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Implication of land use shifting on land degradation and restoration potential of conservation agriculture in India's North-West Himalayan region

Saswat Kumar Kar[a,b,*], R.M. Singh[b], Sridhar Patra[a], M. Sankar[a], Suresh Kumar[c], Abhishek Singh[b]

[a] ICAR-IISWC, Dehradun 248 195, India
[b] Department of Farm Engineering, I.Ag.Sc., BHU, Varanasi 221005, India
[c] IIRS, ISRO, Dehradun 248 001, India

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ABSTRACT

The soil organic matter is a crucial factor in determining soil characteristics and productivity; however various land management practices degrade or aggrade the soil health. The objective of this study was to look at the influence of land-use conversion on soil health by using the concept of stratification ratio (SR) of soil organic carbon (SOC) and total nitrogen (TN) and appraise SR as a predictor of SOC and TN stock and soil health for India's North-West Himalayan region. The research is oriented toward assessing the consequences of various land use regimes' impacts on SOC and TN depth distribution, storage, and stratification and, hence, identifying appropriate sustainable tillage techniques for the region. The research was accomplished in 2020–21 in the long-term experimental plot with four land uses, namely control [natural sal forest (*Shorea robusta* L.), conventional tillage (CT), reduced tillage (RT), and zero tillage (ZT)] in a rainfed system of north-western Indian Himalayas. A decrease of 79% in the mean weighted diameter of CT was observed after conversion from forest land to CT; however, the decrease was only 50% in the case of the adoption of ZT. Further, the surface soil (0–5 cm) SOC was significantly different from each other, with forest soil having the highest SOC (27.5 $\pm$ 0.21 g kg^{-1}) and CT having the lowest SOC (11.0 $\pm$ 0.09 g kg^{-1}). The stock of SOC and TN increased significantly with increment in soil depth, and among landuses, the highest SOM was observed with forest and the lowest with CT. Among the treatments, forest (56.56 $\pm$ 1.90 Mg ha^{-1}) had significantly higher SOC storage than conservation agriculture (CA) (42.84 $\pm$ 0.27 Mg ha^{-1}, ZT, and 41.41 $\pm$ 1.84 Mg ha^{-1}, RT) and CT (41.33 $\pm$ 1.19 Mg ha^{-1}) based on equivalent soil mass approach. For forest land use, except the surface layer (0–5:5–10), all the soil layers had SR >2, whereas, for ZT, the bottom two layers (0–5:20–25 and 0–5:25–30) had SR >2 and for RT, only the bottom layer (0–5:25–30) was having SR > 2. It was observed that the conversion of land use to CT reduced the SR of SOM drastically; however, by adopting CA, the SR had been restored to near normal in forest land use. The carbon pool index (CPI) was used to determine the effects of soil tillage and residue incorporation on soil quality improvement with respect to a sal forest. The CPI value increased significantly with an increase in soil depth for three land uses, and also, at each soil depth, the CPI followed the ZT > RT > CT trend. Thus, CA may be considered a viable alternative to CT for improving soil physicochemical parameters.

1. Introduction

Good soil health is essential to sustain a better livelihood and achieve food security by producing food, feed, fuel, and fibre required to fulfill the entire community's needs. However, following the green revolution, unscientific land use, overgrazing, excessive use of fertilizers, waterlogging, erosion, deforestation, etc., have accelerated the pace of land degradation in agrarian countries like India (Reddy, 2003; Bhattacharyya et al., 2015; Patra et al., 2019a; Singh and Tewari, 2021). Moreover, the erratic climatic changes, the industrial revolution, and various anthropogenic activities worsened the situation (von Braun et al., 2013). Land degradation mainly affects resource-poor farmers due

* Corresponding author at: ICAR-IISWC, Dehradun 248 195, India.
E-mail address: saswatkumarkar@gmail.com (S.K. Kar).

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to a decline in crop yield, as they depend highly on agriculture. However, in the case of developing countries like India, the deterioration of land is a major concern, as it will further deteriorate the declining per capita cultivable land availability. India has only 2.4% of the global land area, which has to feed 18% and 15% of the global human and livestock population, respectively, and also the Indian agriculture contributes around 17% of the national GDP (Bhattacharyya et al., 2015; Sreenivas et al., 2021). A decadal change in the land degradation scenario for India was studied by Sreenivas et al. (2021), which indicates a reduction of degraded land by about 0.1 million hectares during 2015–16 compared to 2005–6, although there was an inter and intra land-use change.

Deterioration of soil health adds risk to maintaining ecosystem services and food security (Mohamed et al., 2019). Globally, land degradation is a severe issue, and its severity is higher in humid and subhumid areas than in arid, semiarid, and hyper-arid regions (Nkonya et al., 2011) and further spreading to more areas, which needs immediate attention to check further expansion (von Braun et al., 2013; Jiang et al., 2020). Due to climate change, further land degradation scenario is expected to occur soon, which necessitates the adoption of climate-resilient management strategies in terms of investment in land resources to attain land degradation neutrality (Bhattacharyya et al., 2015; Bhattacharyya, 2020; Kar et al., 2023). Deforestation of natural forest cover followed by land use change leads to a decline in soil's physiochemical properties (Bahrami et al., 2010). Further destruction of natural biodiversity leads to runoff, erosion, carbon emission, etc. Degrading soil health due to intensive and continuous conventional cultivation practices influences the availability of quality cultivable land, ultimately threatening long-term sustainable agricultural growth (Patra et al., 2019b; Sreenivas et al., 2021). Hence, the conservation and sustainability of natural resources are important for enhancing yield and maintaining livelihood under the changing climatic scenario (Kar et al., 2016; Singh and Tewari, 2021; Kar et al., 2022). Several bioengineering and ecological measures may be adopted to restore soil health (Gao and Liu, 2010). Agronomical and engineering measures like mulching, residue retention, conservation agriculture, bunding, terracing, etc., may be adopted to ensure long-term land management (Kar et al., 2018; Mahala, 2020). To combat land degradation and climate change, India promised, during the 14th Conference of Parties, to rehabilitate 26 million ha of deteriorated land by 2030 (Kar et al., 2022).

With the increased concern for an elevated level of atmospheric CO_2 concentration due to climate change and GHS emission, the carbon sequestration as terrestrial CO_2 stock in the form of soil organic carbon (SOC) by adopting various climate-resilient agricultural practices has much potential for regulating the global carbon cycle (Wang et al., 2010). To combat the problems mentioned above, it necessitates adopting climate-smart and sustainable land management methods. In this instance, conservation agriculture (CA), which consists of the least soil disturbance, incorporation of crop residues, and crop rotation, may be a climate-adaptive and economic land management practice to restore soil health (Franzluebbers, 2010; Pittelkow et al., 2015). CA enhances soil organic matter (SOM) content, sequesters soil carbon, and improves the processes favouring declined runoff and soil erosion rates in contrast to traditional agriculture (Palm et al., 2014). Furthermore, it has the potential to raise the soil fertility level by enrichment of surface soil with organic matter and vertical stratification of SOC with soil depth (Franzluebbers, 2010; Dalal et al., 2011). Studies showed that zero tillage (ZT) has higher SOC concentration and higher SOC stock than conventional tillage (CT) due to more sequestration of C in soils, which ultimately helps to lessen atmospheric carbon emission (Das et al., 2013).

The environment of that particular location largely controls the SOM stock in the soil. However, anthropogenic interferences, viz. change in land use, intensive tillage, etc., degrade the inherent SOM status (Wood et al., 2000; Magdoff and Weil, 2004). However, the depletion of SOM stock occurs due to various unscientific land use management practices. Stratified SOM distribution over depth in a CA system has several soil functional benefits, and it changes depending on soil disturbance level, cropping intensity, and length of cultivation (Magdoff and Weil, 2004). SOC is a key factor in determining soil characteristics and productivity. With the increase in the concentration of SOC in soil, soil health improves due to better stable aggregates, more water retention, and hence becomes less prone to erosion (Krishan et al., 2009; Tiwari et al., 2015). As surface SOM regulates soil health, soil erosion rate, etc., the degree of stratification of SOM with depth may be included as a quality indicator of soil under different land use practices (Franzluebbers, 2002a).

