is ascribed to heavy machinery weight and crop residue removal which in turn resulted in soil compaction. Hobbs and Gupta (2000) had stated out that increasing soil profile depth (15 – 30 cm) increase SBD as the result of destruction of soil aggregates, filling of the macro-pores with finer soil particles, and direct physical compaction caused by implements and trampling. Alabi *et al*. (2019) had indicated that subsoils experience less soil disturbance than top soils, which leads to increase in compaction. The lower SBD exhibited under conservation tillage (T_3) at lower soil profile depth (15 – 30 cm) compared to upper soil layer (0 – 15 cm) and T_1 and T_2 might be due to cumulative retention of crop residues and soil organic carbon. SBD values for weed management were did not vary much. However, SBD increased with depth in all weed management strategies might be attributed to weed roots and plant roots concentration at the soil surface which act as soil cover for preservation and maintenance of soil structure, hence lower SBD on the soil surface compared to sub-surface. Consequently, relatively lower soil compaction, and hence lower SBD were observed in farmers practice (T_1) at soil surface than conservation tillage (T_3) and conservation tillage (T_3) at soil sub-surface than in farmers practice (T_1).

Maximum water holding capacity and total porosity: The maximum water holding capacity (MWHC) is influenced by many inherent factors, *i.e*., soil texture, structure, pore space, and organic matter content and agronomic management practices, *e.g*., changes in the intensity of tillage. The adoption of CA-based management practices had been found to affect soil porosity, pores connectivity, and pore size distribution (PSD), especially in the surface soil layer

(Blanco-Canqui *et al*., 2018; Jensen *et al*., 2019). After harvest of monsoon cotton, the MWHC ranged from 43.98 – 46.99% across all the treatments (Table 5). The range was 44.02 – 47.83% in winter maize post-harvest. Among tillage practices, conservation tillage (T_3) recorded significantly higher MWHC (46.99%) and 47.83% compared to T_1 and T_2 after harvest of monsoon cotton and winter maize, respectively (Table 5). However, MWHC was higher across all tillage and weed management treatments in crops after harvest than the initial value (43.80%) (Table 5). It was also observed that MWHC increased with seasonal crops being higher after winter maize than monsoon cotton.

Weed management treatments did not significantly affect MWHC in both crops and the interaction effect between tillage and weed management was not significant (Table 5). The significantly highest MWHC obtained under T_3 irrespective of the seasonal crops is attributed to conversion of sand particles into clay particles, and continuous addition of previous crop residues which gets converted into soil organic matter through the decomposition process, resulting in high organic matter content, hence more water retention. These results of the current study are supported by that of Schoonover and Crim. (2015) who had reported that soils with finer particle size and high organic matter content hold more water than soils with coarse particle size and low organic matter.

Total porosity (TP) was found to be inversely proportional to MWHC such that the higher MWHC (%) values obtained under T_3, the lower the TP (%) values (Table 5). The range for TP after harvest of monsoon cotton and winter maize was 38.71 – 41.45% and 38.68 – 41.54% respectively across both tillage and weed management treatments (Table 5). Significantly highest TP (41.45%) at soil surface (0 –15 cm) was recorded under T_1 compared to T_3 and T_2 after cotton and the trend was also similar after maize (Table 5). TP increased with seasons (from monsoon cotton to winter maize) under T_1 treatments and decreased in soil surface under T_3 from monsoon cotton to winter maize post- harvest probably due to less pore spaces as a result of no soil disturbance and retention of crop residues, creating closely packed soil aggregates. However, TP across all the treatments in both seasons was above the initial value (40.15%) in T_1, T_2 and below the initial value in T_3. Weed management practices did not influence TP and their interaction with tillage systems was not significant after harvest of both crops (Table 5).

