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Assessment of Conservation Agricultural Practices on Soil Nutrient's Stratification Ratio, Carbon Sequestration Rate, Management Indices and Crop Productivity in Southern Telangana India

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ABSTRACT

The impending crisis for food production is the biggest threat in sustenance of soil resources due to industrial farming practices adopted by multitudes of the farmers on all parts of the the world inclusive of Southern Telangana Zone (STZ) in India. This can extensively degrade the soil if not substituted by soil resource saving agricultural systems. This present experiment is implemented to assess the impact of contrasting tillage practices and weed control tactics on soil quality parameters (SQPs) and monitor the grain yield of maize after three-years in CA with cotton-maize-Sesbania rostrata cropping system. Three tillage practices (main-plots); T_1: CT(C)-CT(M)-fallow (NSr), T_2: CT(C)-ZT(M)-ZT(Sr) and T_3:ZT(C)+SrR-ZT(M)+CR-ZT(Sr)+MS and weed control tactics (sub-plots) involved; W_1-chemical weed control, W_2-Herbicide rotation, W_3- Integrated weed management (IWM) and W_4- single hand-weeded control in split-plot design. Sampling of the soil in the 0 –15 and 15 – 30 cm, subsequent to harvesting of maize, was analyzed for pH, EC, soil macronutrient's availability, soil organic carbon (SOC), and computed for stratification ratio (SR), C-sequestration rate (CSR), carbon management indices (CMI) and carbon retention efficiency (CRE) duly following the standard procedures. The salient findings indicated that 9.1%, 15.3% of SOC, 10.2%, 15.1% of available soil N, 12.2%, 19.6% of available soil P in the 0–15 cm and SR of 1.20 for SOC, 2.0 – 6.5% of active carbon (C_{ACT}) pool in the 0 –30 cm was higher under T_3 relative to T_2, T_1, respectively. Similarly, 36.0%, 58.1% of cumulative CSR, 29.4%, 58.8% of CRE in the 0 –30 cm, and 17.0%, 30.3% of CMI in the 15–30 cm was higher T_3 compared to T_2, T_1, respectively. The C_{PSV} was the dominant contributor of SOC to total SOC over C_{ACT} in the 0-30 cm soil layer. The 49.0% and 52.0% of C_{ACT} pool was observed to be higher under T_3 and single hand-weeded control, respectively. The T_3 had higher Kernel yield (KY) of 8.4%, 11.6% in comparison with T_2, T_1, respectively. KY was also 23.4-43.1% greater under W_1, W_2, W_3 over W_4. The ZT with crop residue retention (T_3), and IWM alternative to chemical weed control/ herbicide can slow-down the soil degradation process and enhance productivity in this zone.

Keywords: *Soil quality; Carbon Management; Conservation Agriculture and Productivity.*

Abbreviations: *CT= conventional tillage, ZT= Zero tillage, R= crop residue retention, C= cotton, M= maize, NSr = no Sesbania rostrata, Sr= Sesbania rostrata, MS= maize stubbles.*

Introduction

The World Summit on nutritional security has announced that in 2050, "The world's population is expected to increase to approximately 10 billion by 2050, boosting agricultural demand – in a scenario of modest economic growth- by some 50 percent relative to 2013" (Mekouar, 2018). Cereal-based production is predominantly followed in Southern Telangana Zone (STZ) of India and contributes to nearly 40% of the overall cereal production of the country (Nthebere *et al.*, 2022). Maize is the second essential crop cultivated during the winter season following rice in STZ of India. Globally, available soil resources are declining at an alarming rate mainly due to overexploitation of these resources under commercial farming practices (Foley *et al.*, 2011), which may pose a challenge of meeting sustainable development goals (SDGs) 1. "no poverty," 2. "zero hunger," and 15. "life on land" coined by the United Nations. About 10 hectares of lands assigned for agricultural production get depleted instantly as a result of various degradation processes such as erosion, nutrient depletion etc. (UNCCD, 2011). These are the consequences of urbanization and industrial agricultural systems.

According to United Nations Environmental Programme (UNEP), during the second half of the 20[th] century, around two billion hectares of lands catered for agriculture had undergone extensive soil degradation (Oldemann *et al.*, 1990). India is comprised of approximately 328.8 M ha, total geographical area, of which 180 M ha falls under agricultural production with various soil kinds. It bolsters up to 17.5% of the global population with 2.4% of global geographical area and 9% of cultivable land. Approximately one hundred and twenty million hectares of cultivable land is regarded as degraded in India (Maji *et al.*, 2010) which is a considerable solicitude for sustainable food production (Nthebere *et al.*, 2023a). Thus, an increase in productivity in attempt to meet the shortage of food with shrinking land resources, must always be supported by a sustainable agricultural system as to cease or at least

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slow-down the adverse effects on the quality and quantity of soil resources, land degradation and biological diversity (Weiss *et al*., 2020). In the light of this challenging context for agriculture, soil organic carbon (SOC) forms the base for sustainable soil resources being a reservoir for the overall soil available nutrients (DeBano and Wood, 1990). In spite of that, the SOC content in India is as low as 0.3 per cent from 1 per cent in the previous 70 years which is of great concern to keep the pace in agricultural production (National Rainfed Area Authority, 2022).

Soil nutrients are of utmost importance in plant nutrition and constitutes about 95% of the food production (Nthebere *et al*., 2023b). The availability of these nutrients in optimum amount in the soil are crop yields determinant factors, thus, the linkage between long-term specific soil management practices like conservation agriculture (CA) through adoption of sustainable tillage systems and weed control strategies are necessitated in order to comprehend soil management practices which can extensively increase crop yield and enhance soil quality (Zulu *et al*., 2022). CA is defined as a notion of soil resource preservation for agricultural production, based on augmenting the activities occurring above and beneath the land naturally and biologically on a long-term basis. Lowering of tillage intensity minimize soil disruption, covering the soil with crop residues and short-duration crops permanently and diversified rotation of crops for attaining greater production while conserving soil and water conservation effectively as well as sequestering adequate SOC align with CA precepts (FAO, 2022). The soil environmental gains of zero tillage (ZT) with at least 30 % crop residues retained in CA are well-established (Hobbs *et al*., 2008; Thierfelder and Wall, 2010) and the main factor behind the success of ZT coupled with other CA precepts is preservation of SOC and soil nutrients via SOC storage and nutrient's accumulation in the soil stratum (Verhulst *et al*., 2010). Several studies have reported the sur face and the spatial distribution of SOC, and various soil nutrients, but research on quantification of their long-term storage and accumulation in different soil profile is very limited in STZ. The stratification of soil nutrients and compositions, particularly of soil pH, EC, CEC, C, N, P have been found to be very common in various vegetation and croplands (Chang *et al*., 2012; Franzluebbers, 2002). The stratification ratio (SR) is defined as the ratio of a soil attribute at the soil surface in a profile to that at a lower soil depth in a profile. The high SR values (generally >2) denote good soil quality (Franzluebbers, 2002).

Alterations in farming management practices comprised of conservation tillage and crop residue incorporation in CA have been observed to furnish some soil health gains on improving essential soil quality parameters (e.g. SOC, nitrogen (N), phosphorus (P), potassium *etc*.) with great potential to sequester SOC in STZ of India (Parihar *et al*., 2016). Bochalya *et al*. (2021) deduced that CA sequesters the greatest SOC adjacent to the upper soil layer. Thus, the contentious outcomes of the influence of tillage with regard to alterations in SOC status and storage may result in misconception of the impacts of tillage practices on soil functions. Further, factors such as variation in various soil types, climatic conditions, and cropping systems will also pose difficulty to get consistent conclusion on how tillage practices affect soil quality (Zhao *et al*., 2015). The knowledge on carbon management index (CMI) under conservation agricultural practices particularly in the semi-arid regions of STZ in India is of utmost importance for preservation of soil resources, and minimal adverse environmental impacts. These insights on these aspects of CMI are crucial in regions where soils are intrinsically low in OC concentration and the productivity is frail as in STZ. To better understand the mechanisms by which C is maintained into the soil, the total organic carbon (TOC) in soil gets split into labile, slow pool, and passive, recalcitrant pool with changes in residence duration (Parton and Rasmussen, 1994). The labile pool of carbon is the portion of TOC having the most instant turnover periods. Simultaneously, this fraction is essential for crop productivity perspective as it provides the soil food systems, thus impacting nutrient cycling for preservation of soil quality and production (Chan *et al*., 2001; Majumder *et al*., 2007).

The latest meta-data analysis indicated that the influence of conservational tillage practice in comparison with conventional tillage (CT) on crop yields, is inconsistent and impacted substantially by certain crop factors (Pittelkow *et al*., 2015). Traditionally, farmers control weeds in maize by pre-emergence herbicide spraying followed by inter-cultivation and manual weeding (Nthebere *et al*., 2023b). The introduction of new generation selective herbicides and scarcity of manual labor to perform manual weeding has led in a significant rise in pre-emergence and post-emergence herbicide utilization in maize crop. Several studies have confirmed the adverse as well as the positive impacts of agro-chemicals on crop productivity (Dhanker *et al*., 2021). However, the over-use and excess application of such herbicides tend to exude into the soil environment resulting in bio-accumulation and generation of a vast quantity of residues which in turn may lead to nutrient imbalance and quality drop-off in crop production (Nthebere *et al*., 2023b). Thus far, research studies on long-term storage of SOC, its management indices, and soil nutrients distribution within various soil layers in STZ of India are scarce with synergistic contrasting tillage and weed management practices in CA. Adoption of conservation tillage can sustain the soil health and quality, and improve cereal-based crop production in STZ. Thus, the current three-years CA experiment has been taken up to identify the best tillage and weed management practice which can maintain high maize production level and improve the soil quality through quantification of stratification ratio of SOC, soil nutrients, SOC sequestration, CMI, and target yield of maize, after third year of maize crop cycle under cotton-maize-*Sesbania* cropping system.

