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Soil carbon dynamics under organic farming: Impact of tillage and cropping diversity

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ABSTRACT

Ecological indicators are herculean contrivance for assessing management practices' impacts on environmental changes. Soil organic carbon (SOC) potentially regulates the agricultural sustainability. Unfortunately, the SOC has been widely degraded through unsustainable land uses and agricultural practices. Hence, the efficacy of conservation tilling and diversified cropping were assessed in terms of restoration of SOC and associated soil properties in fixed plots, which are related with farm productivity and other ecosystem services under organic production systems of the Indian Himalayas. Three tillage management were selected as treatments of the study: i) conventional tilling (CT), ii) reduced tilling (RT), and iii) Zero tilling (ZT) applied to four diversified cropping systems [CS_1- maize–black gram–toria, CS_2 maize–black gram–buckwheat, CS_3- maize–rajmash–toria and CS_4 maize–rajmash–buckwheat]. The ZT had the highest SOC content (19.58 g kg^{-1}) as well as the C pool (25.24 Mg ha^{-1}) at a soil depth of 0–10 cm. On the contrary, ZT had the lowest ρb (1.29 Mg m^3) and soil penetration resistance (1.32 MPa) at 0–5 cm and 5–10 cm soil depth. Concerning SOC partitioning, regardless of soil depth, it had been evident that more SOC were allocated in the active pool over the passive pool. Out of the diversified cropping systems, the CS_2 produced a considerably higher total carbon pool of 24.98, and 23.0 Mg ha^{-1} at 0–10 cm, and 10–20 cm soil depths, respectively, and active and passive C pools. Hence, abolition of tillage and cultivation of legume embedding cropping systems resulted as a sustainable management system under organic farming for SOC restoration and soil quality improvement in the Himalayan ecosystem. Thus, the study suggested that the cultivation of CS_2 under ZT may be promoted for efficient land resource management planning in the study region of the Indian Himalayas.

1. Introduction

Ecosystem services are often linked with soil health given the capacity of soil to balance the ecological functionality (Bünemann et al., 2018). Therefore, changes in land use management not only had multipronged effects on soil health but on ecosystem services as well (Józefowska et al., 2020). Conversion of arable land into urban settlements can alter the supporting services provided by an ecosystem, like carbon and nutrients cycling. Hence, Land Degradation (LD) is one of the crucial environmental concerns for humans (Singh et al., 2021). For this reason, the United Nations Convention to Combat Desertification (UNCCD), in response to the strongly fall in the health and productivity of the Earth, has set the target of Sustainable Development Goal 15 in terms of protection and restoration of the terrestrial ecosystem in order to combat desertification and arrest the biodiversity losses and land degradation (Cowie et al., 2018). The Land Degradation Neutrality (LDN) is the state of terrestrial (land) resources needed to support ecosystem services and food security maintained or improved with in

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time frame (UNCCD (United Nations Convention to Combat Desertification), 2016).

In this perspective, improper land use has negative effect on soil function, biodiversity and ecological health (Babu et al., 2020; de Groot et al., 2012). Traditional farming practices like repeated tilling, monocropping, and residue exclusion are detrimental to the agricultural soils and contribute to ~24 % of global land degradation (Bai et al., 2008). Continued repeated tilling coupled with residue removal cultivation practices aggravates the soil organic carbon (SOC) oxidation and causes ~20–67 % SOC losses (Yang et al., 2019). Hence, it is pertinent to underline that the soil is a crucial element of natural wealth that executes various conservation functions ensuring the supply of diverse ecological functions (Smith et al., 2021) such as carbon sequestration, pollutants immobilization, rainwater control, and habitat provision (Adhikari and Hartemink, 2016), which directly benefit to mankind. These ecosystem services are the diverse tangible and nontangible benefits humans acquire form healthy ecosystem of the environment (Costanza et al., 2017). Thus, the soil can potentially provide ecosystem services that are different in both typology and quantity (Bünemann et al., 2018).

The implementation of farming systems that conserves soil and water through minimal soil disturbances and residue retention cover is one of the best management practices and is being advocated globally to increase C sequestration (Lal et al., 2018; Steward et al., 2018), improving the fertility status and microscopic population in degraded lands (Yadav et al., 2020a). The management strategies can have a greater impact on the active pool of SOC than those of passive SOC pools (Sahoo et al., 2019; Riggers et al., 2021). Therefore, SOC partitioning into different fractions is essential to visualize the effect of management practices on C accrual in a more realistic manner. In general, soil health and economic benefits are linked with active C pools (Zhang et al., 2021; Tu et al., 2021) and long-run carbon storage, mainly contributed by PC pools (Sahoo et al., 2019). The organic C improves the soil's structural stability by modulating bulk density (ρb), porosity, water storage, and enzymatic activities (Sekaran et al., 2021). Effective pedo-edaphic conservation management has significantly altered soil biology under different management scenarios, and ecosystems under inorganic management conditions (Choudhary et al., 2018; Chen et al., 2019). In hilly region, especially under organic management conditions, the impact of tilling on soil C restoration is not widely studied. Therefore, it is imperative to appraise the influence of diverse conservation tillage practices and intensive cropping on C restoration, especially in terraced lands of the Indian Himalayas, to formulate the appropriate management policy for the long-term sustainability of hill farming.

Agriculture in Indian Himalayan Region (IHR) is organic by default, and crop productivity of most of the crops remains low as compared to the mainland (Das et al., 2019). Therefore, hilly areas provide several opportunities to increase food production and restore the risk-prone soils of the region through the adoption of conservation agriculture. Farmers of the region generally grow rainy season crops with minimal organic inputs and left field fallow during the winter mainly due to moisture scarcity. Diversified cropping has the potential to generate high biomass, enhance system productivity per unit area in a calendar year, and contribute to C-sequestration (Nath et al., 2019; Babu et al., 2020). Hence, there is an emerging curiosity among the researchers to apply the principle of conservation effective tillage strategies under organic management to conserve natural resources. The comparative effect of diversified/intensified cropping and conservation effective tilling on soil health restoration and carbon stratification is not adequately addressed under organic management, especially for Himalayan ecosystems.

The SOC dynamics is crucial parts of soil quality and are becoming imperative in organic cultivation (Avasthe et al., 2020). Low external input use being promoted under organic farming implies greater reliance on the self-regulating processes of the soil system (Avasthe et al., 2020). Thus, the conservation tillage and diversified cropping systems impact are to be objectively studied in respect of soil C dynamics, especially in fields of hilly ecosystems. A critical understanding of the effect of co-implementation of conservation tillage and diversified cropping on the partitioning of C into active and stale pools under organic farming systems is the compelling need for sustainable policy formulations green farming in the Himalayan region. The results of current study will guide the policy planners to formulate sustainable land use planning to arrest land degradation and improve current food production without compromising ecosystem sustainability. It has been studied and demonstrated that the results of efficient land management increase cultivated land, C storage in the soil, as well as determining greater mitigation effects in areas characterized by, for example, higher rainfall (Branca et al., 2013). In general, guaranteeing sustainability means protecting what can be considered the backbone of enlightened management of the territory that is based on the need to integrate ecological, economic, and socio-cultural interests, thus allowing to face global challenges and therefore both guarantee and preserve natural values (e.g. food, fiber) and biological resources. Certainly, unsustainable landscape management could, on the other hand, potentially disrupt and prevent future land use options (Baskent, 2020). Hence, the present research aims: (1) to appraise the ability of conservation effective tilling and diversified/intensified cropping systems on SOC restoration across the plow layer and up to 30 cm soil depth in terrace lands; and (2) to assess the impact of different tillage and diversified cropping on selected properties. Thus, the study delivers realistic elucidations to arrest the soil degradation as anticipated in UN-DER, Bonn Challenge and UN-SDGs initiatives, besides addressing some SDGs.

