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Effect of contrasting tillage and fertilization on carbon footprints, soil organic carbon fractions and eco-system services of climate regulation under cereal based systems of North-West India: A review

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Abstract
Inappropriate farm practices can increase greenhouse gases (GHGs) emissions and reduce soil organic Carbon (SOC) sequestration, thereby increasing carbon footprints (CFs), jeopardizing ecosystem services, and affecting climate change. GHGs emissions from agricultural inputs were 6432.3-6527.3 kg CO_2 eq ha^1 yr^1 during the entire growing season, respectively. The GHGs emission from chemical fertilizers and irrigation accounted for >80% of that from agricultural inputs during the entire growing season. Integrating improved farming practices lowers wheat carbon footprint effectively, averaging 256 kg CO_2 eq ha^{-1} yr^{-1}. For each kg of wheat grain produced, a net 0.027–0.377 kg CO_2 eq is sequestered into the soil. With the suite of improved farming practices, wheat takes up more CO_2 from the atmosphere than is actually emitted during its production. Global warming potential (GWP), GHG emission due to consumption energy and greenhouse gas intensity were recorded lower by 43%, 56% and 59% in Climate Smart Agriculture (CSA) with high adaptive measures than farmers practices (3652.7 kg CO_2 eq. ha^{-1} yr^{-1}, 722.2 kg CO_2 eq. ha^{-1} yr^{-1} and 718.7 Mg kg^{-1} CO_2 eq. ha^{-1} yr^{-1}). The total SOC, WSOC, HWSOC, EOC, MBC, POC, and LFOC contents were 13.87–145.97% higher in the $NPKS_2$ treatment than in the CK treatment. The CPMI was highest in the NPKS2 treatment in the top 20 cm soil. SOC correlated positively with labile C fractions and CPMI in the 0–5 and 5–10 cm soil layers with the exception of WSOC and LFOC in the 5–10 cm soil layer.
The sensitivity of each soil labile organic C fraction to the different treatments varied in the 0–5 cm soil layer. Compared to conventional tillage, the percentages of >2 mm macro-aggregates and water-stable macro-aggregates in rice-wheat double conservation tillage (zero-tillage and straw incorporation) were increased 17.22% and 36.38% in the 0–15 cm soil layer and 28.93% and 66.34% in the 15–30 cm soil layer, respectively. Furthermore, the large macro-aggregates (> 2 mm) with the highest proportion of size distribution represented the major pool of SOC stock (47.3–51.2%) and mineralization amount (38.2–43.6%) in the 0–30 cm layer, followed by that in the small macro-aggregates (0.25–2 mm), regardless of tillage practices. Plots with fertilization of 50% NPK + 50% GM (1.8 t ha^{-1}) had significantly higher total soil organic C (TOC), LOC, macro-aggregate-associated C concentrations, and soil aggregation than other treatments. However, increasing the quantity of C input could enhance soil C sequestration or reduce the rate of soil C loss, depending largely on the local soil and climate conditions. SOC can be best preserved by crop rotations with conservation tillage practices such as no or reduced tillage, and with additions of residues, chemical fertilizers and manure SOC change was significantly influenced by the crop residue retention rate and the edaphic variable of initial SOC content. Soil disturbance by tillage leads to destruction of the protective soil aggregate. This in turn exposes the labile C occluded in these aggregates to microbial breakdown. A higher number of macro-aggregates along with greater accumulation of particulate organic C indicate the potential of conservation tillage for improving soil carbon over the long-term in rice-wheat rotation in North India.

Keywords: Greenhouse gas (GHGS), carbon footprint (CFP), energy use efficiency, conservation tillage