Materials and methodologies

Details and characterization of the experimental area

This current field study was undertaken at College Farm, PJTSAU, Southern Telangana Zone of India under All India Coordinated Research Project (AICRP) on Weed Management. The field trial is located at 16^0 18' 17" North latitude and 78^0 25' 38" East longitude presented as satellite outlook in fig 1. The zone is dryland with approximately 708 mm mean annual rainfall (Kadiyala *et al*., 2021). Extreme heat and humidity occur during summer months (March to fortnight of June) with mean temperature of 30 °C. Maximum temperatures often go beyond 42 °C from April to May. December and January are extremely winter months with the lowest temperatures dropping as low as 10 °C occasionally. Rainfall surpass 75% due to the South-West monsoon and happens between June to September (Kadiyala *et al*., 2021). The experiment was implemented from 2020 in the monsoon, winter and summer seasons under cotton (*Gossypium hirsutum*), maize (*Zea mays*), green manure (*Sesbania rostrata*) rotations, respectively. An experiment continued from 2020 until 2023 and collection of soil samples for analysis of soil parameters and yield estimation were done after harvest of winter maize crop in 2022-23 (after third year in the 5^{th} crop cycle).

Fig 1. Satellite view of the experimental field (36 plots inside demarcated with yellow line)

Weather during the development of the crop

Meteorological observations taken during the crop development from the station situated at the Institute of Agricultural Research (IAR), Rajendranagar on weekly basis are presented in figure 2.

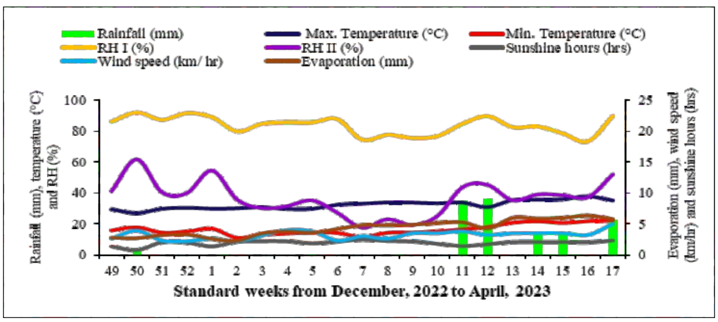

Fig 2 Weekly-base mean meteorological observations during maize development

Soil characteristics

The soil of the study area falls under the soil order *Inceptisol*, sandy clay loam in texture, red chalk in color, slightly alkaline (7.82) in soil pH as a result of available lime concretion beneath the horizon, 1.23 Mg m^{-3} in bulk density, non-saline (0.33 dS m^{-1}), medium range in soil organic carbon (6.50 g kg^{-1}), low range in available soil nitrogen (220.90 kg ha^{-1}), medium range in available soil phosphorus (22.40 g kg^{-1}), and high range in available soil potassium (408.75 kg ha^{-1}) in the soil surface (0 – 15 cm) at initiation of experiment.

Design of the experiment and treatment details

A conservation agriculture (CA) experiment was conducted in accordance with a split plot design with three tillage (s) practices in the main plots, as shown in Table 1; four weed management options in the sub-plots as detailed in Table 2; and treatment combinations of tillage and weed management were replicated thrice. For T_1, which was subjected to conventional tillage, the plots were prepared by ploughing two times, followed by rotovating and seeding. In T_2, no-till of the soil (Zero tillage- ZT) *i.e.*, seeding was done directly by opening the soil followed by surface soil sealing, and in T_3, there was ZT (cotton) + *Sesbania rostrata* residues (*Sr*R) in monsoon – ZT (maize) + cotton residues (CR) in winter – ZT (*Sesbania rostrata*) + maize stubbles (MS) (*i.e.*, *Sesbania rostrata* was sown adjacent to maize stubbles) in summer. The succeeding crops (cotton and *Sesbania rostrata*) residues were shredded and retained (as surface mulch), and seeding was performed directly by opening the soil, accompanied by surface sealing with mulch from crop residues (Table 1).

The cumulative mean annual input of organic biomass/residues from cotton and *Sesbania rosrata* retained in T_3 plots, since the year 2020-2023, was about 200.0 to 240.0 Mg ha^{-1} estimated according to Bolinder *et al*. (2007). The weed management strategies used included: W_1: chemical weed control, W_2: herbicide rotation, W_3: integrated weed management (IWM) and W_4: single hand-weeded control, as fully described in Table 2. No tillage operations or weed management were implemented prior to sowing of summer *Sesbania rostrata*, as it was cultivated up to 45 days to be retained and cover the soil in T_3. There was no *Sesbania rostrata* sown in the T_1 plots; *i.e.*, the plots were fallowed during the summer season.

Table 1. Annotation of tillage treatments with crop diversification in the main plots

Tillage (s)	Seasons		
	Monsoon	Winter	Summer
T_1:	CT (C) –	CT (M) –	Fallow (N*Sr*)
T_2:	CT (C) –	ZT (M) –	ZT (*Sr*)
T_3:	ZT(C) + *Sr*R –	ZT (M) + CR –	ZT (*Sr*) + MS

CT(C)=conventional tillage (cotton), ZT(M)= zero tillage (maize), Fallow (NSr) = Fallow (No Sesbania rostrata), ZT(Sr)= zero tillage (Sesbania rostrata), ZT(C) + Sr =zero tillage (cotton)+Sesbania rostrata residues, ZT (M)+ CR = zero tillag (Maize)+ cotton residues, ZT (Sr)+MS= zero tillage (Sesbania rostrata) + maize stubbles.

Table 2. Weed management (W) in sub-treatments and interaction with tillage (T) in main treatments

	Monsoon (Cotton)				Winter (Maize)			
	W_1: Chemical Weed Control	**W_2: Herbicide Rotation (Alternative year)**	**W_3: IWM**	**W_4: Single hand-weeded Control**	**W_1: Chemical Weed Control**	**W_2: Herbicide Rotation (Alternative year)**	**W_3: IWM**	**W_4: Single hand-weeded Control**
T_1 / **T_2** / **T_3**	Diuron pre-emergence (PE) application 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 (2-3weed leaf stage) *fb* directed spray (inter-row) of paraquat 0.5 kg/ha at 50-55 DAS. **rotated with** Pendimethalin 1 kg ha^{-1} *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 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 600g/ha PE *fb* tembotrione 120 g/ha at 20-25 DAS as PoE (T_2, T_3). Atrazine 1 kg ha^{-1} 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 DASas PoE (T_2, T_3). Atrazine 1.0 kg/ha PE *fb* tembotrione 120g/ha at 20-25 DAS at PoE (T_1). **rotated with** 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 at20-25 DAS as PoE (T_1).	Tembotrione 120 g/ha & Atrazine 50% WP 0.5 kg/ha both applied as early post-emergence) EPoE *fb* brush cutter at 40 DAS.	One hand weeding was done after the critical period of crop-weed competit-ion *i.e.* between 45-50 days after sowing).

T_1= conventional tillage (cotton) – conventional tillage (maize) – Fallow (No Sesbania rostrata), T_2= conventional tillage (cotton) – zero tillage (maize) – zero tillage (Sesbania rostrata), T_3= zero tillage (cotton) + Sesbania rostrata residues (SrR) – zero tillage (maize) + cotton residues (CR) – zero tillage (Sesbania rostrata) + maize stubbles (MS), IWM= integrated weed management.

Crop management

Sowing and fertilizer application during maize development

The DHM 117 maize seeds variety were seeded at 60 cm in between the rows and 25 cm in between the lines with net field plot size of 41.3 m^2 in 10 rows for each plot. Prior to seeding, the experimental plots were ploughed two times accompanied by rotovating and levelling with the hand-raking in T_1: conventionally tilled plots, while the maize seeds were dibbled with no-till in ZT plots. The quantity of the maize seeds utilized for sowing was 20 kg ha^{-1}. The crop was thinned in the portions of the plots with high crop population and gap filled where seeds did not emerge 13 days subsequent to seed emergence. The crop was typically developed and advanced with supplemental irrigation as the amount of rainfall received during the crop developmental period was scanty. Advocated doses fertilizers (ADFs) for N: P: K (200:60:50 kg ha^{-1}) were supplied to raise the crop through urea, di-ammonium phosphate (DAP) and muriate of potash (MOP), respectively. Application of urea and DAP were split thrice as basal, at knee height and maize tasseling period.

Sampling and standard analytical procedures

Soil samples were randomly picked in triplicate and mixed thoroughly from each treatment plot at a depth of 0–15 and 15–30 cm after harvest of maize crop (5^{th} crop cycle) in April, 2023. These collected samples were well air-dried under shade, processed through a wooden hammer and passed through 0.5-millimeter sieving, and then analyzed for organic carbon (OC). For analysis of soil pH, electrical conductivity (EC), and soil macronutrient's availability (nitrogen (N), phosphorus (P), potassium (K)) a 2-millimeter sieve was used for sieving the soil samples.

Laboratory analysis was performed by following the standard protocols suggested by Walkley and Black (1934) for OC, Subbiah and Asija (1956) for available soil N, Olsen *et al* (1954) for available soil P, Jackson (1973) for available soil K, soil pH and electrical conductivity (EC), and Blake and Hartge (1986) for bulk density (BD) in the 0-15 cm and 15-30 cm soil layers. BD was computed on the basis of oven-dry weight using Equation (1):

$$\rho b = M_s/V_{ts} \quad (1)$$

where,

M_s represent the mass of soil on oven-dry basis in megagram (Mg),

V_{ts} is the summation volume of soil core in cubic meters (m^{-3})

Quantification of stratification ratio (SR)

The stratification ratios (SRs) of SOC, EC, pH, N, P and K were computed by (Franzluebbers, 2002).

SOC stock, sequestration and carbon retention efficiency

The grand total for organic carbon (OC) stocks in both 0-15 cm and 15-30 cm (0-30 cm) layers was calculated using equation (2):

$$\text{OC stocks (Mg ha}^{-1}\text{)} = \text{OC x BD (Mg m}^{-3}\text{) x D (m)} \quad (2)$$

The bulk density (BD) for 0-15 cm soil layer was the overall average of the treatment means, which was 1.34 Mg m^{-3} was determined post-harvest of maize crop. Similarly, the BD for 15-30 cm soil depth (D) in meters (m) was 1.36 Mg m^{-3}. The OC stocks of two layers (0-15 and 15-30 cm) were added up as to derive the entire SOC stock of the sampling profile.