2. Material and methods

2.1. Study site

A three-year (2015–2018) field study was executed at the Research farm of the Sikkim Centre of the ICAR Research Complex, India. The Research field lies between 27°32′ North latitude and 88°60′ East longitude with an altitude of 1350 amsl (Fig. 1).

The basal properties of the experimental soils were reported as organic carbon (OC): 17.8 g kg^{-1} at 0–10 cm, 15.9 g kg^{-1} at 10–20 cm, and 14.6 g kg^{-1} at 20–30 cm; and bulk density (ρb): 1.33, 1.36, and 1.40 Mg m^{-3} at 0–10 cm, 10–20 cm and at 20–30 cm soil depths, respectively. Available N, P and K were 312, 295, and 280 15.6, 14.3, and 13.5 and 320.2, 310.6, and 295.8 kg ha^{-1} at 0–10 cm, 10–20 cm and 20–30 cm soil depth, correspondingly.

2.2. Experimental plan and treatment details

The study was led in split-plot design (SPD) with three replications. The main plots comprised three tilling systems, *i.e.* conventional tilling (CT), reduced tilling (RT), and zero tilling (ZT), whereas, subplots consisted of four diversified cropping systems, *i.e.*, [CS$_1$- maize (Zea mays)–black gram (Vigna mungo var. Viridis)–toria (Brassica campestris), CS$_2$ maize–black gram–buckwheat (Fagopyrum sp) CS$_3$- maize–rajmash (Phaseolus vulgaris)–toria and CS$_4$ maize–rajmash–buckwheat]. Under RT and ZT, ~30 % of the residues of maize crops and the entire residues of succeeding crops remained on the soil surface. While the crop residues were completely removed from the field under conventional tilling (CT). Four tilling under CT and two tilling under RT were done at ~8–12 cm depth with a manually operated petrol-fuelled power tiller. Whereas in ZT, the soil was kept undisturbed, only a narrow slit was made by using a ZT row marker for placing seeds. An iron sickle was used to remove the weeds from the ZT plots before the crop sowing in each season. Details of the varieties, the input used, and management practices adopted under different crops were given in Suppl Table 1.

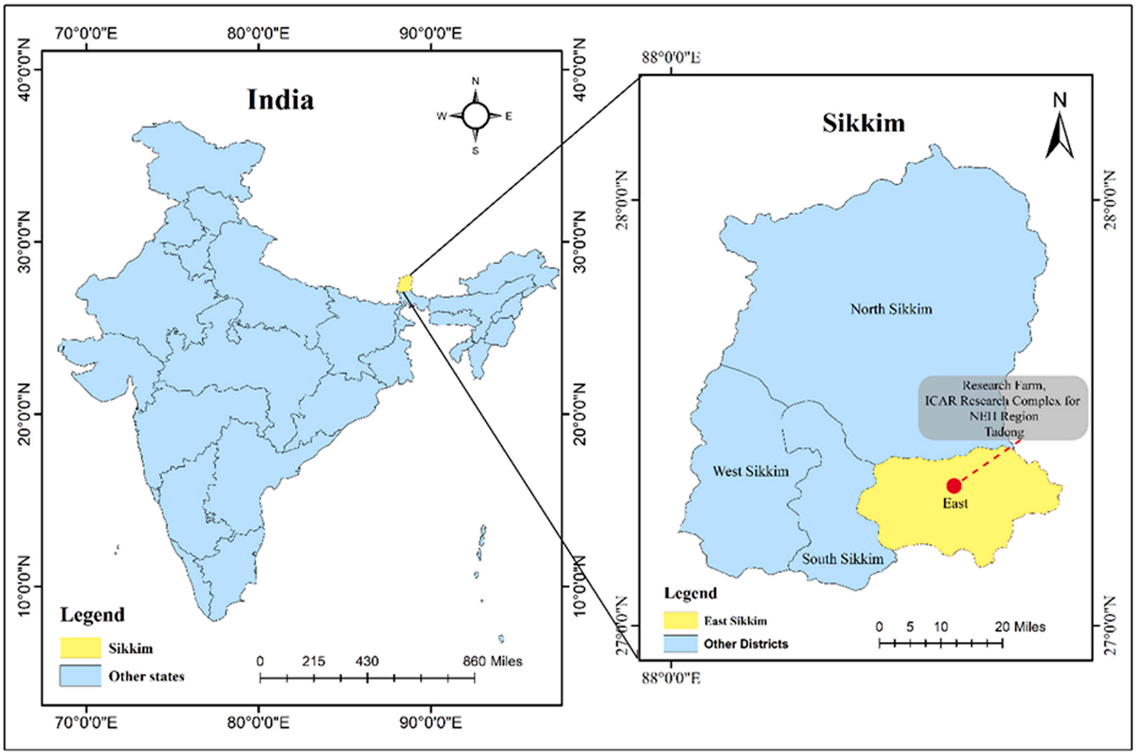

Fig. 1. Map showing study site in the Indian Himalayas.

Table 1
Impact of diverse tilling and diversified cropping on soil ρb, SPR, and SOC after three cropping cycles.

	ρb (Mg m^3)			Soil penetration resistance (MPa)			SOC (g kg^{-1})		
Tilling practices	0–10 cm	10–20 cm	20–30 cm	0–5 cm	6–10 cm	11–15 cm	0–10 cm	10–20 cm	20–30 cm
CT	1.32	1.35	1.38	1.42	1.48	1.57	17.92	16.04	14.98
RT	1.31	1.34	1.38	1.39	1.46	1.56	18.48	16.51	15.10
ZT	1.29	1.34	1.39	1.32	1.42	1.55	19.58	17.14	15.13
SEm±	0.003	0.005	0.01	0.006	0.005	0.01	0.10	0.06	0.04
LSD (p = 0.05)	0.007	0.011	NS	0.014	0.012	NS	0.24	0.16	NS
Diversified cropping									
CS$_1$	1.32	1.35	1.39	1.39	1.46	1.57	18.28	16.38	14.93
CS$_2$	1.30	1.33	1.38	1.37	1.44	1.55	19.26	17.27	15.21
CS$_3$	1.31	1.35	1.38	1.38	1.46	1.58	18.44	16.06	15.06
CS$_4$	1.31	1.33	1.38	1.38	1.45	1.55	18.67	16.56	15.09
SEm±	0.005	0.007	0.01	0.007	0.010	0.02	0.16	0.22	0.12
LSD (p = 0.05)	0.010	0.014	NS	NS	NS	NS	0.32	0.45	0.25

CT: Conventional tilling; RT: Reduced tilling; ZT: Zero tilling; CS$_1$: Maize-black gram-toria; CS$_2$: Maize-black gram-buckwheat; CS$_3$: Maize-rajmash-toria; CS$_4$: Maize-rajmash-buckwheat; SEm±: Standard error of mean; LSD: Least significant difference; NS: Non-significant; ρb: bulk density; SOC: soil organic carbon; SPR: soil penetration resistance.