Introduction

Global demands for major grains such as wheat (*Triticum aestivum* L.) are projected to increase by 70% by 2050 (Tilman *et al*., 2011) [45], driven by the ever-growing human population's need for food, feed, fiber and fuel (Fedoroff *et al*., 2010) [18]. To meet this target, grain production must increase substantially, while, at the same time, agricultures environmental footprint must shrink dramatically (Foley *et al*., 2013). Given the limited availability of uncultivated land on the planet (Garnett *et al*., 2013) [23] and the growing environmental concerns related to converting carbon-rich forests and grasslands to cropland the future increase in grain production must mostly come from existing farmland (Mueller *et al*., 2012) [33]. Soil organic carbon (SOC) is affected by a number of factors like tillage practices, residue management (Sun *et al*., 2015), soil aggregate sizes (Zhang *et al*., 2013) [52] and microbial functional diversity (Guo *et al*., 2016) [24]. Augmenting agricultural management can lessen the SOC loss, or even rise its content. Intensive and continuous soil tilling is in agricultural practices from thousands of years in India (Larkin, 2015) [30]. Intensive conventional tillage results in frequent soil disturbance which reduces the soil aggregate sizes, thus accelerate the SOC oxidation and decreasing its content. For soil microorganisms' major source of energy is soil organic carbon (SOC) (Guo *et al*., 2016) [24] and its content deeply affects the properties of soil that comprise the cycling of nutrients and aggregate stability (Varvel and Wilhelm, 2010) [48]. SOC is also very important in preserving long-term sustainability of agricultural-ecosystems and worldwide bio geo-chemical cycles (Larkin, 2015; FAO 2017) [30, 17].

Agricultural systems not only get influenced by climate change but also influence climate through exchange of important GHGs (CO_2, CH_4, and N_2O), and by affecting storage of carbon in the soil. The resultant change in soil carbon is designated as carbon sequestration while the net accumulation of carbon in the system, positive or negative, is designated as net ecosystem carbon budget or balances (NECB) (Chapin *et al*., 2006) [9]. At an annual scale, the NECB can be determined by making an integrated measurement of the net ecosystem CO_2 exchange as well as non-CO_2 carbon (harvest) (Smith *et al*., 2010) [42]. Eddy covariance (EC) has been used worldwide for quantifying net ecosystem exchange (NEE) of carbon and the net ecosystem production (NEP) derived from eddy flux is considered to be an ideal variable for budgeting of C from local to regional scale. The EC method can measure the net exchange of CO_2 over areas that are typically of the order of several hundred square metres. The EC methods can't derive information under experimental fields of different management trials with multiple small plots (Smith *et al*., 2010) [42].

In India, the information on energy use and CF are mostly based on the estimates made on wheat-based systems (Choudhary *et al*., 2017) [11] and there is a paucity of such estimates in rice-based cropping systems particularly under conservation and conventional systems (Yadav *et al*., 2018) [50]. Most of the CF assessment is based on inputs used for crop production, and information on direct flux of CO_2, CH_4 and N_2O measurement for entire cropping system including fallow period in rice-based system is meagre particularly in the coastal ecosystems. Global rice cultivation accounts for 2.5% of the current anthropogenic warming because of methane emission (Kritee *et al*., 2018) [29] but rice also has the capacity to sink atmospheric CO_2 through photosynthesis by producing huge biomass during its growing period. The review study assessed that the adoption of CA in rice-wheat system for a few uninterrupted years can substantially improves the organic carbon status, and reduce the sub-surface compaction and the modified soil environment may promote rice-wheat system productivity in direct-seeded/ unpuddled transplanted rice and no-till wheat system, in comparison to a conventional system, where rice was puddle-transplanted followed by conventionally tilled wheat. The objective of the manuscript is to review the potential of soils in sequestering C and mitigating the accelerated greenhouse effects by adopting conservation agriculture practices. A major focus was given on the extent and scope of SOC sequestration by shifting from conventional tillage to conservation tillage.

Effect of tillage and fertilization on carbon footprints

A carbon footprint is the total amount of greenhouse gases (including carbon dioxide and methane) that are generated by our actions. To have the best chance of avoiding a 2 ℃ rise in global temperatures, the average global carbon footprint per year needs to drop to under 2 tons by 2050. Ruis *et al*. (2018) reported that the season when tillage occurred (fall for moldboard plow and chisel, spring for disk, chisel, and moldboard plow), fluxes tended to be greater with tillage than with no-till. Fluxes tended to be greater in summer compared to winter and spring, likely due to warmer soil temperatures (Fig 1a).