Calculation for Sequestration of SOC was achieved using equation (3) by Srinivasarao *et al.* (2012):

SOC Sequestration (Mg C ha^{-1} yr^{-1}) = (present - initial SOC)/ duration of the experiment (3)

Retention of carbon efficiency (CRE) was computed using Equation (4) suggested by (Bhattacharyya *et al*. (2009b):

CRE (%) = (final – initial OC) x 100 ÷ CEI (4)

SOC stocks (Mg ha^{-1}) derived from initial and final, and CEI are estimated carbon input accrual (Mg ha^{-1}) calculated in order to evaluate the rates of SOC sequestration.

Soil organic carbon pools and carbon management index

Various pools of OC were computed by a modified Walkley and Black method described by Chan *et al*. (2001). Total organic carbon (TOC) was calculated using the equation (5) by Jha *et al*. (2014);

$\log_{10}$ TOC= 0.725×$\log_{10}$ (Walkley-black carbon) + 0.198 × $\log_{10}$ (silt + clay) – 0.0759 × $\log_{10}$ (mean annual rainfall) + 0.015 (5)

The lability index (LI) and carbon management index (CMI) were calculated as per the following equations (6 and 7) (Blair *et al*., 1995).

Lability index (LI) = (C_{VL}×3÷SOC) + (C_{L}×2÷SOC) + (C_{LL}×1÷ SOC) (6)

CPI = SOC of the sample (g kg^{-1}) ÷ SOC in the reference (g kg^{-1}) (7)

CPI is carbon pool index. The SOC in the reference is from undisturbed soil (collected) under the trees adjacent to the experimental field which was 12.52 g kg^{-1} for 0-15 cm and 8.95 g kg^{-1} for 15-30 cm.

While estimating SOC in the reference, composition of soil in the 0-15 and 15-30 cm soil layers were drawn from virgin soils beneath the trees adjacent to the experimental field. Sample composition was obtained by taking 3 soil samples at random depth-wise (0-15 and 15-30 cm) and intermix them and was the soil samples representative which were collected. The carbon management index was calculated by the following (Blair *et al*. (1995) formula;CMI = CPI × LI × 100 (8)

Crop yield, harvest index and estimated carbon input

Maize grains produced from individual plots were air-dried under shade until 12% moisture content was achieved and weighed prior to threshing, recorded and presented in kg ha^{-1}. Similarly, the stover yield was cut down, air-dried, weighed and expressed in kg ha^{-1}. The harvest index was calculated as the percentage of maize grain yield by biological yield. The cumulative mean annual input of organic biomass/residues to the soil from all crops within the cropping system (cotton – maize – *Sesbania rosrata*) for the year 2020 was estimated as 52.3 to 60.0 Mg ha^{-1}. After three years of the cropping system, 2023 it was about 200.0 to 240.0 Mg ha^{-1}. Thus, about 80.0 – 100.0 Mg ha^{-1} of biomass (C input) was added to the soil in the 0 – 30 cm soil layer through residues incorporation/retention under various tillage and weed management treatments.

The estimated carbon input (ECI) was calculated by taking the maximum value (100.0 Mg ha^{-1}) of cumulative C input and multiplying it with assumed carbon content of 40% (Bolinder *et al*., 2007).

Statistical and Principal component analysis

The data was analyzed statistically by applying the analysis of variance technique, dully following the ANOVA for two-way analysis as described by Panse and Sukhatme (1978). The critical variances for testing the means for statistical significance was computed at 5 per cent probability level. Turkey's test was used to rank the treatment means for their significance at 5% probability level. Standardized PCA was performed on the correlation matrix as proposed by Andrews *et al.* (2002) and Govaerts *et al.* (2006) in 'R' software (Team, 2010).

Results

Soil bulk density

The soil bulk density (BD) ranged from 1.30–1.39 and 1.28–1.44 Mg m^{-3} in 0–15 and 15–30 cm soil depths, respectively across all the treatments (Table 4). Among tillage practices, CT(C)-CT(M)-Fallow (N*Sr*) recorded significantly lower BD (1.30 Mg m^{-3}) in 0 –15 cm compared to ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS. The higher BD (1.44 Mg m^{-3}) was observed under CT(C)-CT(M)-Fallow (N*Sr*) in 15–30 cm compared to ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS (Table 4). Weed management practices did not show any significant influence on BD and the interaction of tillage and weed management effects on BD was not significant. However, the BD values were higher than the initial BD value (1.23 Mg m^{-3}).

Soil physico-chemical properties

Soil organic carbon (SOC)

Adoption of different tillage practices exerted a significant impact on SOC at both soil sampling depths. The distinctiveness on SOC was non-significant for weed management in both soil layers. The treatment interaction effects on SOC were non-significant (Table 3).

The ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS exhibited a significantly higher SOC (7.92 g kg^{-1}) over CT(C)-CT(M)-Fallow (N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*). In the 15–30 cm, SOC was reduced in all the treatments in comparison with 0–15 cm soil depth (Table 3). The trends on SOC in 15 – 30 cm depth were similar to that of the 0–15 cm, based on the treatment performance. Overall, SOC contents were higher in all the treatments than their initial values (Table 3).

***Soil pH* and Electrical conductivity (EC)**

Soil pH and EC were not significantly influenced by tillage and weed management practices, and the treatment's interaction effects on pH and EC were non-significant (Table 3). However, a reduction in pH was observed across all tillage practices and weed management practices over the initial pH values at both sampling depths, while EC was increased above the initial value in both soil layers. Further, pH increased with increase in soil depth and EC decreased with increase in soil depth (Table 3).

Table 3. Impact of tillage practices and weed management options on soil bulk density, pH, electrical conductivity (EC) and soil organic carbon (SOC) after harvest of winter maize, 2022–23.

Treatments	Soil bulk density (Mg m^{-3})		pH		EC (dS m^{-1})		SOC (g kg^{1})	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Tillage practices								
Initial (s)	1.23	1.30	7.82	7.90	0.33	0.30	6.50	5.95
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	1.30	1.44	7.15	7.40	0.42	0.37	6.71	6.11
T_2: CT(C)-ZT(M)-ZT(*Sr*)	1.34	1.39	7.14	7.39	0.42	0.36	7.26	6.48
T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	1.39	1.28	7.04	7.26	0.43	0.36	7.92	6.66
SE(m)±	0.02	0.02	0.05	0.05	0.03	0.02	0.15	0.14
CD(P=0.05)	0.07	0.09	Ns	Ns	Ns	Ns	0.60	0.39
Weed management options								
W_1- Chemical weed control	1.40	1.41	7.11	7.34	0.42	0.36	7.29	6.26
W_2- Herbicide rotation	1.34	1.36	7.09	7.34	0.43	0.36	7.30	6.35
W_3- IWM	1.30	1.35	7.13	7.36	0.45	0.38	7.34	6.43
W_4- Single hand-weeded control	1.33	1.37	7.11	7.40	0.40	0.34	7.25	6.63
SE(m)±	0.03	0.05	0.08	0.06	0.04	0.03	0.19	0.16
CD(P=0.05)	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
Interactions (TxW) CD(P=0.05)	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns

T_1= conventional tillage (cotton) – conventional tillage (maize) – Fallow (No Sesbania rostrata), T_2= conventional tillage (cotton) – zero tillage (maize) – zero tillage (Sesbania rostrata), T_3= zero tillage (cotton) + Sesbania rostrata residues (SrR) – zero tillage (maize) + cotton residues (CR) – zero tillage (Sesbania rostrata) + maize stubbles (MS), IWM= integrated weed management., CD (P= 0.05) = critical difference at 5% probability level, Ns = non-significant, SE(m) = standard error of the mean.

Available soil nutrients

It is evident that available soil macronutrients (N, P and K) content fell below the initial value(s) under CT(C)-CT(M)-Fallow(N*Sr*), CT(C)-ZT(M)-ZT(*Sr*) and weed management practices (Table 4). The ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS significantly enhanced the available soil N, and P slightly over the initial values (Table 4). A drastic decrease of the soil macronutrients was noticed when soil depth was increased from 15-30 cm. Nevertheless, the effect by weed management on soil available macronutrients was non-significant, and the interaction of tillage practices and weed management options effects on soil macronutrients availability were non-significant (Table 4).

Table 4. Impact of tillage practices and weed management options on soil available nitrogen (N), phosphorus (P) and potassium (K) at two various soil depths after harvest of winter maize, 2022–23.

Treatments	Available N (kg ha^{-1})		Available P (g kg^{-1})		Available K (kg ha^{-1})	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Tillage practices						
Initial (s)	220.90	-	22.40	-	408.75	-
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	201.73	160.07	20.16	16.77	413.76	386.04
T_2: CT(C)-ZT(M)-ZT(*Sr*)	213.47	167.78	21.78	17.15	417.88	362.01
T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	237.70	171.86	24.29	18.58	434.11	351.54
SE(m)±	14.85	5.40	0.06	0.04	8.73	11.62
CD(P=0.05)	39.98	21.77	0.26	0.15	Ns	Ns
Weed management options						
W_1- Chemical weed control	216.13	163.59	21.70	17.30	423.64	362.52
W_2-Herbicide rotation	216.69	170.39	22.73	17.47	423.36	360.65
W_3- IWM	219.01	165.13	22.02	17.81	429.61	370.54
W_4- Single hand-weeded control	217.37	160.51	21.86	17.42	413.72	348.28
SE(m)±	6.78	9.08	0.08	0.08	17.31	11.85
CD(P=0.05)	Ns	Ns	Ns	Ns	Ns	Ns
Interactions (TxW) CD(P=0.05)	Ns	Ns	Ns	Ns	Ns	Ns

T_1= conventional tillage (cotton) – conventional tillage (maize) – Fallow (No Sesbania rostrata), T_2= conventional tillage (cotton) – zero tillage (maize) – zero tillage (Sesbania rostrata), T_3= zero tillage (cotton) + Sesbania rostrata residues (SrR) – zero tillage (maize) + cotton residues (CR) – zero tillage (Sesbania rostrata) + maize stubbles (MS), IWM= integrated weed management., CD (P= 0.05) = critical difference at 5% probability level, Ns = non-significant, SE(m) = standard error of the mean.