2.3. Soil sampling and preparation

Soil sampling was carried out in three different sampling locations and in each plot after three cropping cycles (within one week after harvesting of last winter crop). Further, soils at each sampling point were drawn at three depths viz., 0–10 cm, 10–20 cm, and 20–30 cm by using a core sampler of 10 cm scaled with a 5.6 cm inner diameter. Depth-wise composite soil samples were also obtained for each plot. Zip-top plastic bags were used to store the composite samples for laboratory purposes. The fresh samples of soil were weighed in the laboratory before and after aeration. The composed soil samples were gently hammered and sieved with 2 mm sieves. The soil was oven dried 105 °C for 24 hrs for moisture estimation (Gravimetric method). The bulk soil samples were air dried, crushed, ground, and sieved through 2 mm sieves to remove extraneous roots. The strained soil was stored in sealed plastic bags for pending chemical scrutiny. A part of the fresh soil (0–10 cm depth) sample was kept and kept at 4 °C temperature for estimation of SMBC and DHA activities.

2.4. Bulk density and penetration resistance estimation

The core method as proposed by Blake and Hartge (1986) was applied to determine ρb from 0 to 10, 10–20, and 20–30 cm depths after oven drying at 105 ± 1 °C. While cone penetrometer was used to measure the soil penetration resistance (SPR) after three years of experimentation. The SPR was estimated randomly from soil depths ranging from 0 to 5, 6–10, and 11–15 cm from each plot.

2.5. Analysis of soil pools and estimation of carbon stratification ratio

The wet oxidation method (Walkley and Black, 1934) as outlined by Prasad et al (2006) was employed for the determination of soil organic carbon (SOC). The four fractions of C *viz.*, very labile carbon (VLC), Labile carbon (LC), less labile carbon (LLC), and non-labile carbon (NLC) with varying grades of oxidation were determined (Chan et al., 2001). All the fractions were converted into pools. The active carbon pool (AC) was the sum of VLC and LC fractions, while the LLC and NLC fractions collectively represent passive soil C pools (PC) (Chan et al. 2001). Various soil C pools (Mg/ha) of gradual soil depths (0–10 cm, 10–20 cm, and 20–30 cm) were computed based on ρb (Yadav et al., 2021). The VLC stratification ratio was estimated by dividing the concentration of C at 0–10 cm layer by the 10–20 cm and 20–30 cm layers as per the procedure suggested by Franzluebbers (2002).

2.6. *Analysis of soil biochemical properties*

Available-P and Available-K were estimated using Bray's P_1 (0.03 N NH4F in 0.025 N HCl) pH 4.65, and 1 N NH_4OAc extractable K, pH 7.0, while Available-N was evaluated using the Alkaline $KMnO_4$ method (Prasad et al. 2006). The method outlined by Vance et al. (1987) was used to obtain the microbial biomass carbon (MBC) in soil. Dehydrogenase activity (DHA) was assessed by reducing 2, 3, and 5 triphenyl tetrazolium chloride (Casida et al., 1964; Tabatabai 1982). The expression for the DHA and SMBC are, respectively, mg TPF g^{-1} dry soil hr^{-1} and g MBC g^{-1} soil.

2.7. *Statistical analysis*

The results on diverse parameters of tillage and cropping diversity were statistically analyzed according to the technique described by Gomez and Gomez (1984). Statistical Package for Social Sciences (SPSS) software version 27.0 was employed to test the level of significance ($p < 0.05$) in the analysis of variance (ANOVA).

3. Results

3.1. *Soil ρ_b, penetration resistance (SPR), and SOC content*

The tillage system had a considerable effect on ρb, SPR, and SOC concentration in the topsoil profile after three years (Table 1).

However, tilling systems did not bring any noteworthy impact on ρb, SPR, and SOC concentration in the lower depth of soil (20–30 cm depth for ρb and SOC and 11–15 cm for SPR). The ρb in the topmost soil (0–10 cm soil depth) had recorded minimum in zero tilling (ZT; 1.29 Mg m^3) compared to reduced tilling (RT; 1.31 Mg m^3) and highest in conventional tilling (CT; 1.32 Mg m^3). For the 10–20 cm m soil layer, RT and ZT recorded the almost same ρb (~1.34 Mg m^3), which was significantly lower than CT (1.35 Mg m^3). The cropping diversity after three years did not show any significant impact on soil ρb in any of the soil layers (0–10, 10–20, and 20–30 cm depths). Concerning SPR, irrespective of tillage and diversified system, SPR was lower at the upper layer compared to lower depths (Table 1). Tillage practices had failed to affect SPR at lower soil depths (11–15 cm). Among the tilling practices, three consecutive years of adoption of ZT (1.32 MPa and 1.42 MPa) and RT (1.39 MPa and 1.46 MPa) recorded significantly lower SPR than CT in 0–5 cm and 6–10 cm soil depths. Soil depth at 0–5 cm significantly altered the SPR under the diversified system. Similarly, after three years of regular cropping, SPR did not vary substantially across the soil depths under study. The SOC concentration was the highest in ZT systems (19.58 & 17.14 g kg^{-1} at 0–10 cm and 10–20 cm soil depth, correspondingly), followed by RT and CT systems. When comparing the SOC of different diversified cropping systems, the significantly maximum SOC was found under the CS_2 system at all soil depths (0–10 cm, 10–20 cm, 20–30 cm) compared to the rest of the diversified cropping followed by CS_4 (Table 1). The SOC at 0–10 cm and 10–20 cm soil layers influenced significantly by tilling and diversified cropping interaction (Fig. 2).

The ZT with CS_2 had a significantly more SOC concentration at upper 0–10 cm depth (19.6 g kg^{-1} soil) than all amalgamations however, this remained statistically at par with the same tilling in the CS_4 (19.4 g kg^{-1} soil) system. Similarly, significantly higher SOC content in soil was also recorded under ZT in soils under the CS_2 (18.0 g kg^{-1} soil) at 10–20 cm soil depth. In comparison, the lowest SOC content at 0–10 cm depth was observed in soils under CT and CS_4 (17.67 g kg^{-1} soil) system and CT under the CS_3 in the 10–20 cm soil depth (15.43 g kg^{-1} soil).