Available DTPA extractable micronutrients: Changes on soil available DTPA extractable micronutrients as influenced by tillage and weed management practices are presented in table 6. Differences in available micronutrients among tillage practices were significant after harvest of monsoon cotton and non-significant after winter maize (Table 6). Weed management did not influence DTPA extractable micronutrients in both seasons. Significantly highest Mn (7.64 mg kg^{-1}), Cu (1.28 mg kg^{-1}), Fe (15.78 mg kg^{-1}) and Zn (2.24 mg kg^{-1}) were recorded under conservation tillage (T_3) after cotton in comparison with T_1 and T_2. After winter maize post-harvest, the trend was similar to that of monsoon cotton although treatment- based comparison was not significant among tillage and weed management. Interestingly, all micronutrients values across all the treatments were higher than the initial values (Table 6). The availability of micronutrients in both seasons followed the order; Fe > Mn > Zn > Cu. The availability was more after monsoon cotton than winter maize probably due to reduced conditions in monsoon as a result of higher rainfall than in winter season which helps in the conversion of less available cations to readily available forms. Similar findings were exhibited by Ponnamperuma (1972); Sidhu and Sharma (2010) who have reported the conversion of less available Fe^{3+} fractions to readily available Fe^{2+} fractions and higher availability of Mn and Cu under wet soil conditions due to low redox potential, rendering them to become more available under submerged conditions.

Table 2b: Weed management (W) sub-treatment details and interaction with tillage (T) main treatments.

	Monsoon (Cotton)				Winter (Maize)			
	W_1: Chemical Weed Control	**W_2: Herbicide Rotation (Every year)**	**W_3: IWM**	**W_4: Control**	**W_1: Chemical Weed Control**	**W_2: Herbicide Rotation (Every year)**	**W_3: IWM**	**W_4: Control**
T_1 T_2 T_3	Diuron pre-emergence application PE 0.75 kg/ha fb tank mix application of pyrithiobac-sodium 62.5 g/ha + quizalofop-ethyl 50 g/ha as PoE (Post-emergence application) (2-3 weed leaf stage) fb directed spray (inter-row) of paraquat 0.5 kg/ha at 50-55 DAS	Diuron PE 0.75 kg/ha *fb* tank mix application of pyrithiobac-sodium 62.5 g/ha+ quizalofop-ethyl 50 g/ha as PoE (2-3 weed leaf stage) *fb* directed spray (inter-row) of paraquat 0.5 kg/ha at 50-55 DAS. Pendimethalin 1.0 kg/ha fb tank mix application of pyrithiobac-sodium 62.5 g/ha +quizalofop ethyl 50 g/ha as PoE (2-3 weed leaf stage) *fb* directed spray (inter-row) of paraquat 24% SL 0.5 kg/ha at 50-55 DAS.	Diuron PE 0.75 kg/ha *fb* mechanical brush cutter twice at 25 and 60 DAS.	One hand weeding was done after the critical period of crop-weed competition *i.e.* between 45-50 days after sowing)	Atrazine 1.0 kg/ha + paraquat 600 g/ha PE *fb* tembotrione 120 g/ha at 20-25 DAS as PoE (T_2, T_3). Atrazine 1.0 kg/ha PE *fb* tembotrione 120g/ha at 20-25 DAS as PoE (T_1)	Atrazine 1.0 kg/ha + paraquat 600 g/ha PE *fb* tembotrione 120 g/ha at 20-25 DAS as PoE (T_2, T_3). Atrazine 1.0 kg/ha PE *fb* tembotrione 120g/ha at 20-25 DAS at PoE (T_1). Atrazine 1.0 kg/ha + paraquat 600 g/ha PE *fb* halosulfuron-methyl 67.5 g/ha at 20-25 DAS as PoE (T_2, T_3). Atrazine 1.0 kg/ha PE *fb* halo-sulfuron methyl 67.5 g/ha at 20-25 DAS as PoE (T_1)	Tembotrione 120 g/ha Atrazine 50% WP 0.5 kg/ha as Early post-emergence) EPoE fb brush cutter at 40 DAS	One hand weeding was done after the critical period of crop-weed competiti-on *i.e.* between 45-50 days after sowing)

The highest micronutrients obtained under T_3 might be due to no soil disturbance, inclusion of green manure as legume cover crop and retention of its residues which had added some soil micronutrients. These present findings are in line with that of Kumar *et al*. (2023) who recorded higher content of Mn (38.6 mg kg^{-1}), Zn (10.9 mg kg^{-1}) and Cu (9.9 mg kg^{-1}) under CA-scenario (conservation tillage practice). Medvedeva *et al*. (2022) also reported available zinc and copper content to be double as high over the ploughing tillage system due to plough-less tillage or direct sowing. Furthermore, Kaushik *et al*. (2018) recorded higher availability of micronutrients *viz*., zinc, manganese, and iron under zero tillage system with crop residue incorporation. These current results of this study show-case the significance of CA-based practices with conservation tillage plus residue retention through incorporation into the soil on enhancing the levels of DTPA extractable micronutrients.