Stratification ratios (SRs) of soil physico- chemical properties and available nutrients

The SRs of soil physico-chemical characteristics (SOC, pH and EC) and soil macronutrients (available N, P, K) are depicted in figure 1a, b, c and figure 2a, b, c, respectively. The SRs ranged from 0.96 – 0.97 for pH, 1.14 – 1.19 for EC, 1.10 – 1.21 for SOC (figure 3), and 1.26 – 1.38 for available soil N, 1.17 – 1.22 for available soil P and 1.07 – 1.23 for available soil K (figure 4). The SRs for pH and EC were not significant as influenced by tillage and weed management (figure 3b, c). Among tillage practices, the significantly higher SR for SOC (1.21) was recorded under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS relative to CT(C)-CT(M)-Fallow (N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*). Similar results were observed for SRs of N, P, K in which the ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS was significantly higher compared to CT(C)-CT(M)-Fallow (N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) (figure 4a, b, c). Thus, SRs for N, P, K availability followed the order; ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS<CT(C)-ZT(M)-ZT(*Sr*)< CT(C)-CT(M)-Fallow(N*Sr*) in terms of tillage. However, all SRs values obtained were <2.0. Hence, these results have indicated that soil parameters *viz*., SOC and N, P, K availability can improve SRs with the adoption of ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS practice. Weed management practices, and the interaction of tillage and weed management effects on SRs of pH, EC, available macronutrients (N, P, K) were non- significant.

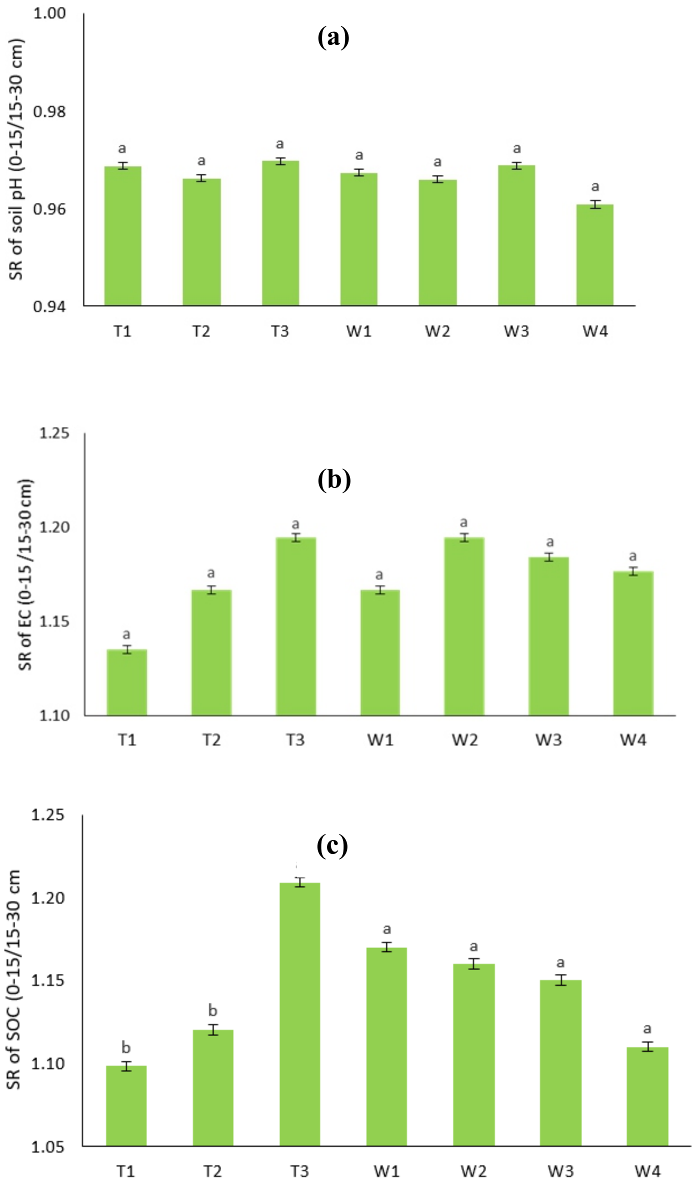

Figure 3 (a), (b), (c) Effect of tillage practices and weed management options on stratification ratio of soil physico-chemical properties (soil pH, electrical conductivity (EC) and soil organic carbon (SOC). Means having distinct symbols demonstrate significant variances between the treatments at 5% probability level (Tukey's test) and means having the same symbols indicate no significant variances among the treatment means at 5% probability level. table 1 and 2 for treatment details.

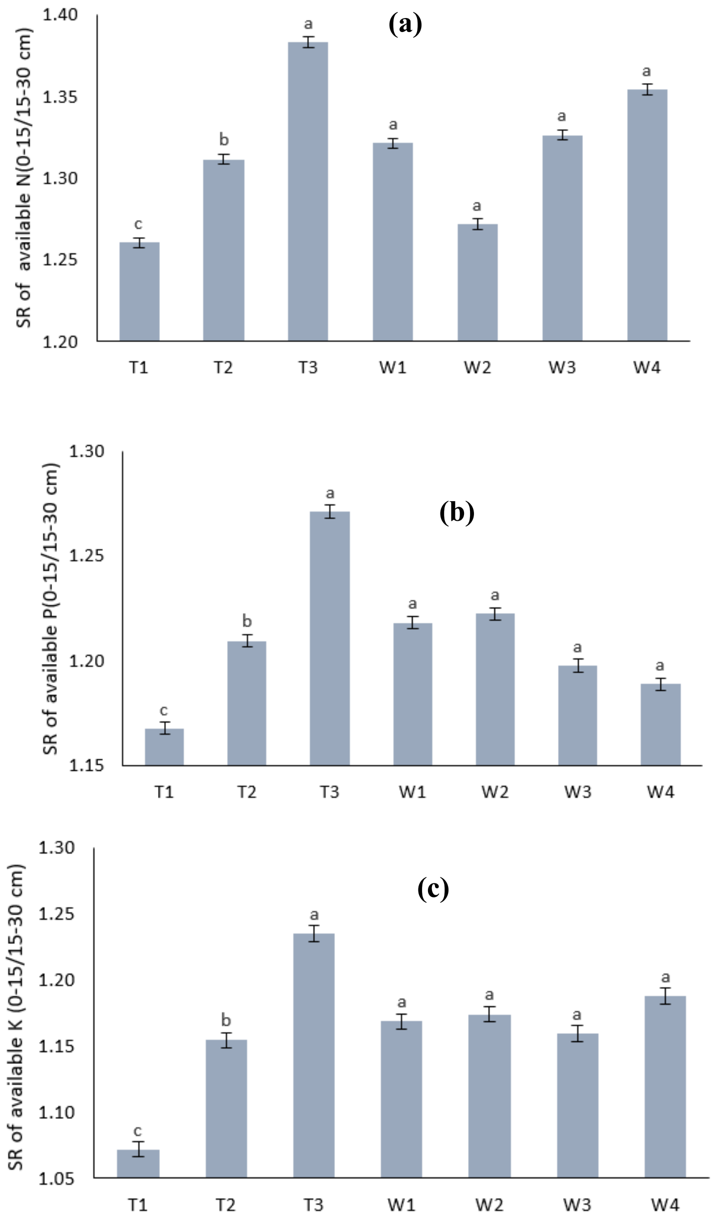

Figure 4 (a), (b), (c) Effect of tillage practices and weed management options on stratification ratio of available soil nutrients (N, P, K). Means having distinct symbols demonstrate significant variances between the treatments at 5% probability level (Tukey's test) and means having the same symbols indicate no significant variances among the treatment means at 5% probability level. Refer to table 1 and 2 for treatment details.

Soil organic carbon (SOC) stocks, SOC sequestration rate (CSR) and Carbon retention efficiency (CRE)

The SOC stocks and SOC sequestration rate varied with increase in soil depths and were significantly influenced by tillage at soil surface (0–15 cm). Weed management practices did not show any significant difference (Table 5). In the 0–15 cm depth, the

SOC stocks was significantly superior (15.92 Mg ha^{-1}) under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS compared to CT(C)-CT(C)-Fallow (N*Sr*) (13.60 Mg ha^{-1}) and CT(C)-ZT(M)-ZT(*Sr*) (14.59 Mg ha^{-1}). The ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS has restored SOC stocks at 0 –15 cm depth, while it was spread over in the soil, particularly in the ploughed profile in CT systems. The treatment interaction effects on SOC stock were non-significant. The cumulative (0-30 cm soil depth) carbon stocks and rates of C sequestration followed the same pattern as SOC stocks and SOC sequestration rate in both the soil layers (0-15 cm and 15-30 cm) (Table 5). The greatest cumulative SOC stocks (29.18 Mg ha^{-1}) and C-sequestration rate (1.98 Mg C ha^{-1} yr^{-1}) were recorded under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS compared to the CT(C)-CT(C)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) (Table 6). The carbon retention efficiency (CRE) was significantly highest (11.90%) under ZT+R(C)-ZT+R(M)-ZT+R(*Sr*) and higher (8.40 %) under CT(C)-ZT(M)-ZT(*Sr*) compared to CT(C)-CT(C)-Fallow(N*Sr*). CRE was significantly influenced by weed management, and tillage and weed management interaction effects were not significant (figure 5). The linear relationship of CRE an C-sequestration rate to cumulative C stocks as indicated by the regression analysis graphs was significant (P=0.05) (figure 6 a and b).

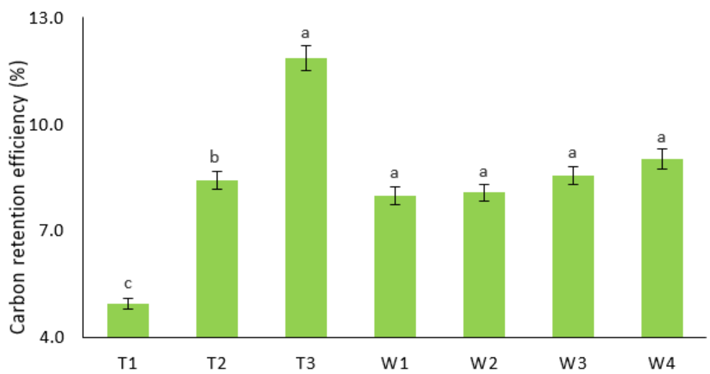

Figure 5. Effect of tillage practices and weed management options on carbon retention efficiency (CRE). Means having distinct symbols demonstrate significant variances between the treatments at 5% probability level (Tukey's test) and means having the same symbols indicate no significant variances among the treatment means at 5% probability level. Refer to table 1 and 2 for treatment details.