3.2. *C fractions pool size*

After three years, different tilling options bring a significant change in very labile C (VLC) pool size only at the upper soil surface *i.e.* 0–10 cm depth (Table 2). However, tilling practices did not alter the VLC pool's dimensions at soil depths of 10 to 20 cm and 20 to 30 cm (Table 2). Among tillages, soils under ZT had a significantly higher VLC pool size (7.74 Mg ha^{-1}) followed by RT at 0–10 cm soil depth than CT (7.13 Mg ha^{-1}). In general, across the soil depths, the minimum VLC pool size was noticed in CT. Three years of diversified cropping significantly altered the VLC pool size at 0–10 cm depth; however, the diversified system failed to modify the VLC pool size at lower soil depths studied (10–20

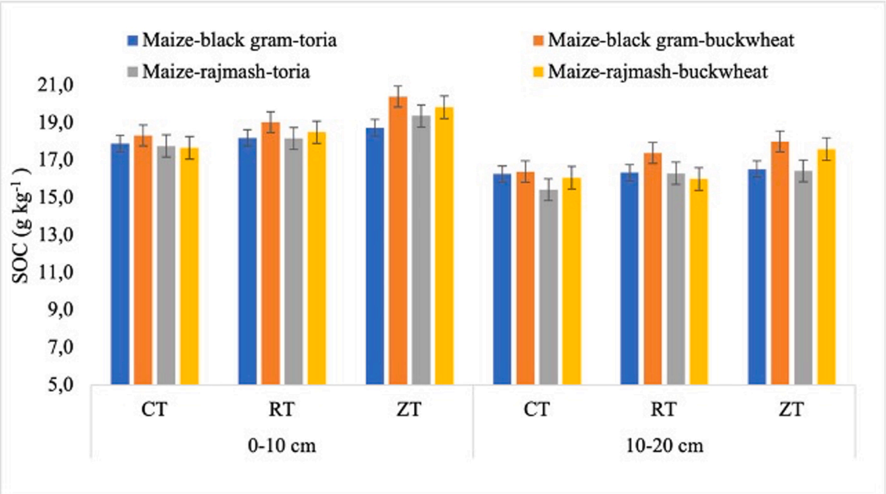

Fig. 2. Interactive effect of tilling and diversified cropping on soil organic carbon (SOC) at 0–10 cm and 10–20 cm soil depths. CT: Conventional tilling; RT: Reduced tilling; ZT: Zero tilling. Error bar indicates the least significant difference (LSD) values at $p = 0.05$.

Table 2
Impact of diverse tilling and diversified cropping on various soil carbon pool sizes after three cropping cycles.

Tilling practices	VLC pool (Mg/ha)			LC pool (Mg/ha)			LLC pool (Mg/ha)			NLC pool (Mg/ha)		
	0–10 cm	10–20 cm	20–30 cm	0–10 cm	10–20 cm	20–30 cm	0–10 cm	10–20 cm	20–30 cm	0–10 cm	10–20 cm	20–30 cm
CT	7.13	6.24	5.53	5.50	4.89	4.71	4.46	4.58	4.79	6.61	5.96	5.61
RT	7.31	6.29	5.56	5.54	4.92	4.71	4.61	4.73	4.85	6.70	6.14	5.64
ZT	7.74	6.30	5.61	5.86	5.15	4.74	4.73	4.90	4.96	6.90	6.57	5.80
SEm±	0.09	0.05	0.03	0.09	0.05	0.06	0.04	0.06	0.02	0.05	0.27	0.13
LSD ($p = 0.05$)	0.22	NS	NS	0.22	0.12	NS	0.10	0.14	NS	0.12	NS	NS
Diversified cropping												
CS_1	7.27	6.29	5.58	5.63	4.90	4.67	4.51	4.74	4.83	6.67	6.25	5.74
CS_2	7.56	6.31	5.52	5.62	5.38	4.80	4.71	4.87	4.96	7.09	6.47	5.68
CS_3	7.21	6.23	5.56	5.79	4.84	4.80	4.58	4.64	4.87	6.44	5.97	5.59
CS_4	7.55	6.29	5.61	5.49	4.84	4.61	4.61	4.71	4.82	6.76	6.20	5.72
SEm±	0.13	0.10	0.09	0.13	0.16	0.09	0.12	0.11	0.09	0.10	0.12	0.12
LSD ($p = 0.05$)	0.27	NS	NS	NS	NS	NS	NS	NS	NS	0.20	26	NS

CT: Conventional tilling; RT: Reduced tilling; ZT: Zero tilling; CS_1: Maize-black gram-toria; CS_2: Maize-black gram-buckwheat; CS_3: Maize-rajmash-toria; CS_4: Maize-rajmash-buckwheat; SEm±: Standard error of mean; LSD: Least significant difference; NS: Non-significant; VLC: Very labile carbon; LC: Labile carbon; LLC: Less labile carbon; NLC: Non-labile carbon.

and 20–30 cm). Among the diversified systems, the CS_2 soils had larger VLC pool size (7.56 Mg ha^{-1}) which was closely trailed by the CS_4 system (7.55 Mg ha^{-1}) at a soil depth of 0–10 cm. The labile carbon (LC) pool size significantly altered the LC pool sizes only at 0–10 and 10–20 cm soil depth by the tillage practices. ZT was noticed to have higher LC pool sizes 5.86 Mg ha^{-1} and 5.15 Mg ha^{-1} followed by RT, correspondingly. The labile C pool did not vary considerably among tillage practices at 20–30 cm soil depth (Table 2).

Similarly, three-year continuous diversified cropping had failed to bring any significant changes in the size of LC pools across the soil depth studied (0–10 cm, 10–20 cm, and 20–30 cm). Despite the statistically non-significant difference, among the diversified system, CS_2 recorded a higher value of LC pool at lower soil (10–20 cm and 20–30 cm depths).

Tillage options significantly ($P \leq 0.05$) mediated the size of less labile carbon (LLC) pools within a soil profile of 0–10 cm and 10–20 cm depths. However, diverse tillage had failed to change the size of LLC at 20–30 cm soil layer significantly. Maximum LLC pool sizes were recorded under ZT (4.73 Mg ha^{-1} and 4.90 Mg ha^{-1}) followed by RT (4.71 Mg ha^{-1} and 4.61 Mg ha^{-1}) at a soil depth of 0–10 cm and 10–20 cm, respectively. The lowest LLC pool size was found under CT practice. Across the soil profile under study, LLC pool size did not vary significantly among the intensified cropping. Like the LLC pool, at lower soil depths (10–20 cm and 20–30 cm depths) non-labile carbon (NLC) pools were also not significantly affected by tillage practices. But at a soil depth of 0–10 cm, tillage practices bring significant changes in NLC pool size after three years. The soil under ZT had a maximum size of NLC pool (6.90 Mg ha^{-1}) trailed by RT. Among the diversified maize-based systems, the CS_2 most impacted NLC pools, followed by CS_4 and CS_1 at soil depths of 0–10 and 10–20 cm, respectively. The NLC pool size at 20–30 cm depths was larger under CS1 than that of 0–10 cm and 10–20 cm soil depths.

3.3. C pools and C stratification ratio

After three years of continuous experimentation, tilling practices and diversified cropping has a substantial influence on the active C pool (Mg/ha) at different soil depth (0–10 cm and 10–20 cm). But, at a 20–30 cm depth profile, both tilling and diversified systems failed to enhance the active C pool (Table 3).