Bijarniya *et al*. (2020) [7] indicated that global warming potential (GWP) and CO_2 emission intensity of RW system was significantly influenced by divergent crop management practices. Among the crop management scenarios, S1 recorded the highest GWP and CO_2 emission intensity followed by S2 and the lowest was in S6 and following overall trend of S6 > S5 > S4 > S3 > S2 > S1 (Fig. 1b). The higher GWP and CO_2 emission intensity in farmer practices scenarios (S1 and S2) reflects the more contributed in carbon footprints. On 3-years mean basis, CSAPs recorded lower GWP by 1598, 1749 and 1876.3 kg CO_2 eq. ha^{-1} yr^{-1} compared to S1 (3652.7 kg CO_2 eq. ha^{-1} yr^{-1}), respectively. Input like diesel fuel (for land preparation, seeding and irrigation water application), fertilizers constitute and puddling in rice, the major share of the total emissions of GHGs (N2O and CH4) estimated for the system (Fig. 1b). The CSA based scenarios (S4 S5 and S6) related to low inputs and no puddling in rice contributed to low emissions of GHGs compared to farmers practice (S1), whereas higher input used and followed repeated tillage in wheat and puddling in rice.

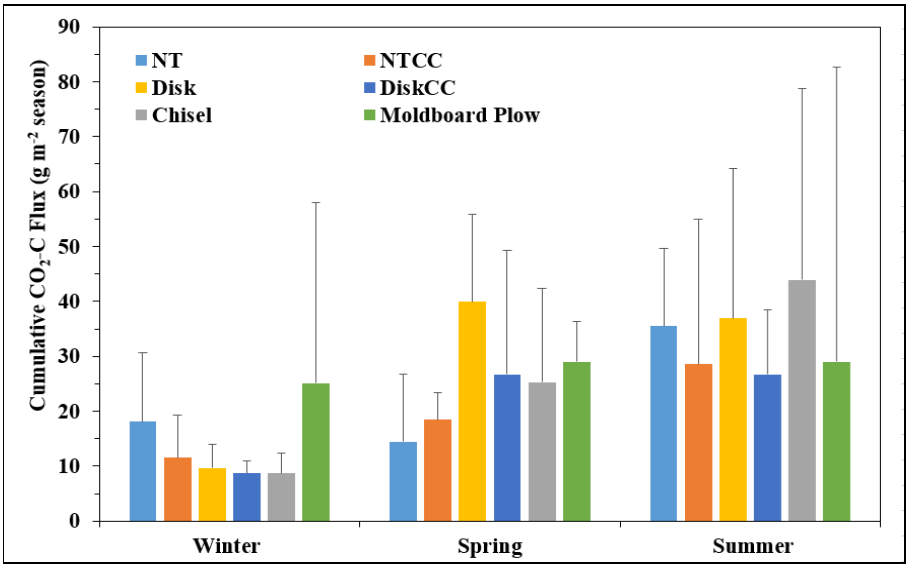

Fig 1a: The influence of tillage system on CO_2-C flux by season in a long-term tillage experiment. NT = no-till, CC = cover crop [Source: Ruis *et al*., 2018].