The stratification ratio (SR) is the soil property in quantitative terms at the soil surface divided by its value in subsequent deeper depths, and thereby the stratification of SOM may be used to assess dynamic soil quality (Franzluebbers, 2002a; Kalambukattu et al., 2018). In the SR, the SOM content in deeper depths is used as a reference to harmonize the evaluation and enable an unbiased comparison amidst the soils from various climatological regions or spatial locations considering intrinsic variations in soil parameters (Zhao et al., 2015; Xu et al., 2017). A higher SR of SOM is an index of improving soil health, and an SR less than two indicates that the soil is under degraded condition, and under deteriorated conditions, an SR value >2 would be rare for different tillage-based land use systems (Franzluebbers, 2002a). However, Wang et al. (2010) suggested that land use with a SOC stratification ratio > 1.2 would be of good soil quality, based on the reference land use as cropland and orchard. The depth-wise stratified distribution of SOM and, thereby, the SR may be used to distinguish the potential of various land uses to sequester SOC, improve soil quality, and choose the best management practices (Xu et al., 2017). A study indicated that due to the stratification of SOM near the surface in CA than in CT, a higher number of earthworms and arthropods were observed in the former (House and Parmelee, 1985). SR of SOM might be used to determine the changes in soil structure owing to various land management practices, and its higher value may indirectly be related to higher infiltration rate, lower bulk density, higher water holding capacity, etc. (Franzluebbers, 2002b). In this perspective, the SR may be employed in the current study to evaluate the soil quality depletion due to landuse conversion from forest land to CT and, again, soil quality restoration owing to the adoption of CA.

The purpose of the current study was to address the demand for research in Indian contexts, specifically for the very highly sensitive Himalayan region, on the consequences of landuse conversion, i.e., deforestation for agricultural use (conventional and conservation agriculture), on soil health. Our research is based on the hypothesis that, in the fragile hilly regions of the Himalayan region, although the conversion of native forest land to CT land degrades the soil health, the soil health will be restored gradually by adopting CA practices in case of these. In a nutshell, the study aimed to look at the influence of land-use conversion on soil health by using the SR of SOC and TN and appraising SR as a predictor of SOC and TN stock for India's North-West Himalayan region. Therefore, the specific objective of this study was to assess the consequences of various land use regimes on SOC and TN depth distribution, storage, and stratification, hence, identifying appropriate sustainable tillage techniques for the region.

2. Materials and methods

2.1. Details about the research area

The present investigation was conducted at the research farm of the Indian Council of Agricultural Research – Indian Institute of Soil and Water Conservation (ICAR-IISWC), Dehradun, India, which is part of the lower Himalayan region of the Doon Valley, has a subtropical climate. The research plots are placed at longitude 77.87°E, latitude 30.34 ^{0}N, and elevation 516.5 m above MSL. For the previous 64 years (1956–2020), the average rainfall in the study area was 1614.4 mm, with the southwest monsoon (July to September) accounting for 80%. In addition, this region has around 72 rainy days. Maximum and minimum rainfall, as well as rainy days, are observed in July and November, respectively. The warmest month is May, with an average daily T_{max} ranging from 20 to 37.1 °C, whereas the coolest month is January, with an average daily T_{min} ranging from 4 to 23.8 °C.

Furthermore, the average daily wind speed varies from 0.7 km h^{-1} in October to 2.6 km h^{-1} in May. The average pan evaporation varies from 1.2 mm day^{-1} in December to 7.3 mm day^{-1} in May. The clear sunshine hour ranges from 4.6 h day^{-1} in August to 9.2 h day^{-1} in May. The climatological attributes for the research region were acquired from the ICAR-IISWC meteorological station next to the study field. Fig. 1 shows a map of the location of the observation site. The soil's average pH (1:2.5) was 5.68, and the average EC (dSm^{-1}) was 0.09 at the experiment site. The most common soil texture class across the treatments was loam and had a nearly homogeneous soil distribution. As per the USDA soil taxonomy of soil order, the soil belongs to Entisols. Clay content varied from 19.29% (forest) to 23.41% (conventional tillage), and silt content varied from 41.72% (forest) to 31.52% (conventional tillage).

2.2. Experimental details

The research was accomplished in 2021 in the long-term experimental plot with four land uses viz. control [natural sal forest (*Shorea robusta* L.), conventional tillage (CT), reduced tillage (RT), and zero tillage (ZT)] located adjacent to each other in a rainfed system of north-western Indian Himalayas. Some portion of the sal forest was cut down during the 1980s and converted into agricultural lands. However, the conservation agriculture (consisting of zero and reduced tillage) experiment was established in 2011; before that, the land was under conventional tillage practices. The prevalent cropping pattern is wheat during the rabi season, followed by maize during the kharif season, whereas the forest consists of natural sal forest of 75 years old. Distinct treatments were structured in a randomized complete block design and replicated three times. In CT, the traditional farmers' practice was adopted for primary tillage with a tractor-drawn tyne cultivator was used six times for ploughing (12–14 cm average tillage depth), followed by secondary tillage for seedbed preparation and manual broadcasting of wheat and maize seeds during rabi and kharif seasons respective. In RT, a tractor-drawn tyne cultivator was used three times (9–11 cm average tillage depth), followed by planking, and here, wheat was sown using a seed drill, and maize was sown by manual broadcasting. In the case of a ZT, a seed drill was used for sowing seeds without much physical disturbance to the soil directly. In all the treatments, the crops were grown in rainfed conditions. An average total residue of 5.09, 5.58, and 6.94 t ha^{-1} yr^{-1} from grass, stubble, and root mass were integrated into the field for the CT, RT, and ZT treatments, respectively. The topsoil layer (0 to 10 cm) had a pH (1: 2.5) of 5.4, EC of 0.09 dSm^{-1}, SOC

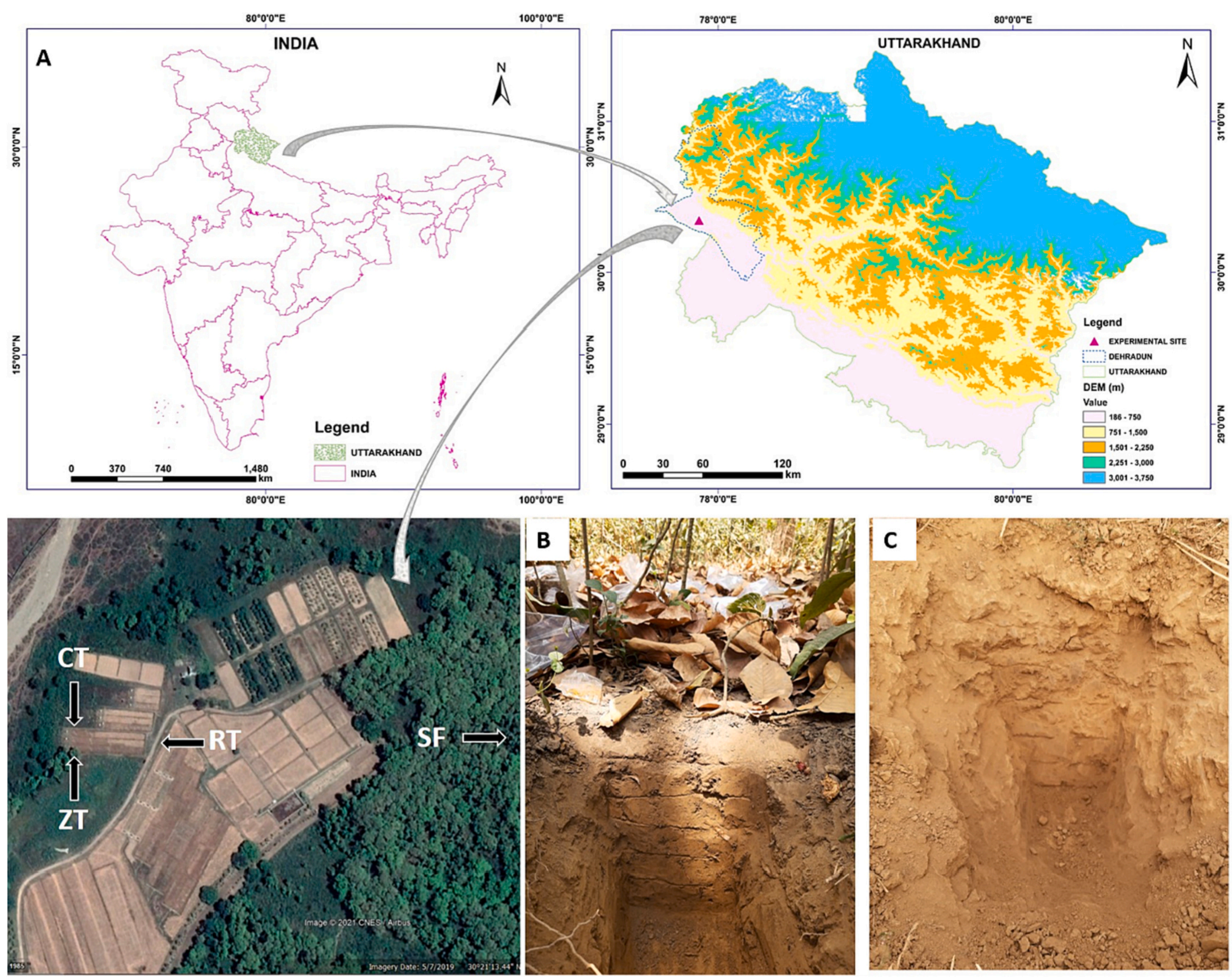

Fig. 1. A: Location map of the research field (SF: Sal forest, ZT: zero tillage, RT: reduced tillage and CT: conventional tillage), B: soil profile of forest land and C: soil profile of reduced tillage field.

concentration of 0.61%, and soil bulk density of 1.42 g cm^{-3} at the start of the field trials.