Irrespective of the tillage and diversified systems, the soil under 0–10 cm had the maximum ACP. ZT had the maximum ACP at 0–10 cm (13.61 Mg ha^{-1}) and 10–20 cm soil depth (11.46 Mg ha^{-1}). Whereas the lowest ACP were registered under CT. Among the diversified system, cultivation of CS_2 recorded a significantly higher ACP at both the soil depth (0–10 cm and 10–20 cm). However, soils under the CS_1 system had the lowest ACP (12.90 Mg ha^{-1}) at 0–10 cm depth, whereas soils under the CS_3 registered the lowest ACP (11.07 Mg ha^{-1}) at soil depths of 10–20 cm. Passive C pool (PCP) represent the total of less labile C and non-labile C fractions and represents long-term soil C storage, was also altered by diverse tillage and cropping but the influence was limited to soil depths of 0–10 cm and 10–20 cm. ZT had registered the highest PCP (11.63 Mg ha^{-1} and 11.47 Mg ha^{-1} at 0–10 cm and 10–20 cm depth, correspondingly) followed by RT at all the soil depths. Among the diversified systems, the cultivation of maize-black gram-buckwheat allocates more C in the PCP at all three soil depths, followed by the maize-rajmash-buckwheat system. Total SOC pools represent both ACP and

Table 3
Impact of diverse tilling and diversified cropping on active and passive C pools after three cropping cycles.

Tilling practices	Active C pool (Mg/ha)			Passive C pool (Mg/ha)			Total C pool (Mg/ha)		
	0–10 cm	10–20 cm	20–30 cm	0–10 cm	10–20 cm	20–30 cm	0–10 cm	10–20 cm	20–30 cm
CT	12.63	11.13	10.24	11.07	10.55	10.40	23.70	21.67	20.64
RT	12.85	11.22	10.27	11.31	10.87	10.49	24.16	22.08	20.76
ZT	13.61	11.46	10.36	11.63	11.47	10.76	25.24	22.93	21.11
SEm±	0.09	0.04	0.08	0.08	0.12	0.10	0.14	0.14	0.31
LSD ($p = 0.05$)	0.21	0.09	NS	0.19	0.30	NS	0.34	0.33	NS
Diversified cropping									
CS_1	12.90	11.18	10.25	11.18	10.99	10.57	24.08	22.17	20.82
CS_2	13.18	11.69	10.32	11.80	11.34	10.63	24.98	23.03	20.96
CS_3	13.00	11.07	10.37	11.02	10.61	10.45	24.02	21.68	20.82
CS_4	13.04	11.13	10.22	11.36	10.91	10.53	24.40	22.04	20.75
SEm±	0.0.8	0.16	0.15	0.18	0.18	0.18	0.26	0.32	0.30
LSD ($p = 0.05$)	0.17	0.33	NS	0.38	0.37	NS	0.53	0.65	NS

CT: Conventional tilling; RT: Reduced tilling; ZT: Zero tilling; CS_1: Maize-black gram-toria; CS_2: Maize-black gram-buckwheat; CS_3: Maize-rajmash-toria; CS_4: Maize-rajmash-buckwheat; SEm±: Standard error of mean; LSD: Least significant difference; NS: Non-significant; C: Carbon.

PCP, which were also altered after three years of diverse tilling practices up to 0–10 cm and 10–20 cm soil depth. The highest and lowest total C pools value was recorded under ZT and CT, respectively at both the soil depths (0–10 and 10–20 cm depths). After continuous adoption of ZT 6.47 and 5.81 % improvement in total C pools was noticed in 0–10 cm and 10–20 cm depth over CT, respectively. Concerning diversified cropping, the soil in the CS_2 system had significantly higher total C pools (24.98 Mg ha^{-1} at 0–10 cm depth) and (23.03 Mg ha^{-1} at soil depths of 10–20 cm). Whereas CS_3 registered the lowest value of the total C pool (24.02 Mg ha^{-1} at 0–10 cm depth) and CS_4 resulted in the lowest total C pool (22.04 Mg ha^{-1}) at 10–20 cm soil depth. Tilling practices and diversified systems exerted a tenacious impact on the C stratification ratio across the soil depth (Fig. 3).

Irrespective of tillage and cropping practices C stratification ratio was higher at 10–20 cm over 20–30 cm soil depth. Among different tillage practices, ZT had recorded higher C-stratification ratio of 1.27 (10–20 m) and 1.17 (20–30 cm) followed by RT. Cultivation of CS_2 had the maximum C stratification ratio of 1.23 and 1.18 at 10–20 cm and 20–30 cm soil depth, respectively. While the lowest C stratification ratio was under the CS_1 system (1.19) at 10–20 cm and CS_3 (1.15) at 20–30 cm soil profile.

3.4. Soil biological properties

Tillage practices bring considerable variations in microbial activities (soil microbial biomass carbon; SMBC and dehydrogenase activities; DHA) in the soil (Suppl. Table 2). Adoption of ZT recorded the significantly higher SMBC (369.7 μg MBC g^{-1} soil) and DHA value (17.4 μg $TPFg^{-1}$ soil h^{-1}) over RT and ZT in upper soil depth (0–10 cm). Three-year of diversified cropping has shown significant variations in soil microbial properties like SMBC and DHA. Maize-black gram-buckwheat system being statistically at par with the maize-rajmash-buckwheat registered considerably higher values of SMBC (354.8 and 353.0 μg MBC g^{-1} of soil) and DHA (16.8 and 16.6 μg TPF g^{-1} soil h^{-1}) over maize-black gram-toria and maize-rajmash-toria system. The interactive impact of tillage and diversified systems was found noteworthy on SMBC and DHA. The maize-rajmash-buckwheat system under ZT had recorded considerably higher SMBC (382 μ g dry $soil^{-1}$) and DHA (18.7 μg TPF g^{-1} soil h^{-1}) than those of others but remained at par with the same tillage in the CS_2 system (372 μ g dry $soil^{-1}$ and 18.1 μg TPF g^{-1} soil h^{-1}) (Fig. 4 and Fig. 5).

4. Discussion

The ability of the soil to support plants, animals, and humans allow it to be defined as a vital living ecosystem capable of playing a crucial role in agriculture (Marinelli et al., 2021). Soil health is the ability of soils to provide ecosystem services (Doran and Zeiss, 2000) by supporting biological productivity, and promoting plant, animal, and human health (Vanlauwe et al., 2010). Management practices aimed at increasing the quality of the soil have direct significances on ecosystem functioning, such as the regulation of water flows, the conservation of soil biodiversity, etc., fundamental both at the local scale and also at global. This means that it is of fundamental importance to identify effective management strategies that can preserve soil quality and counteract its degradation to ensure constant supply of soil ecosystem services (Fine et al., 2017; Nunes et al., 2020). A return to traditional agricultural practices such as crop rotation could lead to this goal, mainly by arresting the land degradation towards the sustainability goal “Land Degradation Neutrality”. The SOC can be considered a key indicator in sustainable land resources management (Nandwa, 2001), as it represents both a foundation and a store of nutrients, supporting soil fertility (Bationo et al., 2007). Consequently, the SOC depletion due to faulty agricultural practices, such as example, exhaustive processing, insufficient nutrient inputs, etc. can therefore lead to very serious consequences in terms of reduction of food production, and therefore, with consequent possible risks for food security (Blum, 2005).