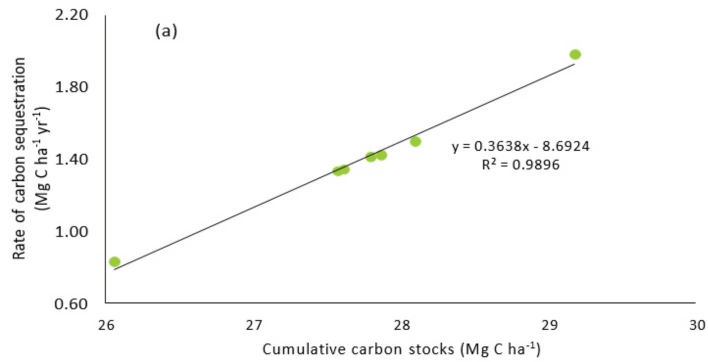

Figure 6. (a) Linear relationship of carbon sequestration rate to cumulative carbon stocks.

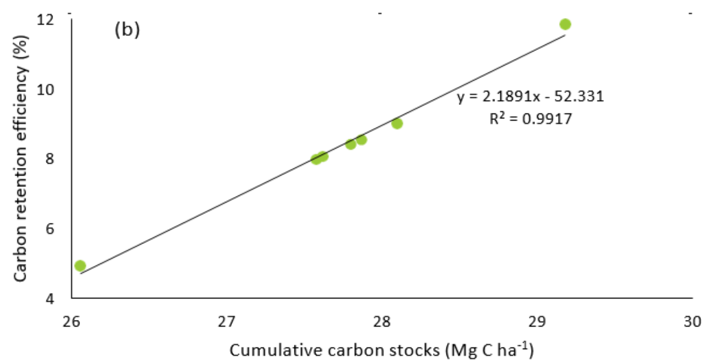

Figure 6. (b) Linear relationship of carbon retention efficiency (CRE) to cumulative carbon stocks.

Table 5. Impact of tillage practices and weed management options on SOC stocks (Mg C ha^{-1}) and C-Sequestration rate (Mg C ha^{-1} yr^{-1}) after third year post-harvest of maize in winter, 2022–23.

Treatments	SOC stocks 0-15 cm	SOC stocks 15-30 cm	Cumulative C stocks	C-Sequestration rate 0-15 cm	C-Sequestration rate 15-30 cm	Cumulative C-Sequestration Rate
Tillage practices						
Initial (s)	11.99	11.60	23.59	-	-	-
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	13.60	12.46	26.06	0.54	0.29	0.83
T_2: CT(C)-ZT(M)-ZT(*Sr*)	14.59	13.21	27.80	0.87	0.54	1.41
T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	15.92	13.49	29.18	1.31	0.67	1.98
SE(m)±	0.30	0.56		0.10	0.19	
CD(P=0.05)	1.21	Ns		0.40		
Weed management options						
W_1- Chemical weed control	14.80	12.78	27.58	0.94	0.39	1.33
W_2-Herbicide rotation	14.67	12.95	27.62	0.89	0.45	1.34
W_3- IWM	14.76	13.11	27.87	0.92	0.50	1.42
W_4- Single hand-weeded control	14.57	13.53	28.10	0.86	0.64	1.50
SE(m)±	0.35	0.36		0.		
CD(P=0.05)	Ns	Ns		Ns	Ns	
Interactions (TxW) CD(P=0.05)	Ns	Ns		Ns	Ns	

T_1= conventional tillage (cotton) – conventional tillage (maize) – Fallow (No Sesbania rostrata), T_2= conventional tillage (cotton) – zero tillage (maize) – zero tillage (Sesbania rostrata), T_3= zero tillage (cotton) + Sesbania rostrata residues (SrR) – zero tillage (maize) + cotton residues (CR) – zero tillage (Sesbania rostrata) + maize stubbles (MS), IWM= integrated weed management, SOC= soil organic carbon, CD (P= 0.05) = critical difference at 5% probability level, Ns = non-significant, SE(m) = standard error of the mean.

Soil organic carbon (SOC) pools and total organic carbon (TOC)

SOC pools and TOC were positively impacted by tillage practices in the 0 –15 and 15 –30 cm soil layers. The very labile carbon: C_{VL} (3.35 g kg^{-1}), less labile carbon: C_L (2.68 g kg^{-1}), less labile carbon: C_{LL} (2.42 g kg^{-1}), and TOC (11.69 g kg^{-1}) were significantly higher under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS in comparison with CT(C)-CT(M)-Fallow(*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) (Table 6). Among weed management practices, there was no significant effect observed on SOC pools and TOC statistically (P=0.05) The treatment interaction effects on SOC and TOC were non-significant (Table 6). The SOC pools followed the order; $C_{VL} > C_L > C_{NL} > C_{LL}$, across all tillage and weed management treatments in both soil sampling depths. In the 15–30 cm, the trend was found to be similar to 0–15 cm soil layer for C_{VL}, C_L and TOC, but the decrease compared to 0–15 cm depth. The C_{NL} and C_{LL} fluctuated inconsistently and were not significantly influenced by the treatments and their interactions (Table 6).

Table 6. Impact of tillage practices and weed management options on concentration of various pools of carbon (g kg^{-1}) and total organic carbon (TOC) (g kg^{-1}) depth-wise after three years (after harvest of maize in winter) in the 5th cropping cycle, 2022–23.

Treatments	0-15 cm					15-30 cm				
	C_{VL}	C_L	C_{LL}	C_{NL}	TOC	C_{VL}	C_L	C_{LL}	C_{NL}	TOC
Tillage practices										
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	2.65	1.95	1.73	1.86	8.19	1.59	1.36	1.73	2.85	7.06
T_2: CT(C)-ZT(M)-ZT(*Sr*)	2.83	2.22	1.93	3.02	10.00	1.80	1.70	2.09	2.91	8.03
T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	3.35	2.68	2.42	3.24	11.69	2.21	2.17	2.13	2.92	8.78
SE(m)±	0.10	0.14	0.22	0.21	0.32	0.05	0.22	0.09	0.24	0.16
CD(P=0.05)	0.40	0.56	Ns	0.85	1.29	0.20	0.80	Ns	Ns	0.63
Weed management options										
W_1- Chemical weed control	2.89	1.95	2.15	2.29	9.28	1.71	1.43	1.72	3.42	7.63
W_2-Herbicide rotation	2.67	2.20	1.59	3.20	9.66	2.27	1.44	1.66	3.00	7.85
W_3- IWM	2.96	2.21	2.04	3.00	10.21	1.85	1.58	2.23	2.76	7.92
W_4- Single hand-weeded control	3.28	2.78	2.32	2.36	10.72	1.63	2.52	2.32	2.38	8.42
SE(m)±	0.18	0.18	0.17	0.08	0.41	0.15	0.16	0.15	0.28	0.18
CD(P=0.05)	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
Interactions (TxW) CD(P=0.05)	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns

CT= conventional tillage, ZT= zero tillage; R= crop residue retention; IWM= integration of chemical weed control + power and 1 hand weeding, C= cotton, M= maize, Sr= Sesbania rostrata, C_{VL}= very labile carbon, C_L= labile carbon, C_{LL} = less labile carbon, C_{NL}= non-labile carbon and TOC = total organic carbon, CD (P= 0.05) = critical difference at 5% probability level, Ns = non-significant, SE(m) = standard error of the mean.

Passive and active pools of oxidizable soil organic carbon

The passive (C_{PSV}) and active (C_{ACT}) pools of carbon were significantly impacted by different tillage systems and weed management choices in the 0 – 30 cm soil layers (figure 5a and b). Three tillage practices indicated that 46–49% of C_{ACT} and 51–54% of C_{PSV} pools were contributed to TOC, in the 0 – 30 cm (figure 7a). Similarly, 45–52% of C_{ACT} and 48 – 55% of C_{PSV} pools were contributed to TOC by four weed management options (figure 7b).

The ratio of C_{ACT} to C_{PSV} pools ranged from 0.90 – 1.50 and 0.60 – 1.80 in the 0 – 15 and 15 –30 cm soil layers, respectively (figure 7). This ratio of C_{ACT} to C_{PSV} pools was found to be greater than 1.0 across all the treatment combinations except under CT(C)-ZT(M)-ZT(M) coupled with herbicide rotation (T_2W_2) and ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS on interaction with herbicide rotation (T_3W_2) in the 0–15 cm soil layer. The treatment combinations; CT(C)-CT(M)-Fallow(N*Sr*) and chemical weed control (T_1W_1), CT(C)-CT(M)-Fallow(N*Sr*) and single hand-weeded control (T_1W_4), and ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS with single hand-weeded control (T_3W_4) recorded higher C_{ACT}: C_{PSV} pool of 1.50 in the 0–15 cm relative to all other treatment combinations. In the 15–30 cm soil layer, significantly higher C_{ACT}: C_{PSV} pool of 1.80, 1.70 and 1.50 was noticed under ZT+R(C)-ZT+R(M)-ZT+R(*Sr*) on interaction with IWM (T_3W_3), ZT+R(C)-ZT+R(M)-ZT+R(*Sr*) in combination with herbicide rotation (T_3W_2), CT(C)-ZT(M)-ZT(M) and single hand-weeded control (T_2W_4) combination, respectively in comparison with overall tillage practices and weed management combinations (figure 8).

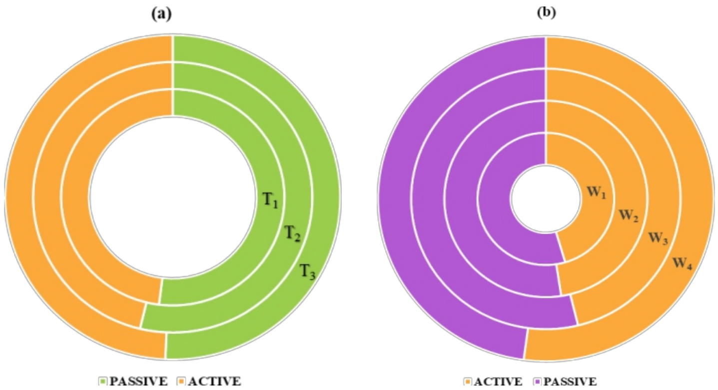

Figure 7. Impact of tillage practices (a) and weed management options (b) on oxidizable soil organic carbon pools, at 0 – 30 cm soil depth after harvest of winter maize (5th crop cycle, after third year). Refer to table 2 and 3 for treatment details.