The recommended P_2O_5 and K_2O doses were coupled with N (50%) and applied as the initial dose, and the remaining N was administered 30–35 days after sowing (DAS) and 60 DAS of maize, respectively. In the case of wheat, appropriate P_2O_5 and K_2O dosages were mixed with N (50%). The remainder of the N was used during the CRI and booting stages. To reduce weeds in a maize field, pre-emergence herbicides such as Atrazine or Pendimethalin (@ 1.5 kg a.i. ha^{-1}) were applied, whereas 2, 4-D (@ 1.0 kg a.i. ha^{-1}) and isoproturon (@ 0.5 kg a.i. ha^{-1}) were applied after 35–40 DAS in wheat. Precautions have been taken throughout the years to avoid insect infestation and disease outbreaks in maize and wheat.

2.3. Soil sampling and physiochemical soil parameter analysis

Soil samples (three replications each) were obtained from all four treatments from 0–5, 5–10, 10–15, 15–20, 20–25, and 25–30 cm depths after the harvest of wheat to estimate bulk density, stone weight, MWD (mean weighted diameter), SOC and TN in the laboratory. Individual intact soil samples were collected from each layer using a stainless-steel core (5 cm each in height and internal diameter) and oven-dried for 24 h at 105 °C to ensure a consistent dry weight in order to analyze soil bulk density (Blake and Hartge, 1986). Prior to this, rock fragments (>2 mm) were removed by sieving, and the fine soil bulk density was determined by subtracting the air-dried, thoroughly cleaned stone weight from the original soil sample weight and accordingly adjusting the soil volume (density of rock fragment taken as 2.6 g cm^{-3}) (Don et al., 2007). Further, the collected soil samples were sieved via a 2 mm sieve, and the coarse particles that remained in the sieve were washed thoroughly with water and dried at 105 °C to obtain stone weight. The MWD of water-stable aggregates was determined by soil's aggregate size analysis using a Yoder apparatus as per the wet-sieving principle (Yoder, 1936). The mechanical sieve shaker consists of a nest of sieves of different mesh sizes, viz. 0–0.12 mm, 0.12–0.25 mm, 0.25–0.50 mm, 0.50–1 mm, 1–2 mm, 2–4 mm, and 4–8 mm. Air-dried soil samples (100 g), free from any foreign material, were processed across an 8 mm sieve and placed on the sieve shaker's topmost sieve (4 mm mesh size). Before beginning the wet-sieving process, the soil sample was slowly rewetted for 10 min, and then the nest of sieves was moved up and down with an amplitude of 3 cm and at a rate of 30 cycles minute^{-1} for 30 min inside the water drum (Zhou et al., 2020). The water-stable aggregates that remained on each sieve at the end of the process were collected and oven-dried at 60–80 °C unless a consistent weight was achieved. To assess the impact of land conversion from forest type to other agricultural practices on soil structure, the MWD of aggregates was determined using the following formula (Kemper and Rosenau, 1986).

$$\mathrm{MWD\ (mm)} = \frac{\sum_{i=1}^{n}(D_iM_i)}{\sum_{i=1}^{n}M_i} \tag{1}$$

where M_i is the soil mass (g) retained in each aggregate class to total soil mass, and D_i is the average diameter of the respective sieve (mm).

The air-dried soil samples were then filtered through a 2 mm sieve to analyze SOC and TN in the laboratory.

2.4. Estimation procedure for soil quality parameters

2.4.1. Determination of concentration of SOC and TN

The SOC was analysed by wet digestion via the Walkley and Black method, i.e., wet oxidation with chromate in the presence of strong acid (Walkley and Black, 1934). A factor of 1.32 is traditionally multiplied by the value obtained by the above method to compensate for SOC's partial oxidation and to obtain total SOC (Magdoff and Weil, 2004). However, the factor is not universally applicable for all soil types; hence we used a revised factor (1.818), as reported by Krishan et al. (2009) for our study area, to compensate for the partial oxidation of SOC and estimate the total SOC. The TN content was determined by the wet oxidation based on the Kjeldahl method (Bremner, 1965).

2.4.2. Calculation of stratification ratio

As shown in Eq. (2), the stratification ratio (SR) of bulk density, MWD, SOC, and TN were computed by dividing the value of each soil parameter in the top (0–5 cm) soil layer by the values of the following deeper layers (5–10, 10–15, 15–20, 20–25, and 25–30 cm) (Franzluebbers, 2002a).

$$\mathrm{SR} = \frac{\text{Value of soil parameter in the top } (0-5 \text{ cm}) \text{ soil layer}}{\text{Value of soil parameter in the subsequent bottom soil layer}} \tag{2}$$

2.4.3. Calculation of SOC and TN storage

The equivalent soil mass (ESM) approach was used to compute SOC and TN storage (Ellert and Bettany, 1995; Xue et al., 2015; Zhao et al., 2015; Patra et al., 2019a). The SOC and TN storages were represented cumulatively at soil depths of 0–5, 0–10, 0–15, 0–20, 0–25, and 0–30 cm.

The ESM of SOC and TN were calculated using Eq. (3):

$$M_{ESM} = \left[\sum_{i=1}^{n} M_{soil,i} \times conc_i + \left(M_k - \sum_{i=1}^{n} M_{soil,i}\right) \times conc_{extra}\right] \times 0.001 \tag{3}$$

where M_{ESM} (Mg ha^{-1}) is the ESM of SOC and TN storage; $M_{soil,\ i}$ (Mg ha^{-1}) is the soil mass of ith soil layer, $i = 1, 2, 3, 4, 5$ and 6, representing 0–5, > 5–10, > 10–15, > 15–20, > 20–25 and > 25–30 cm soil layers, respectively; $conc_i$ (g kg^{-1}) is the concentration of SOC and TN in the ith soil layer; M_k is the certain soil mass, and when k = 1, 2, 3, 4, 5 and 6, it indicates the maximal soil mass following various management practices in the 0–5, 5–10, 10–15, 15–20, 20–25, 25–30 cm soil depths; $conc_{extra}$ (g kg^{-1}) is the extra SOC and TN concentration, and when $i = 6$, the $conc_{extra}$ was considered to be equal to the bottom soil depth because SOC and TN altered less in greater depth; 0.001 is a conversion factor (Mg kg^{-1}).

$M_{soil,\ i}$ (Mg ha^{-1}) was computed based on Eq. (4).

$$M_{soil,i} = \rho_{b,i} \times X_i \times 10000 \tag{4}$$

where $\rho_{b,i}$ (Mg m^{-3}) is the fine soil (< 2 mm) bulk density and X_i (m) is the soil thickness; 10,000 is a unit conversion factor (m^2 ha^{-1}).

2.4.4. Carbon pool index (CPI)

The CPI was computed as follows (Blair et al., 1995; de Oliveira Ferreira et al., 2013).

$$\mathrm{CPI} = \frac{TOC_S}{TOC_R} \tag{5}$$

where TOC_S = Total SOC content in sample treatment (Mg ha^{-1}) and TOC_R = Total SOC content in reference treatment (Sal forest) (Mg ha^{-1}).

2.5. Statistical analysis

Three samples from each treatment were obtained as three replications from depths 0–5, 5–10, 10–15, 15–20, 20–25, and 25–30 cm. Analysis of variance (ANOVA) was performed separately for testing the significance among the means of bulk densities, concentration, storage, and SR of SOM parameters (SOC and TN) for the same soil depth and for testing the significance of means among different depths for same treatment (Patra et al., 2019a). The Shapiro-Wilk test (Shapiro and Wilk, 1965) was used to evaluate the normality of the treatment data, and transformation was performed in order to normalize data in case of non-normal data. A parametric test (Least Significant Difference test)

(Webster, 2007) was used to make multiple comparisons among means. A nonparametric (Kruskal–Wallis) test was used to determine if there was a significant difference ($p < 0.05$) among the means of parameters that were not normally distributed even after appropriate transformation (Zhang et al., 2021). The SPSS software (version 21) was used to conduct all statistical analyses.