Soil ρb and penetration resistance (SPR) are the imperative soil physical properties that modulate the soil nutrients supplying capacity and can potentially regulate the overall plant growth (Singh et al., 2021). Nonetheless tillage and diversified systems, soil ρ_b increases with soil depth proceeded (Singh et al., 2021). The tendency of ρ_b to upsurge with soil profile depth is ascribed to the weight of upper soil mass. SOC content had a negative correlation with soil ρb at soil depth increases SOC content reduced and ρb increased (Ruehlmann, 2020). Conservation effective tilling increases total soil porosity, macro, and microflora diversity, and SOC storage hence, resulting in lower ρb of soil (Ramadhan 2021). Parihar et al. (2016) also noted a 4–7 % reduction in soil

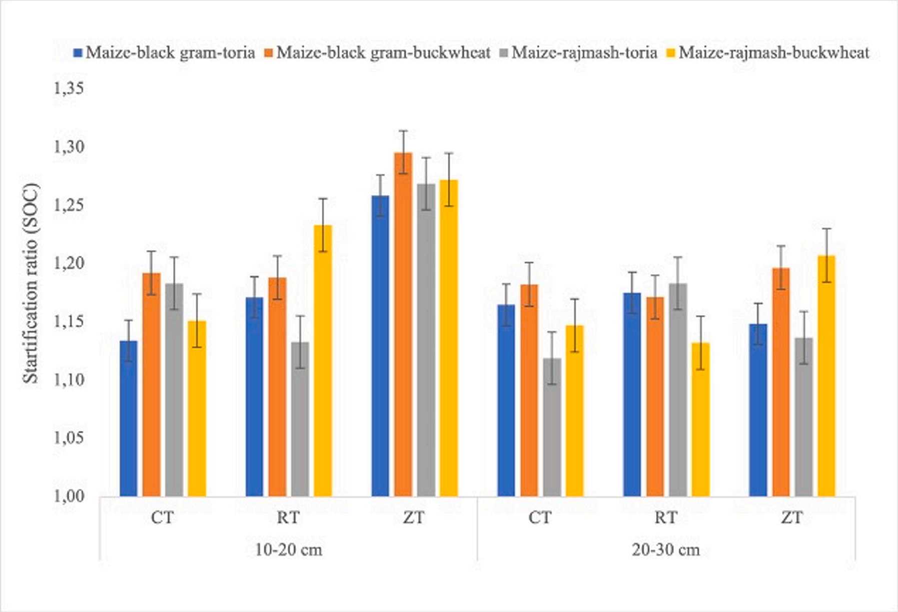

Fig. 3. Interactive effect of tillage and diversified cropping on C stratification ratio at various soil depths. CT: Conventional tilling; RT: Reduced tilling; ZT: Zero tilling. Error bar indicates the least significant difference (LSD) values at $p = 0.05$.

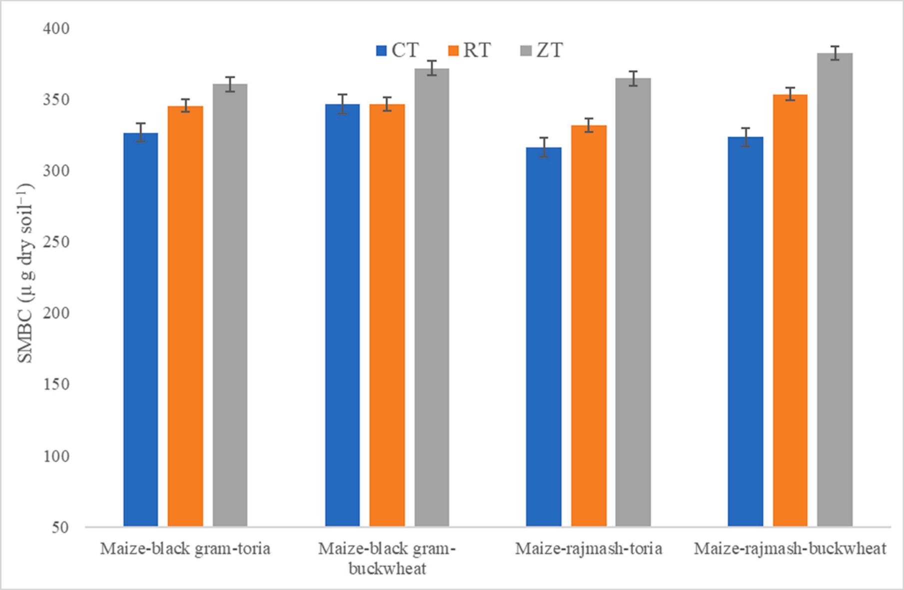

Fig. 4. Interactive effect of tillage and diversified cropping on soil microbial biomass carbon (SMBC) at 0–10 cm soil depth. CT: Conventional tilling; RT: Reduced tilling; ZT: Zero tilling. Error bar indicates the least significant difference (LSD) values at $p = 0.05$.

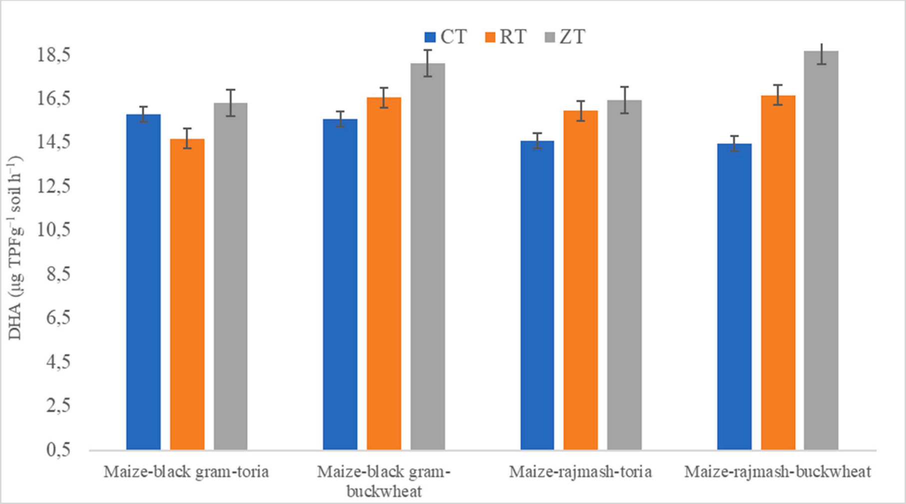

Fig. 5. Interactive effect of tillage and diversified cropping on dehydrogenase activities (DHA) at 0–10 cm soil depth. CT: Conventional tilling; RT: Reduced tilling; ZT: Zero tilling. Error bar indicates the least significant difference (LSD) values at $p = 0.05$.

ρb up to a depth of 30 cm in India as a result of long-term ZT usage over CT. Conservation tilling especially ZT had minimum soil perturbation, and more residue addition which favors the earthworm population which facilitates the biopores formation and results in lower ρb (Das et al., 2018). A noteworthy fall in soil ρb under RT/ZT plots was also noted by Singh et al. (2021) and Das et al. (2020).