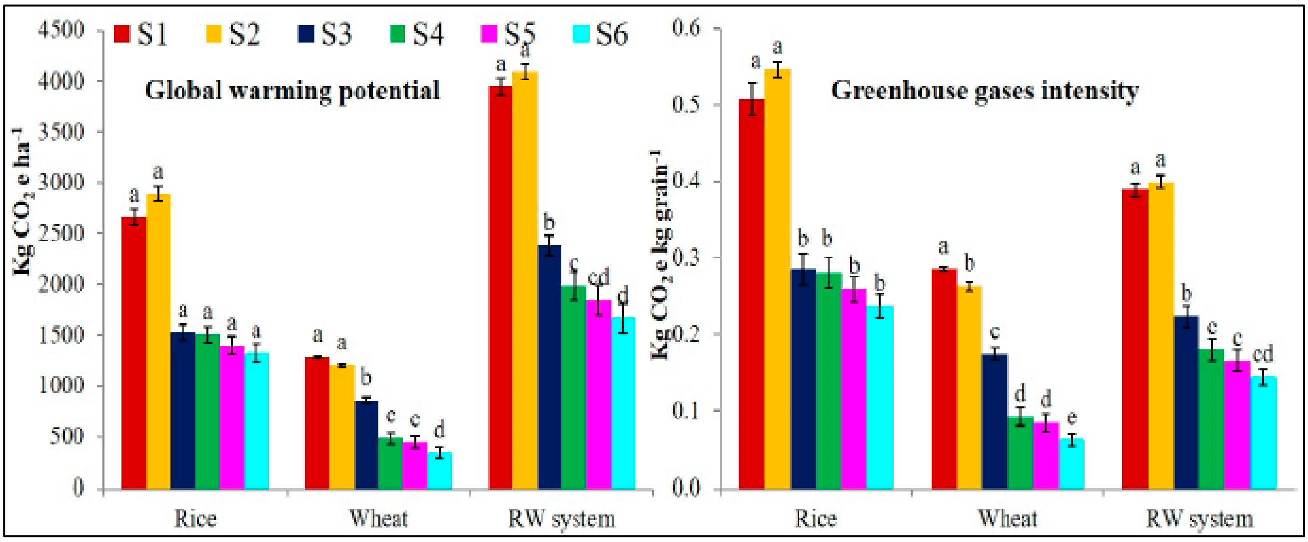

Fig 1b: Mean annual global warming potential (GWP) and greenhouse gases intensity of rice-wheat system under divergent crop management scenarios. S1- Conventional tillage (CT) without residue; S2- CT with residue, S3- Reduced tillage (RT) with residue + Recommended dose of fertilizer (RDF); S4- RT/zero tillage (ZT) with residue + RDF, S5-ZT with residue + RDF + green seeker + tensiometer +Information & communication technology +crop insurance and S6- S5 + site specific nutrient management [Source: Bijarniya *et al*., 2020] [7].

Gan *et al*. (2014) [22] observed that carbon footprint value represents the balance between carbon emissions and carbon sequestration. Averaged over the 25-year study period, the annual greenhouse gas emissions averaged 357 kg CO_2 eq ha^{-1} in dry years, 577 in normal years and 687 in wet years (Fig. 2a). The emissions included those from crop residue decomposition, applied inorganic N and phosphorus fertilizers, N leaching losses, application of pesticides, fuel used in various farming operations and fossil energy used during the manufacture, transportation, storage and delivery of these crop inputs to the farm gate. However, these emissions were more than offset by the greater carbon conversion of wheat plants from atmospheric CO_2 into plant biomass and ultimately sequestered into the soil. On average, annual soil carbon gain was 877±15 kg CO_2 eq ha^{-1} in normal years and 961±14 in wet years, which were 69% and 85% more, respectively, than the soil carbon gain obtained in dry years. Greater crop productivity under more favourable weather conditions leads to greater crop residue and root biomass production (Gan *et al*., 2009) [20], which helps enhance soil organic carbon.

Among the four cropping systems, the LentW system gained an average 1,039 kg CO_2 eq ha^{-1} annually through soil carbon sequestration, which was 26% more than the gain for ContW, 56% more than for FWW and 62% more than for FFlxW. This cereal–legume rotation had the advantage that the lentil plants fixed N_2 from the atmosphere (Jensen *et al*., 2012), and the increased N availability enhanced plant biomass accumulation (Gan *et al*., 2011) [21]. Despite the large variation in carbon emissions and sequestration between the four systems (Fig. 2a), the overall ranking of their carbon footprint values was consistent across the dry, normal and wet growing conditions.

However, calculated by decade, the annual mean value of per-area carbon footprint in the 1980s was 181±12 kg CO_2 eq ha^{-1}, significantly lower than those obtained in the 1990s and 2000s (Fig. 2b); similarly, the mean value of per-yield carbon footprint in the 1980s was also lower than those obtained in the 1990s and 2000s. However, the carbon footprint values obtained in the 1990s did not differ from those in the 2000s, even though overall crop yield has been trending lower in recent years (Fig. 2b). In this context, it is clear that the wheat carbon footprint is an outcome of a complex of various factors, including the change in SOC, the quantity and method of crop inputs, the crop yield response and other relevant factors.