3. Results and discussion

3.1. Soil physicochemical properties

The variation of soil bulk densities (ρ_b) as influenced by various land use practices and due to increment of soil depth is presented in Fig. 2. Under all treatments, the ρ_b increased with increasing soil depth. The ρ_b varied from 1.00 ± 0.11 (0–5 cm) to 1.38 ± 0.01 (20–25 cm) g cm^{-3} for the forest, 1.14 ± 0.01 (0–5 cm) to 1.27 ± 0.05 (25–30 cm) g cm^{-3} for ZT, 1.18 ± 0.07 (0–5 cm) to 1.43 ± 0.02 (25–30 cm) g cm^{-3} for RT and 1.25 ± 0.05 (0–5 cm) to 1.42 ± 0.07 (10–15 cm) g cm^{-3} for CT. In the topsoil layer, the lowest ρ_b was noticed in forest land usage, followed by ZT, RT, and CT, respectively, and the ρ_b of CT was significantly ($p <$ 0.05) higher than forest and ZT. Up to 15 cm soil depth, the ρ_b of CT was significantly higher than all other land uses. Beyond 15 cm soil depth, the ρ_b did not vary significantly among soil depths for all four land use practices. The rising trend of soil bulk density with soil depth was also reported (Mehler et al., 2014; Liu et al., 2020), and it may be due to lesser SOM content and less microbial activity at deeper depths. The lowest soil bulk density in forest land and ZT may be attributed to the perennial plant cover, continued litter addition and crop residue retention, etc., accompanied by a minimal mechanical disturbance that avoids soil compaction and increased SOC input (Kabir et al., 2020). The bulk density was inversely related to SOC (Don et al., 2007), and its variation also followed a similar trend as SOC for all land uses. Due to the use of frequent heavy farming equipment (Patra et al., 2019b) for primary and secondary tillage followed by compaction of soil (Havaee et al., 2014) and a decrease in total porosity, lowering of SOC and earthworm activity (Li et al., 2021) higher bulk density was observed in CT, and RT land uses as compared to forest and ZT.

Likewise, the influence of various land-use practices on soil aggregate MWD is visible, as presented in Fig. 3. In the topsoil layer, the forest soil had significantly ($p < 0.05$) higher MWD (mm) (3.76 ± 0.56) among all other treatments, likely due to higher SOC and stable aggregate. It was followed by ZT having significantly ($p < 0.05$) higher MWD (1.87 ± 0.12) as compared to RT (1.04 ± 0.05) and CT (0.78 ± 0.03). However, beyond 5 cm soil depth, the CT, RT, and ZT did not vary significantly, although it was significantly different from forest lands. With the increase in soil depth, a decline in MWD was observed for all the land uses. It was observed that a decrease (79%) in MWD of CT was observed after conversion from forest land to CT; however, the decrease was only 50% in the case of the adoption of ZT. The MWD varied from 3.76 ± 0.56 (0–5 cm) to 0.70 ± 0.11 (25–30 cm) for the forest, 1.87 ± 0.12 (0–5 cm) to 0.53 ± 0.06 (25–30 cm) for ZT, 1.10 ± 0.24 (5–10 cm) to 0.46 ± 0.03 (25–30 cm) for RT and 0.80 ± 0.01(10–15 cm) to 0.47 ± 0.01 (25–30 cm) for CT. Higher aggregate stability in terms of MWD for ZT and RT than CT indicates that the improved soil structure leads to low soil erosion due to less soil disturbance and reduced aggregate disruption (Liu et al., 2020). The higher water-stable aggregation in the forest (3.76 ± 0.56 mm) and conservation agriculture (1.87 ± 0.12 mm) may be due to higher SOC (27.47 ± 0.21 g kg^{-1} in the forest and 17.98 ± 0.07 g kg^{-1} in CA), root-induced physical entanglement of aggregates, increased root exudates, and reinforcement of soil particle contact due to better root growth (Parihar et al., 2016; Patra et al., 2019b). A similar finding of higher MWD in CA compared to CT was also observed by several other researchers (Govaerts et al., 2009; Kan et al., 2020; Parihar et al., 2020; Nyambo et al., 2022), and the attributing cause was minimum soil disturbance, increased earthworm activity, and higher SOC leading to higher abundance of macro aggregates. Converting virgin forest land to conventional tillage practices reduced soil aggregate stability significantly, and it was restored near to its original level by adopting conservation agricultural practices.

The depth-wise SOC (g kg^{-1}) distribution among different land uses presented in Fig. 4 (A). The surface soil (0–5 cm) SOC was significantly different from each other, with forest soil having the highest SOC (27.47 ± 0.21) and CT having the lowest SOC (11.00 ± 0.09). The SOC in the topsoil layer followed the trend; forest > ZT > RT > CT. The SOC varied

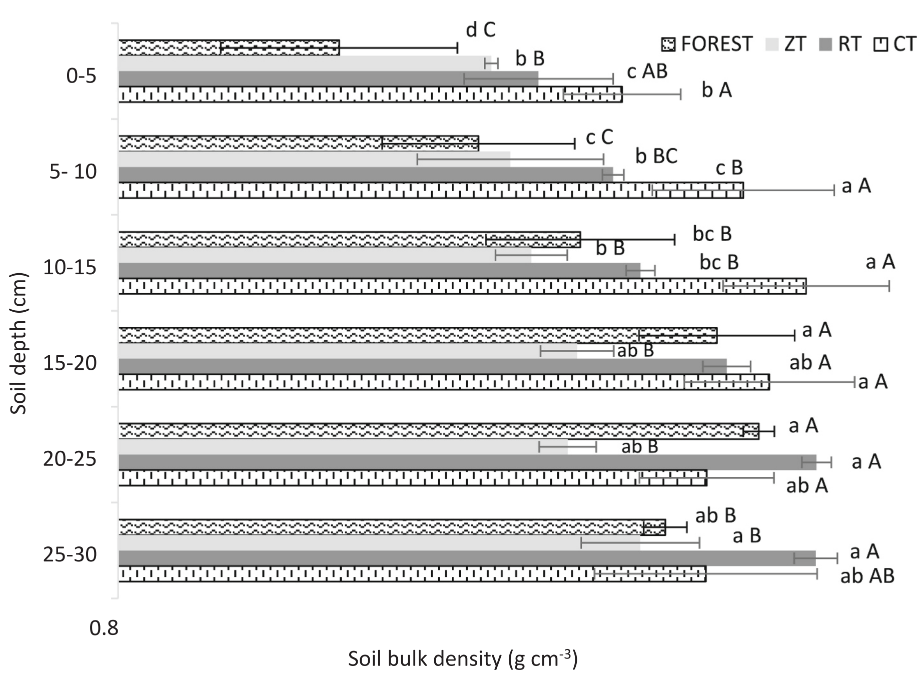

Fig. 2. Soil bulk density depth variation under various land use patterns (Forest, ZT, RT, and CT). The bars present mean ± SD (m = 3). The different uppercase alphabets imply significant differences across treatments for a given soil depth, and the lowercase alphabets imply significant differences across the soil depths for a given treatment ($P < 0.05$).

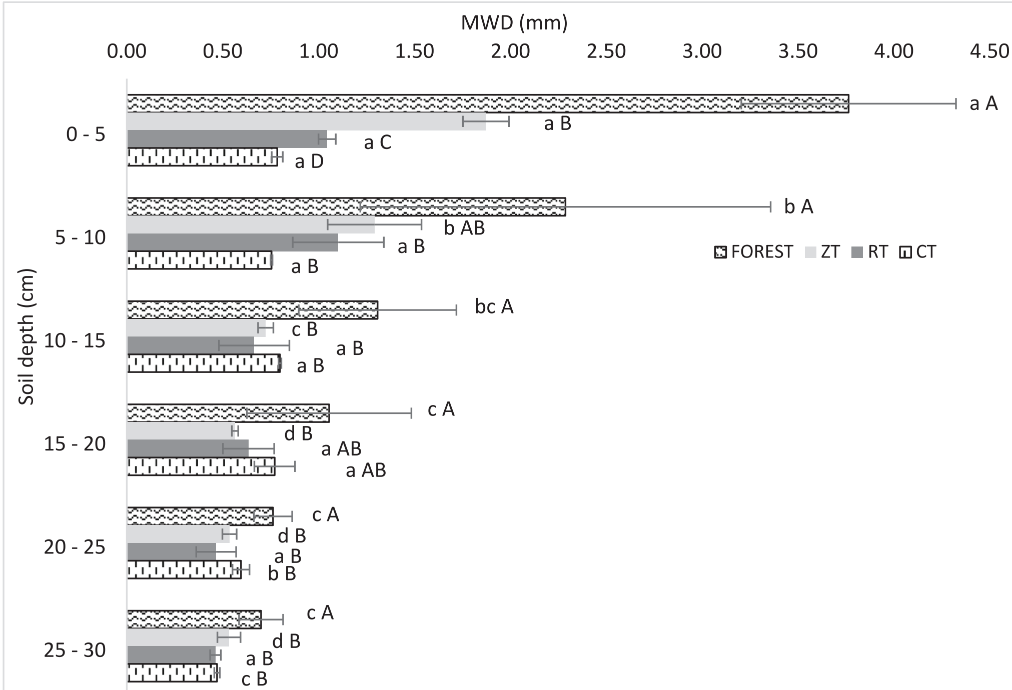

Fig. 3. Depth distribution of MWD (mm) under different land use practices (Forest, ZT, RT, and CT). The bars present mean ± SD (m = 3). The different uppercase alphabets imply significant differences across treatments for a given soil depth, and the lowercase alphabets imply significant differences across the soil depths for a given treatment ($P < 0.05$).