Table 3: Effect of tillage practices and weed management options on soil particle size distribution (SPSD) and textural class after harvest of monsoon cotton – 2022 and winter maize – 2022-23.

Treatments	Monsoon Cotton – 2022				Winter Maize – 2022-23			
	% Sand	% Silt	% Clay	Textural class	% Sand	% Silt	% Clay	Textural class
Tillage practices								
Initial (s)	66.00	12.50	21.50	Sandy clay loam	66.00	12.50	21.50	Sandy clay loam
T_1 (CT- CT-Fallow)	65. 12	12.74	22.14	Sandy clay loam	65.02	12.75	22.23	Sandy clay loam
T_2 (CT - ZT- ZT)	65.31	12.60	22.09	Sandy clay loam	65.00	12.74	22.26	Sandy clay loam
T_3 (Triple ZT + R)	64.95	12.77	22.28	Sandy clay loam	64.81	12.69	22.52	Sandy clay loam
SE(m)±	0.65	0. 10	0.40		0.57	0.08	0.55	
CD(P=0.05)	NS	NS	NS		NS	NS	NS	
Weed management options								
W_1- Chemical control	65.53	12.51	21.96	Sandy clay loam	64.51	12.52	21.97	Sandy clay loam
W_2- Herbicide rotation	64.43	12.70	22.87	Sandy clay loam	64.32	12.70	22.98	Sandy clay loam
W_3- IWM	65.33	12.77	21.90	Sandy clay loam	64.92	12.77	22.31	Sandy clay loam
W_4- Unweeded control	65.21	12.84	21.95	Sandy clay loam	65.21	12.73	22.06	Sandy clay loam
SE(m)±	0.40	0. 10	0.37		0.52	0. 12	0.41	
CD(P=0.05)	NS	NS	NS		NS	NS	NS	
TxW	NS	NS	NS		NS	NS	NS	

Abbreviations; T= tillage; W= weed management, CT= conventional tillage, ZT= zero tillage, (Triple ZT + R) =ZT +R – ZT +R – ZT +R, R= crop residue retention; IWM= integrated
Weed management; CD (P= 0.05) = critical difference at 5% probability level, SE(m) = standard error of the mean; NS = not significant.

Table 4: Effect of tillage practices and weed management options on soil bulk density (Mg m^{-3}) after third year of monsoon cotton – 2022 (4^{th} crop cycle) and winter maize – 2022-23 (5^{th} crop cycle), post-harvest.

Treatments	Monsoon Cotton – 2022		Winter Maize – 2022-23	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Tillage practices				
Initial	1.23	-	-	-
T_1 (CT – CT – Fallow)	1.12	1.34	1.30	1.44
T_2 (CT – ZT – ZT)	1.13	1.28	1.34	1.39
T_3 (Triple ZT + R)	1.20	1.17	1.39	1.28
SE(m)±	0.01	0.02	0.02	0.02
CD(P=0.05)	0.05	NS	0.07	0.09
Weed management options				
W_1- Chemical control	1.20	1.30	1.40	1.41
W_2- Herbicide rotation	1.14	1.26	1.34	1.36
W_3- IWM	1.13	1.24	1.30	1.35
W_4- Unweeded control	1.13	1.25	1.33	1.37
SE(m)±	0.03	0.04	0.03	0.05
CD(P=0.05)	NS	NS	NS	NS
TxW	NS	NS	NS	NS

Abbreviations; T= tillage; W= weed management, CT= conventional tillage, ZT= zero tillage, (Triple ZT + R) =ZT +R – ZT +R – ZT +R, R= crop residue retention; IWM= integrated Weed management; CD (P= 0.05) = critical difference at 5% probability level, SE(m) = standard error of the mean; NS = not significant.

Table 5: Effect of tillage practices and weed management options on maximum water holding capacity and total porosity (%) after third year of monsoon cotton – 2022 (4th crop cycle) and winter maize – 2022-23 (5th crop cycle), post-harvest.