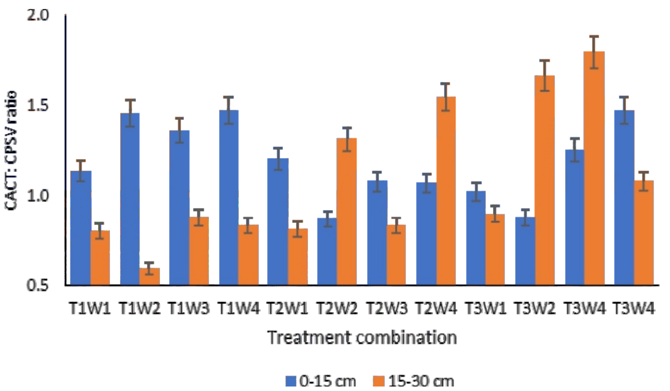

***Figure 8.** Impact of tillage practices and weed management options on active to passive pool ratio depth-wise (vertical bars represent standard error of the mean). Refer to table 2 and 3 for treatment details.*

Carbon lability, pool, and management index

LI and CPI were significantly influenced by tillage practices in 0-15 and 15-30 cm soil layers, whereas weed management effects on LI and CPI were non-significant at the same soil layers (0-15 and 15-30) (Table 7). The ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS was observed with significantly higher LI (2.26), CPI (0.63) and CMI (142.47) in 0-15 cm compared to CT(C)-CT(M)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) (Table 7). The trend observed in the 0-15 cm, was similar for 15-30 soil layer, in which ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS was found to be significantly higher on LI, CPI and CMI. Among weed management options, there was no significant effect observed on LI, CPI and CMI in both 0-15 cm and 15-30 cm soil layers. The treatment interaction effects on LI, CPI and CMI were non-significant in both soil layers (Table 7). Interestingly, depth-wise comparison of CMI had indicated that a significantly higher CMI (146.32) was recorded under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS, followed by CMI of 121.50 under CT(C)-ZT(M)-ZT(*Sr*) in the 15-30 cm compared to 0-15 cm soil layer, indicating better soil management with increase in soil depth from 15-30 cm (Table 7).

Table 7. Impact of tillage and weed management options on carbon management index depth-wise after 3rd year (after harvest of maize in winter) in the 5th cropping cycle, 2022–23.

Treatments	**0-15 cm**			**15-30 cm**		
	Lability index (LI)	**Carbon poolindex (CPI)**	**Carbon management index (CMI)**	**Lability index (LI)**	**Carbon pool index (CPI)**	**Carbon management index (CMI)**
Tillage practices						
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	2.04	0.54	108.43	1.53	0.68	102.94
T_2: CT(C)-ZT(M)-ZT(*Sr*)	2.06	0.58	118.72	1.69	0.72	121.50
T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	2.26	0.63	142.47	1.99	0.74	146.32
SE(m)±	0.02	0.01	3.08	0.08	0.01	5.56
CD(P=0.05)	0.08	0.05	12.40	0.34	0.03	22.40
Weed management options						
W_1- Chemical weed control	2.02	0.58	117.29	1.58	0.70	108.36
W_2-Herbicide rotation	1.91	0.58	111.42	1.79	0.71	126.98
W_3- IWM	2.09	0.59	122.77	1.71	0.72	122.34
W_4- Single hand-weeded control	2.46	0.58	141.33	1.86	0.74	136.65
SE(m)±	0.08	0.02	4.32	0.08	0.02	5.18
CD(P=0.05)	Ns	Ns	12.92	Ns	Ns	15.52
Interactions (TxW) CD(P=0.05)	Ns	Ns	Ns	Ns	Ns	Ns

T_1= conventional tillage (cotton) – conventional tillage (maize) – Fallow (No Sesbania rostrata), T_2= conventional tillage (cotton) – zero tillage (maize) – zero tillage (Sesbania rostrata), T_3= zero tillage (cotton) + Sesbania rostrata residues (SrR) – zero tillage (maize) + cotton residues (CR) – zero tillage (Sesbania rostrata) + maize stubbles (MS), IWM= integrated weed management., CD (P= 0.05) = critical difference at 5% probability level, Ns = non-significant, SE(m) = standard error of the mean.

Crop yield and harvest index

Tillage and weed management practices exerted a significant influence on maize grain yield (kernel yield). There was no significant effect (P=0.05) observed on harvest index (HI) by tillage practices and weed management options subsequent to harvest of maize. The treatment interaction effects on kernel yield (KY) and HI were non-significant (Table 8).

A significantly higher KY (6801 kg ha^{-1}) was recorded under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS, while significantly lower KY (6014 kg ha^{-1}) was observed with CT(C)-CT(M)-Fallow(N*Sr*). Adoption of chemical weed control and chemical (herbicide) rotation resulted in significantly higher KY (7245kg ha^{-1} and 7324 kg ha^{-1}), followed by integrated weed management (IWM) with KY of 6722 kg ha^{-1}. The significantly lower KY (4099 kg ha^{-1}) was exhibited by single hand-weeded control (Table 8).

Table 8. Yield and harvest index (HI) of maize as influenced by tillage practices and weed management (WM) options after 3rd year in conservation agriculture, 2022-23.

Treatment Interaction		kernel yield ($kg\ ha^{-1}$)	HI(%)	
Tillage	**WM**			
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	W_1	6822	44.76	
	W_2	6854	42.50	
	W_3	6354	43.82	
	W_4	4025	40.38	
T_2: CT(C)-ZT(M)-ZT(*Sr*)	W_1	7133	46.21	
	W_2	7662	41.07	
	W_3	6558	43.80	
	W_4	3559	39.36	
T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	W_1	7780	46.85	
	W_2	7456	41.94	
	W_3	7253	45.90	
	W_4	4713	41.19	
Tillage practices				
T_1: CT(C)-CT(M)-Fallow (N*Sr*)	6014		43.87	
T_2: CT(C)-ZT(M)-ZT(*Sr*)	6228		43.97	
T_3: ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS	6801		43.39	
Weed Management options				
W_1- Chemical weed control	7245		43.88	
W_2-Herbicide rotation	7324		44.25	
W_3- IWM	6722		43.68	
W_4- Single hand-weeded control	4099		43.17	
	SE(m)±	**CD(P=0.05)**	**SE(m)±**	**CD(P=0.05)**
Tillage	144.83	568.66	0.90	Ns
Weed Management	126.98	377.28	0.82	Ns
Interactions				
W at same level of T	219.94	Ns	1.43	Ns
T at same level of W	239.28	Ns	1.53	Ns

T_1= conventional tillage (cotton) – conventional tillage (maize) – Fallow (No Sesbania rostrata), T_2= conventional tillage (cotton) – zero tillage (maize) – zero tillage (Sesbania rostrata), T_3= zero tillage (cotton) + Sesbania rostrata residues (SrR) – zero tillage (maize) + cotton residues (CR) – zero tillage (Sesbania rostrata) + maize stubbles (MS), IWM= integrated weed management., CD (P= 0.05) = critical difference at 5% probability level, Ns = non-significant, SE(m) = standard error of the mean.

Discussions

Soil bulk density (BD)

BD is an attribute which change based on certain soil characteristics such as stable soil aggregation, content of soil organic matter (SOM), soil pore spaces and compaction (Chaudhari *et al*., 2013). The soil management practices which involve(s) tillage, and diversified cropping system in conservation agriculture (CA) may alter the BD. In this present investigation, significantly lower BD values observed in the top soil layer under CT(C)-CT(M)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) might be ascribed to the tillage operations employed during ploughing. In accordance with these research findings, Busari and Salako (2015), and Al-Hamed *et al*. (2018) found the lower BD under conventional tillage (CT) probably due to intensive tillage, disintegrating the soil surface. Similarly, Abaganduru *et al*. (2017) had observed that the BD in the top soil, from 0 –20 cm was higher for Zero tillage (ZT), accompanied by minimum tillage (MT), and the lower BD with CT, which demonstrated that low soil disturbance, consequently lead to a rise in BD in the upper soil layer. The rise in BD with increase in soil depth under CT(C)-CT(M)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) could be attributed to heavy farm machinery load and continuous removal of crop residues having a bearing on creating soil compaction. In line with the results of this current study, Hobbs and Gupta (2000) observed a rise on BD from 15–30 cm soil layer, as a result of soil aggregates destruction, replenishing the macro-pores with very tiny soil particles, and also direct physical activities brought about by the implements and trampling during ploughing in conventionally tilled plots. According to Alabi *et al*. (2019), sub-surface soils encounter low soil disturbance relative to surface soils, which result in a rise in BD.

Less BD exhibited by ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS in the 15–30 cm could be ascribed to continuous retention of cotton and *Sesbania* crop residues in fixed plots, and enhanced SOC content. The impact of weed control strategies on BD remain unknown, hence the effect was non-significant on BD by weed control practices. Anshuman *et al*. (2021) had also indicated no significant influence on BD by four hand weeding and integrated weed control with physical tillage operations and herbicides.

Soil physico- chemical properties

Among all other soil factors, tillage and weed management strategies contribute in the alteration of soil physico-chemical attributes. The lower pH observed in the soil surface under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS could be attributed to cumulative retention and incorporation of crop residues well-known to contain acidifying effects mainly due to secretion of organic acids (OAs) from added soil organic matter (SOM). Hong and Chen (2019) had also declared the pH values to be lower in the upper soil layer possibly due to the richness of the layer in SOM and its decomposition which in turn may consequence in the production of huge amounts of OAs, thus reducing the soil pH. Similar research findings were reported by Singh *et al*. (2014) in which upper soil was found to be more acidic comparative to the lower soil layer, and the reduction in soil pH in the upper soil was observed under CA-based practices which retains the crop residues. In addition to that, Rasmussen (1999) had also confirmed that crop nutrients and SOM accumulation under zero tillage (ZT) in the presence of decomposed previous crop residues, produces carbonic acids which in turn slow-down the soil pH. The increased soil pH with increase in soil profile depth might be due to erosion, tillage and spatial plant's root distribution hindering the movement of plant debris to drain down in the soil sub-surface.