from 27.47 ± 0.21 (0–5 cm) to 7.71 ± 0.25 (25–30 cm) for the forest, 17.98 ± 0.07 (0–5 cm) to 8.80 ± 0.47 (25–30 cm) for ZT, 14.97 ± 0.05 (0-5 cm) to 7.50 ± 0.41 (25–30 cm) for RT and 11.00 ± 0.09 (0–5 cm) to 8.94 ± 1.03 (25–30 cm) for CT. The SOC content of the topsoil layer significantly varied from subsequent subsoil layers in forest, ZT, and RT; however no significant variation among soil depths beyond 5 cm.

In the case of CT, there was no significant variation throughout the soil depth. There was no significant variation in SOC among treatments beyond 15 cm of soil depth. The SOC decreased with soil depth for all treatments, and similar results with forest land having higher SOC compared to agricultural land were also reported by several other researchers (Xu et al., 2017; Chao et al., 2019). The better MWD due to lesser soil disturbance is mainly responsible for the higher SOC (Liu et al., 2020) in forest and conservation agriculture land uses compared to conventional tillage land uses. Tillage leads to surface soil disturbance, erosion, and SOC mixing, as in the case of CT, and the soil health gradually improves toward conservation agriculture and forest land use due to less soil disturbance, higher residue retention, litter addition, and slowing down of SOC mineralization (Patra et al., 2019a; Kabir et al., 2020; Kan et al., 2020). However, in the subsoil, the lower SOC content of forest (7.71 ± 0.25) and ZT (8.80 ± 0.47) as compared to CT (8.94 ± 1.03) may be due to less incorporation of crop residues to deeper depths (Chao et al., 2019). Although the SOC (%) in surface soil (0–5 cm) was significantly reduced ($P < 0.05$) by conversion of forest land to conventional tillage practices from 27.47 ± 0.21 g kg^{-1} to 11.00 ± 0.09 g kg^{-1}, but by adopting conservation agriculture practices, the SOC was significantly improved to 17.98 ± 0.07 g kg^{-1}.

Furthermore, the soil TN concentrations (g kg^{-1}) reduced as soil depth increased across all treatments, as presented in Fig. 4(B). The vertical variations of TN concentrations changed across treatments as well. In the surface soil, the TN content of forest (2.02 ± 0.29) and ZT (1.28 ± 0.01) were significantly higher than RT (0.85 ± 0.03) and CT (0.86 ± 0.10), although there was no significant difference between RT and CT. The soil TN ranged from 2.02 ± 0.29 (0–5 cm) to 0.59 ± 0.07 (25–30 cm) under forest, 1.28 ± 0.01 (0–5 cm) to 0.64 ± 0.04 (25–30 cm) under ZT, 0.85 ± 0.03 (0–5 cm) to 0.70 ± 0.02 (10–15 cm) under RT and 0.86 ± 0.10 (5–10 cm) to 0.70 ± 0.09 (25–30 cm) under CT. The maximum TN concentration was found under forest lands at 0 to 15 cm soil depth, whereas, beyond 15 cm soil depth, RT showed the highest TN. However, beyond 15 cm soil depth, there were no significant TN content differences among land uses or depth-wise. The depth-wise variation among land uses followed the same pattern as the distribution of SOC. The TN content in forest and conservation agriculture land use may be associated with adding agricultural residues and litter on the soil surface, less soil disturbance, and less soil nitrogen mineralization (Patra et al., 2019a). Moreover, after plough depth (> 15 cm), neither the tillage nor the crop residue addition had any impact on soil total nitrogen distribution, and it may be due to minimal soil disturbance, less SOM input, and mixing of soil below this depth.

3.2. Stratification ratio of MWD and SOM

The stratification ratio of MWD (mm) under different land use practices is presented in Fig. 5. Under all treatments, the SR of MWD rose considerably ($p < 0.05$) with increasing soil depth from 0–5:5–10 to 0–5:25–30 cm soil depths. The SR of MWD followed the trend Forest> ZT > RT > CT for all soil depth ratios, indicating a decrease in SR with increased tillage intensity. In the surface 0–5:5–10 soil depth, the SRs among the land uses were not significantly different; however, from 0–5:15–20 soil depth onwards, the SRs were significantly different among them. Moreover, the ZT land use indicated substantially higher SR values than RT and CT. The SR values of MWD varied from 2.01 ± 1.17 (0–5:5–10) to 5.57 ± 1.83 (0–5:25–30) for the forest, 1.50 ± 0.38 (0–5:5–10) to 3.56 ± 0.63 (0–5:25–30) for ZT, 0.97 ± 0.17 (0–5:5–10) to 2.26 ± 0.04 (0–5:25–30) for RT and 0.98 ± 0.05 (0–5:10–15) to 1.67 ± 0.01 (0–5:25–30) for CT. The SR value of MWD >2 indicates an improvement in soil quality (Franzluebbers, 2002a). Furthermore, in the current research, the SRs for all the soil depths for forest land use was >2, and for ZT, all the soil depths except surface soil (0–5:5–10) were >2. For RT, only the bottom two layers had SRs >2. In the case of CT, none of the soil layers had SR values >2. It indicates that the minimum soil disturbance-based conservation agriculture leads to improved soil