The SPR plays an imperative role in overall performance of crops by influencing the root-soil interaction (Stosic et al., 2020). SPR is positively connected with ρb and negatively related to soil moisture and SOC status (Bogunovic et al., 2021; Yadav et al., 2021). In the current study, ZT had the lowest SPR as compared to RT and CT. Lower SPR in conservation effective tilling is attributed due to higher SOC and, lower ρb, especially at the plow layer. On the contrary, repeated tilling increase soil compaction, reduce SOC and increase SPR. Lower SPR under the ZT field was also reported by Franzluebbers (2002). Minimum soil perturbation reduces soil traffic under ZT/RT, hence reducing SPR. Diversified cropping accumulated various types of organic residue and secreted root exudates leading to increase soil porosity and reduced ρb and SPR. In the present study cultivation of maize-black gram-buckwheat (CS_2) had the lowermost SPR followed by maize-rajmash-buckwheat. Buckwheat had more root biomass and most of the fibrous roots of buckwheat were mainly confined at up to 15 cm soil depth. Furthermore, being a legume, black gram accumulated more OC in the soil as compared to another counterpart of the early post-rainy season in other diversified systems. The addition of more biomass substantially reduces soil ρb and ultimately SPR. The soil covered with live crops added plenty of different kinds of biomass, increasing soil porosity, and hence reducing soil compaction and SPR (Sartori et al., 2021).

Different tillage practices change the SOC content considerably at soil depths of 0–10 cm and 10–20 cm. Despite the organic manure addition in the present investigation, we did not observe any significant impact of tillage practices at lower soil depths after the end of three cropping cycles. These results indicated that under organic management conditions C accumulated at the upper soil surface. Higher organic matter accumulation on surface soil under organic tillage was also stated by Vian et al. (2009) and Seitz et al. (2019). The SOC storage is mainly confined up to 15 cm soil depth under inorganic systems described by Nandan et al. (2019) and Srinivasarao et al. (2019). Nevertheless, the current experiment was carried out in a high rainfall zone, mild temperate organically managed condition, which may have favored the SOC accumulation up to 20 cm soil depth. Nevertheless, at lower soil depths (below 20 cm) soil organic carbon does not change due to tilling operation due to low microbial activities (Das et al., 2018).

In the current investigation, increased biomass inputs than those in other systems may be the cause of the CS2′s higher SOC storage. Due to a proliferation in C input, the increase in biomass turnover may have resulted in a surge in SOC content (Chen et al., 2019). Surface accumulation of SOC in response to diversified cropping under organic farming was also described by Blanco-Canqui et al. (2017). The greater SOC in surface soil (0–10 cm and 10–20 cm) suggested that residue recycling was important for C dynamics, especially at the effective root zone, and had a huge impact on the soil's ability to deliver nutrients. Crop configuration promotes SOC translocation in the plow layer which facilitates more OC storage in soil (Lorenz and Lal, 2005). The higher SOC buildup in ZT and maize-black gram-buckwheat was mostly linked to the accumulation of more crop residue. The maize-black gram-buckwheat system under ZT may enhance the SOC storing capacity on terraced land more fasten than other tillage and cropping systems in heavy rainfall zone of the Indian Himalayas.

Minimum soil disturbance in presence of mixed biomass retention under conservation effective tillage practices can hasten micro aggregate formation within macroaggregates (Yadav et al., 2020b). Macroaggregate formation diminishes the decomposition of surface retained crop residue and organic matter (Zhou et al 2020; Lal et al., 2018). This possibly subsidized the larger size of the VLC, LC, LLC, and NLC pools under ZT and RT over CT. The bigger size of various C fractions pool in the surface soil (0–10 cm depth) under diverse conservation tillage practices than CT is possible because of high organic residue addition (Dou and Hons, 2006). Changes in the LLC and NLC pool sizes in the current study, at various soil depths, may be caused by variations in plowing and residue management under various tilling regimes. Cropping system diversification added a variety of biomass into the soil and altered soil C fraction pools. In the present study replacement of toria with buckwheat during the winter season and rajmash with black gram during the early post-rainy season increased the VLC, LC, and non-labile C pools in surface soil. Increment in various soil C pools might be due to the enhancement in beneficial soil parameters and the addition of mineralizable and stable C sources via plant biomass inside the soil. An increment in soil C pools in surface soil due to cropping system diversification was correspondingly described by Babu et al (2020) and Yadav et al (2020b). Similarly, diversified cropping expressively affected the different carbon pools, but the impact was limited up to the 20 cm soil depth.

VLC and LC fractions constituted the active C pool in soil. The AC pool is the most active C in soil, degraded very fast, and greatly affected by changes in manipulation strategies (Babu et al., 2020; Nandan et al., 2019; Meena et al., 2018). Hence, it is a very reliable indicator to predict the SOC dynamic in response to management changes (Liu et al., 2014; Curtin et al 2020). In other hand, passive C pool (LLC + NLC): stable C portion of SOC and stored for a longer period (Mandal et al., 2012). SOC fractionated into the more passive pool over the active pool below the surface soil (>20 cm). In the present study also, more C was allocated in the passive pool below 20 cm soil depth. A higher amount of passive C pool over the active C pool at lower depth may be due conversion of readily decomposable C into a stable form. ZT favored the addition of different kinds of crop biomass, and minimum soil disturbance, which reduces the SOC oxidation and is attributed to higher AC and PC pools.

The rate and quality of SOC buildup under tillage operations were mainly determined by the amount of crop residues recycled and the C input added (Yadav et al., 2019a). Diversified cropping favored cropping diversity and added a different kind of C inputs to the system. In the present study maize-black, gram-buckwheat system allocated more C into both AC and PC pools over other systems followed by maize-rajmash-buckwheat. Black gram being a legume added more carbon over the other counterpart during the early post-season crop in diversified systems. Similarly, buckwheat has the potential to add more biomass to the soil as compared to toria. Black gram is a good candidate as a cover crop and protected SOC losses better than other crops like cereals (Chen et al., 2019). Trapping the time window by legume embedding between two crops improves SOC in C-hungry soil (Yadav et al. 2021). Growing more biomass-producing crops under intensified systems accumulated more C in soil (Nieder and Benbi, 2008), which ultimately increase AC and PC pools. It indicates the selection of crops under a diversified system played a noteworthy part in determining the soil C status and partition.

Conservation effective tilling redistributes the carbon and nutrients in the soil and can potentially affect C stratification in the soil profile. In our experiment, irrespective of tillage and cropping systems SR of VLC decreases with depth increment. ZT recorded ~2–7.8 % higher SR-VLC over CT at 10–20 and 20–30 cm soil depths. Franzluebbers et al. (2002) also concluded that SR > 2 in degraded soil is very uncommon. It indicates that the ZT accumulated more active SOC, which is readily available for microbial growth and nutrient transformation. Thereby increasing the growth and development of crops under ZT over CT. Higher C- SR under conservation tilling practices especially under RT/ZT was also reported by many workers (Chen et al., 2015; Patra et al., 2019). The SOC storage under high-frequency cropping is significantly influenced by crop diversification. In the represent investigation C stratification is greatly influenced by the nature of crops cultivated under a different system. Maize-black gram-buckwheat registered the highest VLC stratification followed by maize-rajmash-buckwheat which could be due to a higher concentration of active SOC and microbial activities. Higher C stratification with the inclusion of more biomass-producing crops under a more diversified system was also reported by Saha et al (2021).