EC was inversely proportional to soil pH such that soil EC became higher under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS relative to initial soil EC value and tillage with continuous removal of crop residues. The soil EC value (s) became higher comparative to the initial soil EC probably due to salinity of water supplied to maize crop through supplemental irrigation.

The SOC concentration of the upper soil layer in no-till with at least 30% maintenance of the crop debris is less prone to depletion due to lower soil disturbance and crop residue build-up, thus higher SOC (Kumar *et al*., 2022). This greater SOC observed with ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS could be attributed to continuous adoption of ZT, accrual retention and incorporation of the preceding cotton and *Sesbania* crops into the soil for consecutive years, which in turn may tend to enhance aggregation, shield the soil against SOC loss via erosion. These results of the present investigation on SOC are supported by Bitew *et al*. (2022) who had demonstrated that adoption of CA–based maize–legume cropping sequence continuously enhanced SOC by 37% compared to continuous adoption of CT (maize). In like manner, Liben *et al*. (2018) had observed enhanced SOC by 12 $g\ kg^{-1}$ under CA-based practices comparative to maize monocropping with CT. In zones in which soil and weather conditions are conducive for the production of biomass, and where adverse crop yield effects are unnoticed, then CA practices demonstrate greater quantity of SOC comparative to CT managed systems, more especially in the upper soil surface. CT transpose the soil, shatter the soil clods, and exposes SOM to wetting-drying phenomena resulting in the reduction of SOC contents (Bossuyt *et al*., 2022).

The reduction in SOC levels observed under CT(C)-CT(M)-Fallow(N*Sr*) could be the result of continuous removal of crop leftovers, and primary and secondary tillage implements employed for ploughing, disturbance of the soil aggregation which may increase susceptibility of the soil to erosion. Likewise, the reduction of SOC content while increasing soil sampling depth could be attributed to less spatial distribution of SOC content due to more root and crop debris assemblage in the soil surface than in the sub-surface soil. Thus, CA-based practices like minimum tillage (MT) and no-tillage (NT) are directly associated with the maintenance of crop residues and nutrient management, which in turn impacts SOC accumulation and dynamics under diversified cropping systems. Conservation tillage practices which retain crop debris tend to maintain optimum and stabilize the soil pH conditions, EC and elevate SOC contrary to the CT with continuous disposal of crop residues away.

Available soil nutrients

The soil nutrient availability like soil available nitrogen (N) and phosphorus (P) tend to be enhanced with the adoption of best management practices such as zero tillage with retention of crop remains. The availability of soil N, and P were significantly improved under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS possibly due to added crop remains which in turn decomposed into SOM. These research findings concur with the ones discovered by Sapre *et al*. (2019) in which numerical increment on soil N and P availability was observed with adoption conservation tillage in which *Sesbania rostrate* and maize remains were retained in rice, rice remains in wheat and wheat debris in maize relative to other tillage systems in a four-years CA experiment. This is attributed to build-up of crop residues regularly, augmenting the soil system with N and P as a from decomposed SOM. Alam *et al*. (2014) had also announced higher N availability in the upper soil surface under ZT as compared to CT in wheat-mungbean cropping sequence. The response of soil nutrient availability to weed management options still remain quite unclear indicated by no significant difference among the treatment means. Cotton and maize are predominant and exhaustive crops in nature (Nthebere *et al*., 2022) and absorb vast amounts of available soil nutrients particularly in conventional tillage systems as in CT(C)-CT(M)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*), where the crop leftovers were removed subsequent to harvest, which caused soil nutrient availability to fall below the initial values. The results in congruence with the ones of present investigation were reported by Sapre *et al*. (2019) who noticed a non-remarkable variation on N, P, K under CT and weed management sub-treatments comparative to the initial status. The remarkable decline in overall soil nutrients availability with increase in depth of soil profile could be ascribed to low distribution of decomposed crop remains in the sub-surface soil and also high nutrient uptake in the soil surface probably due to high roots concentration resulting in low nutrient content in the sub-surface soil.

Stratification ratios of soil physico- chemical properties and available soil nutrients

The stratification ratio (SR) is a great measure of soil quality and values of SR are normally higher at deeper soil profile. SR becomes significant where a huge variation between the soil surface and sub-surface exist. In this present study, the SRs were found to be equal to or greater than 1 in overall treatments. However, the significantly higher SRs were noticed in ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS relative to CT(C)-CT(M)-Fallow (N*Sr*) in the 0-15: 15-30 cm which could be due to less soil disruption and high SOM content resultant to added continuous crop residues. These results concur with Franzlueebbuers (2002) who had reported the variation for SR of SOC as 1.1 - 1.9 in the 0 - 15: 12.5 - 20 cm soil sampling depth under CT and 2.1-3.4 under ZT, although they have done soil sampling at different depths. Further, he had indicated a rapid enhancement of SR for SOC under no-till treatments induced by continuous build-up of soil surface C input. Similarly, Sapre *et al*. (2019) had proclaimed the overall significant rise of SR for SOC and total nitrogen (TN) in deeper soil depths under all the tillage treatments with greatest observed under ZT (2.24) followed by reduced tillage (RT) (1.62) and CT (1.42). However, there is no consistent figure for SR which has been announced to signify a high soil quality (Patra *et al*., 2019). Among all soil attributes studied, SOC and available soil N were found to have higher SRs indicating that the soil quality can be assessed better through SRs of SOC and soil N availability. Our results on SR had also clearly indicated the potential of ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS for enhancing SR of soil nutrients. The response of SR to weed management still remain unknown under CA practices.

Soil organic carbon stocks, carbon sequestration rate and Carbon retention efficiency

The decrease in an intensity of tillage and continuous maintenance of crop remains under CA are essential tactics for preservation of soil resources and sustenance of agro-ecosystems with limited mechanical practices and judicious use of chemical inputs (Liu *et al*., 2015). Soil play a key role as a source or sink for carbon, depending on advanced agricultural management techniques, and also contribute significantly in carbon cycling (Blakemore, 2018). These interface implementations can modify nutrient pathways and availability to the crop, slow-down rates of evaporation, decomposition of SOM and, consequently improve carbon repository capacity (Iqbal *et al*., 2011). In this present investigation, Soil organic carbon (SOC) stocks were significantly superior under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS probably due to accrual of surface crop remains relative to CT(C)-CT(M)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) and the initial SOC stock value. Bhattacharyya *et al*. (2013) had also reported the highest SOC contents under no-till with the application of surface residue mulch. The results similar to our study were discovered by Das *et al*. (2018) in which SOC stocks were higher under conservation tillage over conventional tillage practices in their field experiment which was carried-out in the eastern Himalaya zone. SOC stocks were reduced when soil sampling depth increased which could be ascribed to soil surface residue accrual and less concentration of the roots in the soil sub-surface. These research findings concur with that of Yadav *et al*. (2021) and Choudhary *et al*. (2013).

Tillage exerts a significant influence on the amount and distribution of SOM. The soil disruption as a result of intensive tillage, decreases the stable soil aggregates, and SOM becomes prone to depletion (Six *et al*., 2000) which might be one of the reasons for lower SOC stocks recorded in CT(C)-CT(M)-Fallow (N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*). The gains for sequestering SOC as to sustain the soil resources and crop production via adoption of a suitable conservation tillage are well-established and documented (Bhattacharyya *et al*., 2012; Bono *et al*., 2007). In this study, the greatest cumulative SOC sequestration rate exhibited by ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS could be attributed to no-disruption of the soil aggregates and high SOM content brought about added crop remains as well as permanent soil cover maintenance under diversified cropping system. Yadav *et al*. (2021) had also indicated the beneficial effects of no-till with addition of crop debris and adequate C-inputs on enhancing C-reserves and transposing the process of soil degradation over conventional tillage with continuous removal of crop residues. Thus, it may be deduced that ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS had the higher cumulative SOC stock, SOC sequestration rate, and CRE. The highly significant regression linear relationship (P=0.05) between CRE, SOC sequestration rate and cumulative SOC stocks, indicated that tillage had more determinant factor over CRE as well as SOC sequestration rate. Weed management effects on SOC stocks, SOC sequestration and CRE is unclear under CA practices.

Pools of soil organic carbon and total organic carbon (TOC)

Tillage which retains the crop left-overs favors the decomposition of soil SOM and, thus, more rapid turn-over for active C (C_{ACT}) pool. The highest percentage of C_{ACT} pool and TOC observed under ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS in the 0 –30 cm might be attributed to less soil disturbance, diversified cropping system involving predominant crops (cotton and maize) and *Sesbania*, and continuous retention of the preceding crop remains in every year. The higher percentage of passive (C_{PSV}) pool noticed under CT(C)-ZT(M)-ZT(*Sr*) in the 0 –30 cm could be ascribed to recalcitrant of this pool, well- known to have a long turn-over period under certain soil management practices. Kumar *et al*. (2018) had stated out that intensive ploughing and removal of the plant debris are favored by low C_{ACT} pool which is one of the reasons for less percentage of C_{ACT} pool observed in the 0–30 cm soil layer. Similarly, Khambalkar *et al*. (2013), and Chivane and Battacharyya (2010) had discovered that the distribution of SOC pools were very less in CT tillage systems in the absence of the crop residues probably due to less biomass production. Further, they had observed no-significant effect (P=0.05) on SOC pools by weed management practices. The decrease in SOC pools (C_{VL}, C_L, C_L, N_{LL}) and TOC with increase in soil depth (15-30 cm) observed could be the result of less distribution of the crop debris in the sub-surface compared to soil surface. Similar outcomes were reported by Kumar *et al*. (2018). However, N_{LL} was significantly higher in CT(C)-CT(M)-Fallow(N*Sr*) in the 15–30 cm compared to 0 –15 cm soil layer, probably due to recalcitrant of N_{LL}.