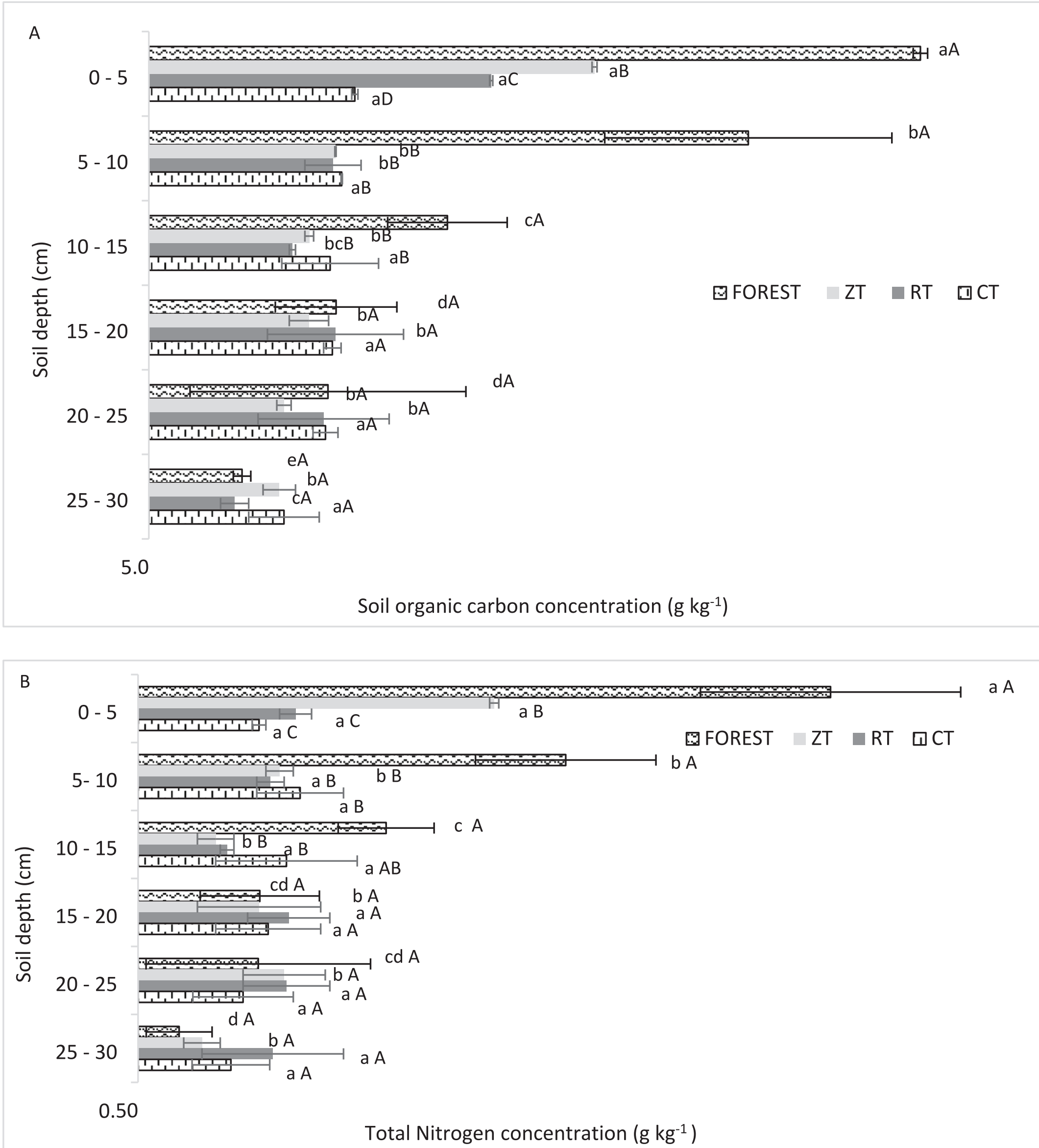

Fig. 4. Variation of concentration of (A) SOC and (B) TN under different land use practices (Forest, ZT, RT, and CT). The bars present mean ± SD (m = 3). The different uppercase alphabets imply significant differences across treatments for a given soil depth, and the lowercase alphabets imply significant differences across the soil depths for a given treatment ($P < 0.05$).

quality in terms of MWD compared to CT, as observed from SR.

The SR of SOC increased significantly along with the soil depth for all land use. However, a nonsignificant increase was observed in ZT and CT land uses (Table 1). For forest land use, except the surface layer (0–5:5–10), all the soil layers had SR >2, whereas, for ZT, the bottom two layers (0–5:20–25 and 0–5:25–30) had SR >2 and for RT, only the bottom layer (0–5:25–30) was having SR > 2. However, for the CT land use, all the soil layers had SR < 2, and no significant differences in SR were observed among layers. The SR values varied from 1.25 ± 0.22 to 3.56 ± 0.11 for forest lands, 1.72 ± 0.01 to 2.05 ± 0.12 for ZT, 1.45 ± 0.12 to 2.00 ± 0.12 for RT and 1.02 ± 0.02 to 1.23 ± 0.14 for CT.

Similarly, the SR of TN also increased significantly with the increase in the soil depth for all three land uses except RT (Table 1). The forest land use had SR > 2 at (0–5:15–20) and (0–5:25–30), while ZT had SR > 2 at (0–5:25–30). However, the RT and CT had SR < 2 for all the soil layers. The ZT land use had significantly higher SR values than RT and CT for all the soil layers, although there was no significant difference between RT and CT. It implies that soil quality improves more rapidly under CA than under CT. Hence the adoption of conservation agriculture will enhance soil health. It was observed that converting land use to CT reduced the SR of SOM drastically. However, by adopting CA, the SR had been restored to near-normal in forest land use. The highest SR of SOC and TN in forests and CA are in line with the observations of other trials (Franzluebbers, 2002a; Xue et al., 2015; Zhao et al., 2015; Patra et al., 2019a), which indicate better sequestration of SOM and thereby improvement of soil quality in forest and CA practices over CT (Zhao et al., 2015). Due to the continuous build-up of higher SOM in the surface layer, the SR of SOM was higher in forest and CA land use compared to CT land uses (Franzluebbers, 2002a; Zhao et al., 2015; Chao et al., 2019). Moreover, the C input due to crop residue addition and leaf litter incorporation is also more in the forest, ZT, and RT than CT, which may have promoted the gradual stratification of SOM in these land uses (Patra et al., 2019a). The SR of SOM increased significantly along with the soil profile down the soil depth due to the lowering of the concentration of SOM from surface to subsurface (Ussiri and Lal, 2009; Patra et al., 2019a). The variation in SR among land uses may have developed due to soil profile disturbance by different tillage practices, as tillage leads to the incorporation of SOM in deeper layers (Xue et al., 2015). The

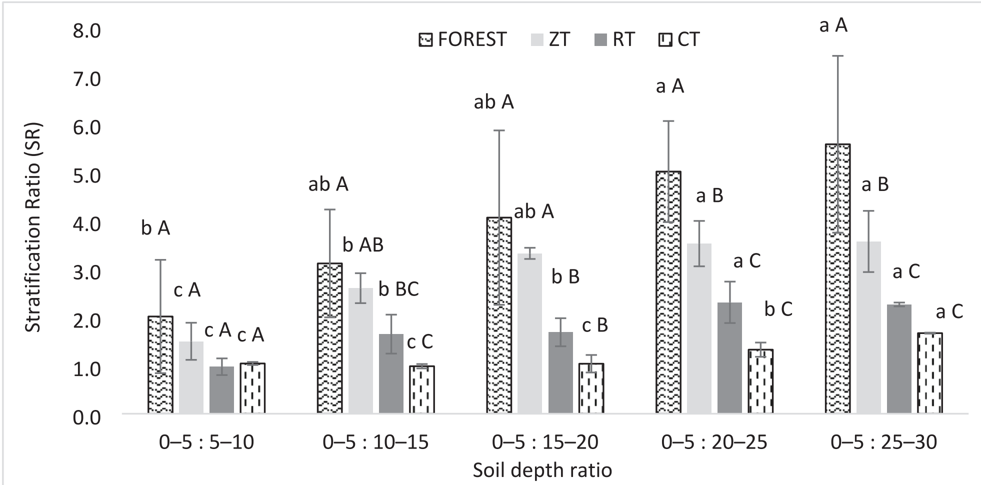

Fig. 5. Stratification ratio of MWD (mm) under different land use practices (Forest, ZT, RT, and CT). The bars present mean ± SD (m = 3). The different uppercase alphabets imply significant differences across treatments for a given soil depth, and the lowercase alphabets imply significant differences across the soil depths for a given treatment ($P < 0.05$).

Table 1
Stratification ratio (SR) of SOC and TN under different land use practices (Forest, ZT, RT, and CT). The data present mean ± SD (m = 3). The different uppercase alphabets imply significant differences across treatments for a given soil depth, and the lowercase alphabets imply significant differences across the soil depths for a given treatment ($P < 0.05$).

Parameters	Soil depth	Treatments			
		Forest	ZT	RT	CT
SR of SOC	0–5:5–10	1.25 ± 0.22 dB	1.72 ± 0.01 aA	1.45 ± 0.12 bAB	1.02 ± 0.02 aB
	0–5:10–15	2.03 ± 0.26 cA	1.86 ± 0.02 aA	1.63 ± 0.01 abA	1.07 ± 0.16 aB
	0–5:15–20	2.68 ± 0.47 bA	1.87 ± 0.12 aB	1.47 ± 0.29 bBC	1.05 ± 0.04 aC
	0–5:20–25	2.95 ± 1.00 bA	2.01 ± 0.06 aB	1.52 ± 0.29 bC	1.07 ± 0.04 aC
	0–5:25–30	3.56 ± 0.11 aA	2.05 ± 0.12 aB	2.00 ± 0.12 aB	1.23 ± 0.14 a C
SR of TN	0–5:5–10	1.44 ± 0.39 cAB	1.58 ± 0.07 bA	1.07 ± 0.01 aBC	0.94 ± 0.10 c C
	0–5:10–15	1.96 ± 0.43 cA	1.92 ± 0.13 aA	1.22 ± 0.02 aB	0.98 ± 0.17 bcB
	0–5:15–20	2.65 ± 0.29 bA	1.71 ± 0.29 abB	1.02 ± 0.07 aC	1.03 ± 0.14 abcC
	0–5:20–25	2.74 ± 0.46 bA	1.57 ± 0.16 bB	1.04 ± 0.16 aC	1.10 ± 0.15 abBC
	0–5:25–30	3.41 ± 0.14 aA	2.00 ± 0.11 aB	1.10 ± 0.26 aC	1.14 ± 0.07 aC

concentration of SOM in surface soil is increased because agricultural residues are retained in the topsoil, and also, an undisturbed soil profile was caused due to relatively higher SR in CA practices than in CT (Zhao et al., 2015).