Treatments	Maximum water holding capacity		Total porosity	
	Monsoon Cotton (2022)	Winter Maize (2022-23)	Monsoon Cotton (2022)	Winter Maize (2022-23)
Tillage practices				
Initial	43.80	-	40.15	-
T_1 (CT – CT – Fallow)	43.98	44.02	41.45	41.54
T_2 (CT – ZT – ZT)	45.64	46.19	40.92	40.98
T_3 (Triple ZT + R)	46.99	47.83	38.71	38.68
SE(m)±	0.45	0.53	0.52	0.16
CD(P=0.05)	1.82	2.15	2.11	0.64
Weed management options				
W_1- Chemical control	45.34	45.83	39.81	39.89
W_2- Herbicide rotation	45.00	45.47	40.07	40.11
W_3- IWM	45.44	45.92	40.66	40.69
W_4- Unweeded control	46.36	46.83	40.91	40.92
SE(m)±	1.15	1.20	0.48	0.44
CD(P=0.05)	NS	NS	NS	NS
TxW	NS	NS	NS	NS

Abbreviations; T= tillage; W= weed management, CT= conventional tillage, ZT= zero tillage, (Triple ZT + R) = ZT +R – ZT +R – ZT +R, R= crop residue retention; IWM= integrated Weed management; CD (P= 0.05) = critical difference at 5% probability level, SE(m) = standard error of the mean; NS = not significant.

Table 6: Effect of tillage practices and weed management options on soil available DTPA extractable micronutrients after third year harvest of monsoon cotton (4th crop cycle) and winter maize (5th crop cycle), post-harvest.

Treatments	Monsoon Cotton - 2022				Winter maize – 2022-23			
	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})
Tillage practices								
Initial (s)	5.57	12.50	0.80	1.58	-	-	-	-
T_1 (CT – CT –Fallow)	5.67	13.09	0.83	1.64	5.65	12.70	0.82	1.60
T_2 (CT – ZT – ZT)	6.46	13.35	0.94	1.65	7.11	12.93	0.90	1.61
T_3 (Triple ZT + R)	7.64	15.78	1.28	2.24	8.76	14.44	1.01	2.10
SE(m)±	0.28	0.53	0.09	0. 11	0.78	2.70	0.06	0.39
CD(P=0.05)	1.12	2. 13	0.34	0.46	NS	NS	NS	NS
Weed management options								
W_1- Chemical control	5.77	13.24	0.93	1.81	6.40	12.95	0.90	1.64
W_2- Herbicide rotation	7.13	13.72	1.15	1.89	7.38	13.68	1.00	1.80
W_3- IWM	7.19	14.00	0.92	2.13	7.58	12.91	0.78	1.99
W_4-Unweeded control	6.29	15.33	1.05	1.55	7.34	13.88	0.98	1.53
SE(m)±	0.59	0.70	0.09	0.14	0.72	1.67	0.08	0.30
CD(P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
TxW	NS	NS	NS	NS	NS	NS	NS	NS

Abbreviations; T= tillage; W= weed management, CT= conventional tillage, ZT= zero tillage, (Triple ZT + R) =ZT + R – Z + R – ZT + R, R= crop residue retention; IWM= integrated Weed management; CD (P= 0.05) = critical difference at 5% probability level, SE(m) = standard error of the mean; NS = not significant.

CONCLUSIONS

Conservation tillage (T_3) enhanced all DTPA extractable micronutrients with manganese (Mn) and iron (Fe) contents higher than copper (Cu) and zinc (Zn), increased maximum water holding capacity (MWHC), soil bulk density (SBD) after maize, but reduced SBD (15 – 30 cm soil depth) after cotton, and decreased total porosity (TP) after harvest of both crops compared to the initial values and other tillage practices. Soil texture was classified into sandy loam soil. The influence of weed management on some soil physical properties and soil micronutrients availability remain unknown. Thus, this current study gives an idea about best management practices to be followed as far as tillage and weed management practices are concerned for maintaining soil health, reducing soil degradation and sustaining crop production under cotton – maize – *Sesbania* rotation systems.

FUTURE SCOPE

— Long-term CA practices should be implemented with assessment of more important soil biological properties to fast track the changes as a result of CA-based practices coupled with physical and chemical properties to comprehend their relationship

— Stratification ratio of soil micronutrients should be quantified under CA as to monitor the changes on soil quality.

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