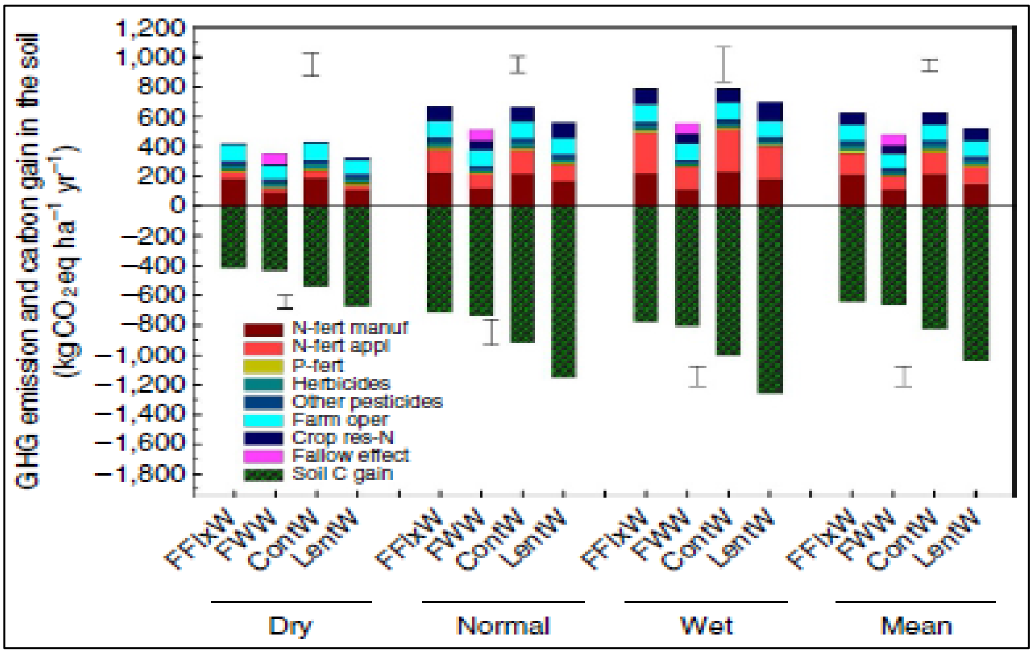

Fig 2a: Carbon emissions and sequestrations for alternative wheat cropping systems [Source: Gan *et al*., 2014 [22]].

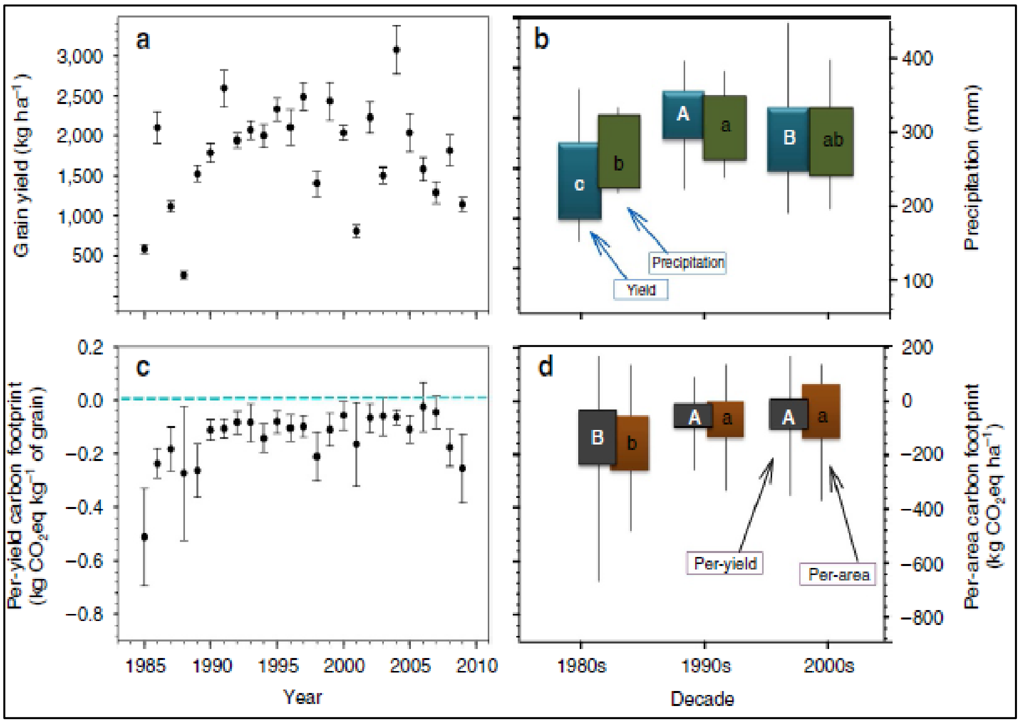

Fig 2b: Grain yield and carbon footprints of spring wheat in different years or decades [Source: Gan *et al*., 2014 [22]]

In western Canada, for example, the carbon footprint of spring wheat is estimated at 0.383 kg CO_2 eq kg^{-1} of grain produced in the semiarid brown soil zone, which was 32% lower than the carbon footprint (0.533 kg CO_2 eq kg^{-1} of grain) of the same wheat crop produced in the more humid black soil zone (Gan *et al*., 2011) [21]. The main contributor to the large difference in the spring wheat carbon footprint between the two soil zones was precipitation and the amount of fertilizer applied to the crop.