3.3. Storage of soil organic matter

To correct the error in the estimation of storage of SOM due to variations in soil bulk density developed due to different land uses, tillage practices, and residue management (Zhao et al., 2015), an ESM method was considered in the current research. In the ESM approach, the variation in soil mass for different land uses due to variation in soil bulk density was considered for assessment on an equivalent mass basis. As in the case of the fixed depth method, the layer having higher bulk density would lead to higher soil mass and higher storage of SOM, which is incorrect. For example, considering the topsoil layer given in Fig. 6, the bulk density also varied among land uses due to various land management practices. As compared to CT, all other land uses have lower bulk density; hence for the top layer (0–5 cm), CT has more soil mass (626.66 Mg ha^{-1}) followed by RT (589.11 Mg ha^{-1}), ZT (567.87 Mg ha^{-1}) and forest (546.52 Mg ha^{-1}). Therefore, a certain amount of soil mass was hypothetically added to the top layers in RT, ZT, and forest to attain an equivalent soil mass in the top layer. Then, the exact amount of soil mass was subtracted from the subsequent bottom layer. In the present case, 37.55 Mg ha^{-1}, 58.79 Mg ha^{-1}, and 80.14 Mg ha^{-1} of soil mass were subtracted from the bottom layer and added to the top layer for RT, ZT, and forest land, respectively, to attain an ESM of 626.66 Mg ha^{-1}. The revised soil mass of the second layer was 585.10 Mg ha^{-1}, 517.69 Mg ha^{-1}, and 530.01 Mg ha^{-1} for RT, ZT, and forest land, respectively.

Based on the ESM method, the vertical stock of SOC and TN for four land use practices are given in Table 2. For all the treatments, the storage of SOC (Mg ha^{-1}) increased significantly with soil depth increase, and the storage of SOC was lowest at the soil surface and highest at the bottom of the soil surface. Among the treatments, forest (56.56 ± 1.90) had significantly higher SOC storage than CA (42.84 ± 0.27, ZT and 41.41 ± 1.84, RT) and CT (41.33 ± 1.19). However, ZT and RT had significantly higher storage than CT up to 20 cm soil depth; beyond that, there were no significant differences. The storage of SOC followed the trend Forest>ZT > RT > CT. Similarly, TN storage (Mg ha^{-1}) increases significantly with an increment in soil depth, and among land uses, the highest TN was observed with forest and the lowest with CT. The storage of TN followed the trend, forest>ZT > RT > CT. At the surface (0–5 cm), the storage of TN for forest (1.20 ± 0.09) and ZT (0.77 ± 0.02) were significantly different from each other and also from the other two land uses. Beyond 10 cm soil depth, the storage of TN for ZT, RT, and CT did not vary significantly. Because SOC and TN storage along the soil profile was associated with SRs, they rose concurrently with SR levels. The increased SOC and TN stocks in the soil surface in CA may be due to higher residue retention in the surface soil than in CT (Xue et al., 2015). The findings show that the CA practices improve the surface SOM storage compared to the CT practices, and the same trend was also reported by Patra et al. (2019a) in cereal-based cropping systems. Similar results of higher SOM storage in CA practices were also observed by other experts (Chao et al., 2019; Patra et al., 2019a; Liu et al., 2020). Overall, the results indicated that, while SOM storage was reduced owing to the conversion of land use from forest to CT, adopting CA approaches improved SOM storage compared to CT practices.

The SOC concentration and MWD were significantly positively correlated (R^2 = 0.82, p-value <0.001 and Fig. 7(a)), and both the

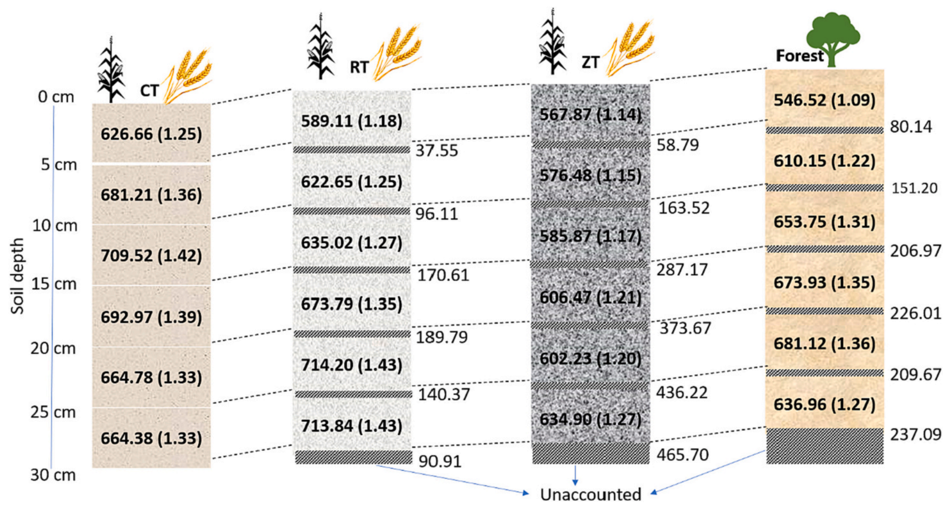

Fig. 6. Example of the equivalent soil mass calculation for a given data set in CT, RT, ZT, and forest lands. The numbers in bold represent soil mass (Mg ha^{-1}), and the numbers in parenthesis represent bulk density (Mg m^{-3}). The quantity of soil mass from a deeper layer transferred to the succeeding top layer to obtain an equal soil mass for a particular layer is indicated by the numbers outside the box.

Table 2
Storage of SOC and TN under different land use practices (Forest, ZT, RT, and CT). The data present mean ± SD (m = 3). The different uppercase alphabets imply significant differences across treatments for a given soil depth, and the lowercase alphabets imply significant differences across the soil depths for a given treatment ($P < 0.05$).

Parameters	Soil depth (cm)	Treatments			
		Forest	ZT	RT	CT
Storage of SOC (Mg ha^{-1})	0–5	16.80 ± 1.02 fA	10.82 ± 0.34 fB	9.21 ± 0.43 fB	6.90 ± 0.35 fC
	0–10	29.68 ± 2.69 eA	17.82 ± 0.71 eB	16.15 ± 1.28 eBC	14.12 ± 0.79 eC
	0–15	38.05 ± 3.14 dA	24.62 ± 0.96 dB	22.97 ± 2.00 dBC	21.39 ± 0.18 dC
	0–20	44.95 ± 2.75 cA	31.07 ± 0.96 cB	29.88 ± 3.00 cBC	28.54 ± 0.40 cC
	0–25	51.37 ± 1.87 bA	36.96 ± 0.89 bB	36.46 ± 1.90 bB	35.33 ± 0.88 bB
	0–30	56.56 ± 1.90 aA	42.84 ± 0.27 aB	41.41 ± 1.84 aB	41.33 ± 1.19 aB
Storage of TN (Mg ha^{-1})	0–5	1.20 ± 0.09 eA	0.77 ± 0.02 fB	0.53 ± 0.04 fC	0.50 ± 0.02 fC
	0–10	2.08 ± 0.04 dA	1.31 ± 0.06 eB	1.06 ± 0.09 eC	1.11 ± 0.01 eC
	0–15	2.71 ± 0.18 cA	1.79 ± 0.08 dB	1.58 ± 0.15 dB	1.70 ± 0.09 dB
	0–20	3.24 ± 0.24 bA	2.35 ± 0.04 cB	2.14 ± 0.21 cB	2.25 ± 0.12 cB
	0–25	3.70 ± 0.29 aA	2.82 ± 0.02 bB	2.68 ± 0.15 bB	2.72 ± 0.18 bB
	0–30	4.10 ± 0.37 aA	3.25 ± 0.07 aB	3.21 ± 0.02 aB	3.18 ± 0.24 aB

parameters increased simultaneously. Additionally, storage of SOM along the soil profile was significantly ($p < 0.001$) related to the SR (Fig. 7(b) and 7(c)). With the increase in SR, the storage of SOC ($R^2 = 0.46$ and p-value <0.001) and TN ($R^2 = 0.36$ and p-value <0.001) along the soil profile increased significantly. This resulted in a concurrently growing trend in SR and SOM along the soil profile (Tables 1 and 2). It suggests that the SR might serve as a reliable index of SOM storage along the soil profile. Several other researchers reported a similar correlation among SR, SOM, and MWD (Zhao et al., 2015; Chao et al., 2019; Patra et al., 2019a).