The SMBC and DHA are good pointers for soil indicators in response to agronomic management (Lal et al., 2018). Tillage practices considerably impacted the SMBC and DHA at soil depths of 0–10 cm. Continuous adoption of ZT up to three years recorded 17 % and 13.4 % higher SMBC and DHA over CT, respectively. ZT and RT favored SMBC and DHA activities mainly due to minimal soil disturbance which improved soil structure, porosity, and SOC content (Yadav et al., 2021). More SOC under conservation effective tillage practices facilitates the food provision to the microorganism, which fastens their multiplications (Das et al., 2020; Álvaro-Fuentes et al., 2014). Higher SMBC under ZT plots over CT plots were likewise observed by Das et al (2018). Positive correlations between SOC fractions and soil enzymatic reactions were also reported by Zhao et al. (2019). Cropping diversity under different cropping systems added a variety of C inputs which modify the microbial dynamics and activities by changing the food substrate, soil nutrients status, and other related soil parameters (Choudhary et al., 2018). The replacement of toria with buckwheat in the maize-black gram system increases SMBC by 3.5 % and DHA by 7.3 % at soil depths of 0–10 cm in current study. Similarly, the replacement of toria under a maize-rajmash system with buckwheat had an optimistic impact on SMBC and DHA. The embedding of buckwheat and black gram in a maize-based system added more root biomass which will increase the soil's biological activities. Higher SMBC and DHA actions by the inclusion of pulses and high biomass-producing crops in existing cropping systems accelerate the soil enzymatic reaction and microbial diversity (Kumar et al., 2021).

5. Policy implications of the study

Unemployment and poor economic returns from the agricultural production system threatened the rural economies around the world. Undoubtedly contemporary agricultural production system increases food production several folds but at the same time had negative environmental outcomes (Babu et al., 2022; Das et al., 2022). Hence there is a need to search for alternative practices which can minimize the hostile effect of contemporary agricultural systems without comprising food security. Under the current scenario of climate change and ever-increasing population diversification of existing production systems with resource-efficient cropping and farming systems along with conservation effective soil and crop management practices could be a main agroecological approach for improving the farm income, production resilience besides maintaining the environmental quality (Babu et al., 2016; Yadav et al., 2019b). Diversified cropping offers myriad of environmental benefits besides providing more employment opportunities as compared to mono-cropping or specialized farming (Rathore et al., 2022). Besides the environmental and employment benefits diversified cropping is associated with better crop yield and economic returns (Das et al., 2016; Rathore et al., 2022).

The unique Himalayas ecosystem covers 16.4 % geographical area of India and is spread over 13 Indian states. The Indian Himalayan Region (IHR) (53.7 Mha area) suffers from tremendous pressure of land degradation. Owing to climatic conditions and soil characteristics region is well suited for organic farming. Organic farming is an alternative to conventional agricultural production systems and is often promoted as an environmentally robust production model (Yadav et al., 2013; Singh et al., 2021). However, organically managed fields have ~19.2 % less farm productivity over conventionally managed fields (Knapp and van der Heijden 2018). But the magnitude of yield reduction depends on the soil type, management practices, cropping diversity, climatic conditions, etc. Similarly, the response of tillage systems on farm productivity and profitability also varied among the soil, climate, and crop types. Consistency in crop yield under various tillage practices is mainly regulated by the crop type, soil, and environmental condition, in some cases no-tillage/zero-tilling produced equal or even high crop yield over conventional tiling (Pittelkow et al, 2015). The same is true in the case of the Himalayan ecosystem of India, where equal and/or higher crop yield was reported under conservation tillage over convention tilling (Singh et al., 2021; Yadav et al., 2021; Yadav et al., 2020b). Diversified cropping along with conservation effective tillage practices could be a feasible substitution for conventional production practices under organic farming in sustaining crop productivity besides improving soil C and mitigating climate change (Babu et al., 2020; Singh et al., 2021). Diversified cropping under organic farming can potentially enhance resource use efficiency, boost the provision of ecosystem restoration and reduce the yield gap by increasing SOC content and production resilience (Rodriguez et al., 2021). The finding of the current study showed that the adoption of zero tilling and pulses-based diversified cropping increases SOC stocks by 6.1 % and ~4 %, respectively over conventional tilling and cropping under organic farming. As SOC is positively correlated with crop yield and negatively correlated with CO_2 emission. Hence, the findings of the current study will guide policy planners in framing environmentally robust agricultural planning for advancing food security and off-setting fossil fuel emissions. However, an in-depth understanding of the linkage between diversified cropping and human-environmental wellbeing is a prerequisite for supporting environmentally friendly policy agendas.

6. Conclusions

Nowadays, there is the acknowledgement that soils contribute to the provision of ecosystem services and that soil quality can be seen as a central topic for many global sustainability goals such as food security, water security, climate stability, and biodiversity protection (Keith et al., 2016). Soil organic carbon (SOC) management is a global issue as it regulates the delivery provision of soil-driven ecosystem services like climate change mitigation and food production (Yadav et al., 2021). Hence, SOC management is imperative to halt climate change besides ensuring food security and soil functionality. Therefore, a thorough understanding is warranted to explore the effect of soil and crop manipulation strategies on SOC dynamics and its relation to food production as SOC underpinned ecosystem services. Long term impact of manipulation strategies on SOC dynamic has widely been assessed however very few studies appraise the impact of short-term soil and crop manipulations on SOC, associated soil properties, and food production, especially tillage and intensified cropping under organic management. In this perspective interdisciplinary teams are needed with expertise in relevant areas for research linking soils, ecology and health. The success of this integration is becoming more and more recognized as the "One Health approach'', based on the idea that human and animal health depend on the health of the ecosystems in which they live (OIE, 2020). This approach is able to increase the understanding and better influence human behavioural change, by promoting soil stewardship for more sustainable and resilient agricultural production.

Undoubtedly total SOC is a herculean indicator of soil fertility but does not provide the SOC dynamic changes in response to management practices which is highly warranted to design sound management planning to restore the soil carbon. Hence the present study proved the hypothesis that integration of conservation tillage and diversified cropping under organic farming can changes the soil carbon dynamics and other soil properties. Therefore, the present study inferred that cultivation of an diversified cropping system (maize-black gram-buckwheat and maize-rajmash-buckwheat) in conjunction with ZT/RT enhances the soil's physical characteristics, SOC storage, active and passive C pool size, and plant nutrient availability in the terraced lands. The results of the current study will also help to achieve the targets and goals of UN-land neutrality, Bonne challenges, and COP-26. Although, these targets can only be reinforced by joint efforts of farmers, through conservation effective management practices, scientists, by the results of practically feasible and environmentally robust research, and policy-makers by their contribution to designing and developing policies and market regulations.

CRediT authorship contribution statement

Subhash Babu: Conceptualization, Investigation, Methodology, Writing – original draft. **Raghavendra Singh:** Investigation, Writing – original draft. **Ravikant Avasthe:** Supervision, Resources. **Sanjeev Kumar:** Resources. **Sanjay Singh Rathore:** Formal analysis, Writing – review & editing. **Vinod K. Singh:** Resources, Writing – review & editing. **M.A. Ansari:** Writing – review & editing. **Donatella Valente:** Writing – review & editing. **Irene Petrosillo:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.109940.

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