Passive and active pools of oxidizable soil organic carbon

The C_{PSV} pool percentage became more than that of C_{ACT} across all the treatments, indicating that the contribution of C_{PSV} pool to TOC was more than C_{ACT}, thus, C_{PSV} pool was the dominant pool over C_{ACT} pool irrespective of the tillage and weed management treatments, and their combinations in the 0-30 cm soil layer. Among the tillage practices, ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS had significantly higher C_{ACT} pool relative to CT(C)-CT(M)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) which could be ascribed to no-till with crop residue incorporation. Several studies had reported that reducing tillage intensity along-with addition of crop left-overs resulted in the build-up of very labile and labile carbon under CA scenarios (Prasad *et al*., 2016; West and Post, 2002). The ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS when interacted with non-weeded control resulted in significantly higher C_{ACT}: C_{PSV} in the 15–30 cm soil layer, and was the dominant contributor of C_{ACT} pool to TOC for the entire sampling depth (0–30 cm), probably due to less soil disturbance, crop residue addition in combination with cultural weed control methods well-known to harbor a vast diverse group of microbes, for decomposition of the crop residues, thus more SOM and higher C_{ACT} pool. In general, all the treatment combinations had the ratio greater than 1 except CT(C)-ZT(M)-ZT(*Sr)* on interaction with chemical (herbicide) rotation and chemical weed control, ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS coupled with chemical (herbicide) rotation and chemical weed control, in which the C_{ACT}: C_{PSV} was less than 1 particularly in the 0 –15 cm. The C_{ACT}: C_{PSV} was more than 1 in ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS on interaction with overall weed management choices in the 15–30 cm soil layer, signifying that more easily labile or oxidizable fractions than recalcitrant form of carbon. However, the ratio less than 1 was noticed in all CT(C)-CT(M)-Fallow(N*Sr*) in combination with every weed management practice in the 15–30 cm. Kumar *et al*. (2018) had also reported less than 1 of C_{ACT}: C_{PSV} ratio under CT and weed management combinations, indicating more of recalcitrant carbon than easily oxidizable pools.

Carbon lability, pool, and management index

Lowering of tillage intensity in conservation agricultural (CA) practices along with maintenance of crop remains tends to modify the lability of SOC and its indices *viz*., lability index (LI), carbon pool index (CPI) and carbon management index (CMI), consequently influencing the soil quality (Babu *et al*., 2020b). In this current experiment, ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS had acquired a higher LI in the 0–15 cm soil layer attributed to a greater amount of C_L pool under ZT+R(C)-ZT+R(M)-ZT+R(*Sr*). Hazra *et al*. (2019) had elucidated the LI as the sum of corresponding weightage of C_L pool, thus a greater LI signifies a productive soil with the highest C_{ACT}. The CPI was used to show the accrual of carbon (C) with respect to the reference C (C was drawn from virgin soils in the trees adjacent to the study area). Parihar *et al*. (2018) had indicated that the greater CPI signifies the accrual of SOC in the soil relative to the lower CPI. It is well-known that SOC under the trees particularly from virgin soils is more than that of the cultivable lands. It is also well-established and documented that agricultural management strategies such as CA can bolster the CPI under diversified cropping systems. Conservation tillage (ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS) adopted in this current experimental trial had recorded a higher CPI over continuous CT(C)-CT(M)-Fallow(N*Sr*) and CT(C)-ZT(M)-ZT(*Sr*) without crop residue, which revealed that the more accrual of SOC for the entire soil profile (0-30 cm). Similar research findings were revealed by Yadav *et al*. (2021).

Crop rotation which includes legume component under no-till with maintenance of crop leftovers, add vast amounts of the debris in the form of C input within a very short period of time, thus elevating the CPI (Yadav *et al*., 2021). In our present experiment, higher CPI was exhibited by ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS particularly in the 15-30 cm possibly due to inclusion of *Sesbania rostrata* well-known to have a rapid decomposition rate due to less lignin content and low C:N ratio leading to more C input. No-till and or reduced tillage (RT) under intensive cropping systems is broadly deemed as a viable alternative for enhancing CMI under various agro-ecological systems (Blair *et al*., 1995). The CMI is acquired from the total soil organic carbon (TOC) pool, and is essential for assessing the magnitude of agricultural systems adopted for promoting soil quality and enhancing SOC sequestration (Blair *et al*., 1995; Babu *et al*., 2020b; Vieira *et al*., 2007). The higher CMI value (s) signify best agricultural management practices significant for elevating SOC and bolstering the soil quality (Parihar *et al*., 2019b). In our study, adoption of tillage practices and weed management options in the 0-15 and 15-30 cm soil layers had positively influenced CMI. The higher CMI values were found in the15-30 cm than in the 0-15 cm soil layer which could be interlinked with appropriate tillage and weed management combination practices adopted and C inputs. Nevertheless, a significantly higher CMI was exhibited by ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS in the 15-30 cm soil layer which could be associated with less possibility of soil disruption and crop residue maintenance. Yadav *et al*. (2021) revealed the same findings.

Crop yield and harvest index

The better growth/development of crops and increased yield rely to a large extent on the tillage practices, as these play a crucial role in determining the development of the crop's rooting system, the soil volume explored by the roots for moisture and nutrients, the availability of air, and the regulation of soil temperature, among other factors. The importance of crop-weed interaction in determining the competition faced by the crop plants for the light, moisture and space is well-established. Confined root growth lead to decreased nutrient uptake and poor crop growth (Kumar-Raj *et al*., 2017). The meta-data analysis of ZT with residue retention indicated that the effect on crop yields in comparison with CT, is inconsistent and impacted substantially by cropping systems followed by aridity index, crop residue maintenance, ZT duration, and weed management strategies (Pittelko *et al*., 2015). In this present investigation, maize grain, and harvest index demonstrated higher values when subjected to the ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS treatment in comparison to other tillage methods. This superior performance can be interconnected to the development of robust, deep-rooted systems in the crops facilitated by the practice of zero tillage.

The implementation of ZT is thought to augment the nutrient absorption capacity of the crops, thereby fostering their physiological growth and overall development. Furthermore, the preservation of crop residues on the soil surface under the ZT(C)+*Sr*R-ZT(M)+CR-ZT(*Sr*)+MS treatment likely contributed to the enhanced retention and availability of soil moisture. This aspect proves especially crucial during the post-tasseling stage of the maize crop, which coincided with a hot period from mid-March to May. Given the limited moisture conditions during this period, supplemental irrigation was applied to ensure optimal soil moisture levels throughout the crop development. The research outcomes by You *et al*. (2016) also indicated that short-term reduced tillage (rotary-till and no-till) and residue incorporation enhanced soil properties and spring maize grain yield, growth and attributes and increased root biomass and shoot ratio. Furthermore, the interaction of tillage and residue treatments can increase crop biomass and yield (Abdullah, 2014 and Radicetti *et al*., 2016). A number of previous studies conducted on short-term conservation tillage have not paid full attention as to how yield can be improved.

No-till enhance root biomass, shoot biomass, regulate shoot to root ratio and increase yield in comparison with plow-till and rotary-till (Jin *et al*., 2010; He *et al*., 2010). Residue incorporation can also enhance crop biomass and yield due to enhanced soil buffer capacity (Getahun *et al*., 2016; Rusinamhodzi *et al*., 2011). The post-emergence tank-mix combination of atrazine and tembotrione herbicide was applied at recommended rates in both W_1 and W_2 which resulted in effective weed control and no phyto-toxicity. The absence of phytotoxic effects suggests the efficacy and safety of the tembotrione and atrazine combination in weed management, contributing to better crop performance. Poor crop performance was also observed under unweeded control which ultimately reflected in yield. This could be due to high weed density at critical crop growth stage which out competed with the crop for available moisture, nutrient, light and rooting space. Ganapathi *et al*. (2022) also recorded higher kernel, harvest index and least weed dry weight with IWM compared to the use of only advocated herbicides and non-weeded treatments due to less weed infestation. Similar results were obtained by Kumar *et al*. (2018) who observed that when pre-emergence herbicide was applied followed by one rotary hoeing at 35 DAS led to increased grain and stover yield. The results of Ahmad *et al*. (2018) concur with the findings of this present investigation, who noticed that Nicosulfuron application and one hand weeding with a hoe at 15 DAS led to greater kernel yield, whereas the least kernel yield was obtained from unweeded control. In the current study, there was an increase in corn yield and HI when employing a zero tillage with crop residue retention (ZT + R) and chemical weed control and IWM. This improvement could be attributed to the synergistic effects of efficient weed management achieved through the use of both chemical and cultural mechanical control tactics, along with the moisture and nutrient preservation facilitated by no-till practices that retained crop residues. These results are supported by Ahmad *et al*. (2018) who had deduced that maize can flourish when cultivated in zero tillage either with application of atrazine, glyphosate or with hand weeding (HW) at 40 DAS alternative to manual weeding in spring seasons to attain higher grain yield.

Conclusions

A Conservation agricultural experiment was undertaken to examine the impact of conventional tillage (CT) in the absence of the crop residues retained (R), CT followed by zero tillage (ZT) without R, ZT with R in main treatments, and weed management options in sub-treatments on soil quality parameters (SQPs) and monitor the yield of maize post-harvest. The salient findings had indicated that ZT with R enhanced the SOC, available soil nutrient status and stratification ratio (SR), cumulative Carbon sequestration rate, carbon retention efficiency (CRE), active carbon (C_{ACT}) and passive carbon(C_{PSV}) pools in the following order very labile carbon (C_{VL})> labile carbon ($_{CL}$)> non-labile carbon (C_{NL})> less labile carbon (C_{LL}), kernel yield (KY) and C_{ACT} to C_{PSV} pool ratio in the sub-surface soil layer (15-30 cm). C_{PSV} pool was the dominant contributor of soil organic carbon (SOC) to total organic carbon (TOC) exhibited by CT(C)-ZT(M)-ZT(*Sr*) and non-weeded control. KY was significantly higher under chemical weed management practices and IWM. It may be deduced that, this present investigation offers a decisive insight on the impact of tillage practices and weed management choices on evaluating soil quality and crop yield to better identify the best management practices that can sustain the soil resource and increase crop productivity under diversified cropping system. No-till with crop residues retained and IWM alternative to chemical weed control can be the best treatment combination to increase maize productivity and reduce soil degradation crisis through soil quality improvement in this region. Nevertheless, this necessitate long-term CA experiments to further monitor the crop yield response and evaluate soil quality, considering the soil depth beyond 30 cm in order to authenticate these soil quality parameter indicators on implemented agricultural management practices.

Informed Consent Statement: Not applicable.

Data Availability Statement: Available upon request

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