3.4. Soil quality assessment by CPI

The CPI index was used to monitor the impact of soil disturbance and residue incorporation on soil quality improvement with respect to a reference site, and the outcomes are depicted in Fig. 8. The loss of C from a land use with higher CPI is of less consequences in comparison to the same amount of C loss from a land use having lower CPI (Blair et al., 1995). Hence the state of land degradation can be assessed from the CPI values of respective land uses (Bayer et al., 2009). As shown in Fig. 8, the CPI value increases significantly with an increase in soil depth for three land uses. Additionally, the CPI follows the same trend for each soil depth as for SOC storage: ZT > RT > CT. It indicates that the CPI value decreases with an increase in soil mechanical disturbance level. Similarly, for a humid subtropical region in Southern Brazil, the CPI followed linearly with SOC stock, and higher CPI values were observed for low grazing intensity area (0.79 ± 0.01) than higher grazing intensity area (0.75 ± 0.01) (da Silva et al., 2014). The ZT and RT have significantly higher CPI values than CT up to 15 cm soil depth; beyond that, there are no significant differences among them. The CPI of ZT and RT are respectively 57% and 34% higher than CT. The higher CPI value for CA than CT is attributed to higher SOC storage with deeper depth (da Silva et al., 2014). As the CPI value is sensitive toward aggradation or degradation of SOC (Bayer et al., 2009; de Oliveira Ferreira et al., 2013; Stavi et al., 2015); hence the lower value for CT suggests that the overall disruption of the SOC pool by land use conversion from virgin forest to CT is more than conversion from forest to CA. The CA land uses show better soil health than CT based on CPI values; hence CA is well land management status. Similarly, a higher CPI value was observed in no tillage (0.91–0.98) than CT (0.88–0.90) in the wheat - soyabean cropping system of south Brazil due to reduced soil disturbance and adoption of suitable crop rotation in NT (de Oliveira Ferreira et al., 2013). According to a study done in maize fields with varying biochar application rates in a continental monsoon climate, the field with the highest application rate (47.25 t ha^{-1}) contained 21.50 g kg^{-1} SOC, while the field with the lowest application rate (15.75 t ha^{-1}) displayed 15.30 g kg^{-1} SOC. This was supported by a similar trend in CPI (Yang et al., 2018).

4. Conclusions

This study assessed the effect of various land use practices (forest, ZT, RT, and CT) on SOC and TN depth distribution, storage, and stratification in the soil profile and, hence, identifying appropriate sustainable

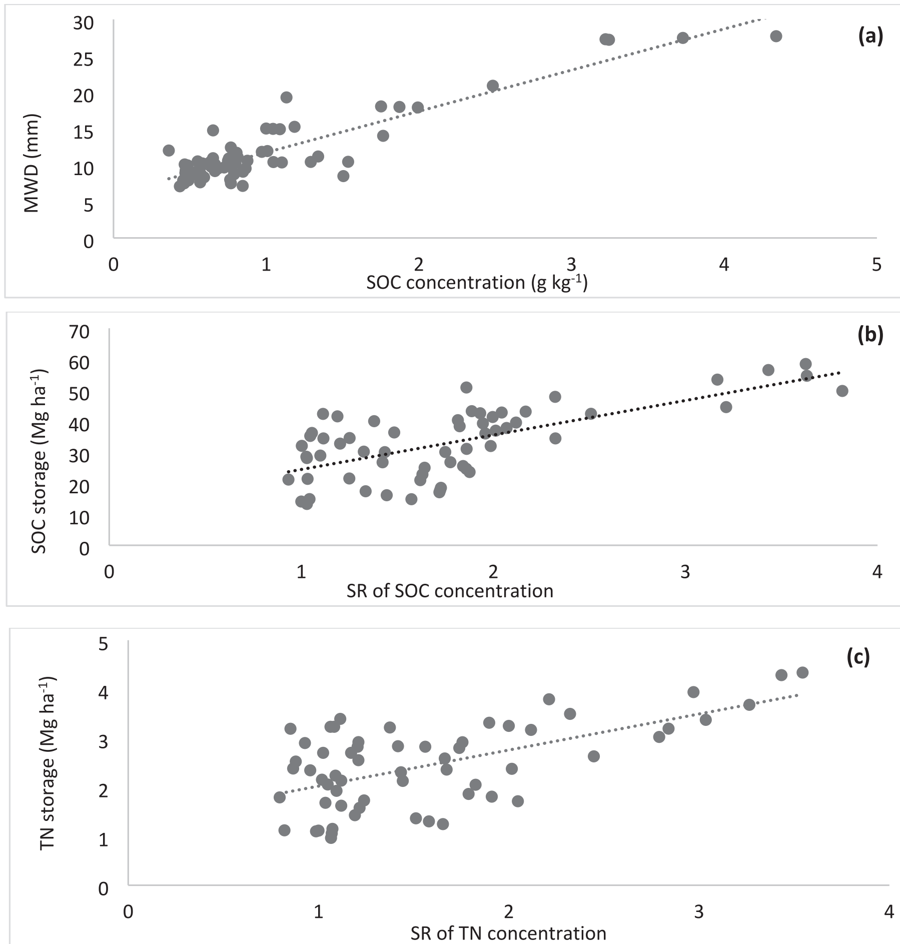

Fig. 7. Relationships between (a) soil organic carbon (SOC) concentration (g kg^{-1}) and MWD (mm), (b) stratification ratio (SR) of SOC concentration and storage of SOC (Mg ha^{-1}), (c) SR of TN concentration and storage of TN (Mg ha^{-1}) under different land use practices (Forest, ZT, RT, and CT). The SRs 0–5:5–10, 0–5:10–15, 0–5:15–20, 0–5:20–25, and 0–5:25–30 cm necessarily correlate to SOC and TN storage at 0–10, 0–15, 0–20, 0–25 and 0–30 cm, respectively.

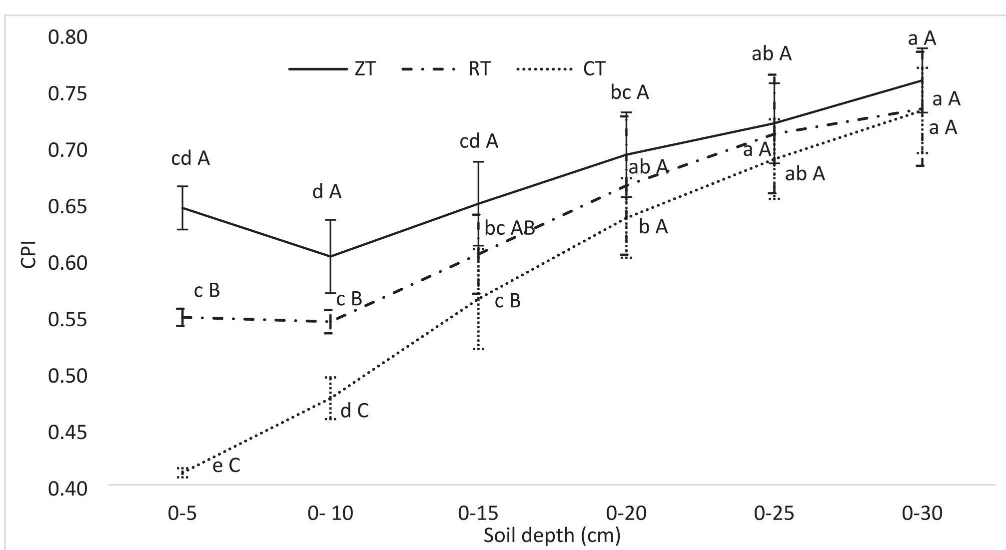

Fig. 8. Changes in soil CPI among different land uses (ZT, RT, and CT) with reference to Sal forest at six soil depths. The data present mean ± SD (m = 3). The different uppercase alphabets imply significant differences across treatments for a given soil depth, and the lowercase alphabets imply significant differences across the soil depths for a given treatment ($P < 0.05$).

tillage techniques for the North-West Himalayan region of India. The SR of MWD followed the trend Forest> ZT > RT > CT for all soil depth ratios. It suggests that conservation agriculture with minimal soil disturbance improves soil quality in terms of MWD compared to CT, as seen by SR. Compared to CT land uses, the SR of SOM was greater in the forest, and conservation agricultural land uses due to the continued build-up of higher SOM in the surface layer. The forest had the highest SOM among land uses, and CT had the lowest. In comparison to CT (41.33 ± 1.19 Mg ha^{-1}) and CA (42.84 ± 0.27 Mg ha^{-1}, ZT, and 41.41 ± 1.84 Mg ha^{-1}, RT), forest (56.56 ± 1.90 Mg ha^{-1}) had significantly higher SOC storage based on equivalent soil mass approach. Moreover, the SR of SOM was highly correlated with the SOM storage along the soil profile, making SR a reliable predictor of SOM storage. The higher CPI value for CA than CT contributed to higher SOC storage with deeper depth. Additionally, CA stratifies the distribution of SOM, promotes its surface storage, and subsequently sequesters more SOM into the soil. Our results suggest that CA may be a viable alternative for improving soil physicochemical parameters degraded due to CT. Considering these results, CA-based land management is advantageous for enhancing SOC and TN stocks in the soil profile, and they may be a suitable climate change adaptable agricultural strategy for the Himalayan region. Thus, the results of this study support our hypothesis that although the conversion of native forest land to CT degrades soil health, by following CA practices, soil health will be progressively restored in the North-West Himalayan region. Further, SR should be recommended as a suitable indicator for determining the extent of soil degradation for various regions with spatially heterogenous soil profiles.

Declaration of Competing Interest

The authors of this article declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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