Mandal *et al*. (2021) [32] also found that the estimated net ecosystem production (NEP) from the kharif rice ecosystem varied from 3.72 to 4.60 Mg C ha^{-1} whereas for rabi rice and cotton NEP varied from 2.71 to 3.25 Mg C ha^{-1} and 0.29 to 2.13 Mg C ha^{-1} respectively. The NEP was equal but opposite in sign to NEE (NEE = - NEP). The annual NEP for rice-rice and rice-cotton system varied from 6.18 to 7.30 Mg C ha^{-1} yr^{-1} and 3.71 to 5.89 Mg C ha^{-1} $1yr^{-1}$, respectively (Fig. 3a). Carbon inputs through crop residue, root biomass, rhizodeposition and aquatic biomass were added with NEP to get the total C inputs to the system. The ecosystem C removal processes were harvest of straw and grain for rice and seed cotton fibre and crop biomass in case of cotton, C loss with runoff as dissolved C and with sediments and C loss as CH_4 emission. The annual C removal as harvest varied from 6.49 to 7.70 Mg ha^{-1} yr^{-1} and 4.58 to 6.44 Mg ha^{-1} yr^{-1} for rice-rice and rice-cotton systems. The cumulative CH_4–C emission varied from 0.133 to 0.208 and 0.076 to 0.117 Mg C ha^{-1} yr^{-1} in case of rice-rice and rice-cotton systems, respectively whereas C loss through runoff was 0.311 Mg ha^{-1} yr^{-1}. The system was found to have the potential to store C in the tune of 0.63–2.51 Mg C ha^{-1} yr^{-1} and -0.15 to 1.81 Mg C ha^{-1} yr^{-1}, respectively in case of rice-rice and rice –cotton system (Fig. 3a).

The treatment RC-ZTNR acted as a source of C in the ecosystem as had been recorded during the evaluation of C sequestration wherein there was a depletion of soil C in the same treatment. The relative contributions of the different components to the total NECB were assessed by summing up their absolute values and presented on a percent basis. Overall NEP represented 39.2% of the total NECB compared to 42.9%, 0.89%, 2.1%, 14.8% for C export as harvest, and CH_4-C and C loss as runoff as dissolved C and sediments and, C inputs to the soil as crop residue, root biomass, rhizodeposition and aquatic biomass, respectively. Considering the NEE, and inputs used (organic fertilization and seeds) and outputs of non-CO_2 carbon (harvest), the NECB was evaluated in different cropping systems, climatic conditions and management practices for European crop lands and the value varied from 2580 and 6450 kg C ha^{-1} yr^{-1} (Ceschia *et al*., 2010) [8].

Bhattacharyya *et al*. (2014) [5] also estimated ecosystem C balance for Indian tropical low land rice systems and using open-path EC and the results revealed that flooded rice ecosystem acted as net C sink both seasonally and annually. Our results showed that low land rice-based double cropping system having high NEP acts as a net C sink. However, when NEP was comparatively low because of poor crop stand particularly for cotton as was found in case of ZT with no residue treatment under rice-cotton system turned into a net C source. The GHGB was also evaluated by considering the GWP of direct emission of N_2O and CH_4 and converted to Kg CO_2-eq ha^{-1} yr^{-1}, carbon emission due to inputs used and field operation and other management practices along with NECB excluding CH_4-C converted to CO_2-eq kg ha^{-1} yr^{-1}.

Mandal *et al*. (2021) [32] observed that he carbon footprint (CF) for the rice-rice system was higher than that for rice-cotton system. Without considering soil C sequestration, the CF under ZT, RT and CT were 0.96, 0.99 and 1.37 kg CO_2-eq kg^{-1} yr^{-1}, respectively in rice-rice and 0.89, 0.80 and 1.27 kg CO_2-eq kg^{-1} yr^{-1}, respectively in rice-cotton system. When SOC sequestration was included, the CF under ZT, RT and CT were 0.80, 0.81 and 1.19 kg CO_2-eq kg^{-1} yr^{-1} respectively for rice-rice system compared with 0.84, 0.67 and 1.15 kg CO_2-eq kg^{-1} yr^{-1} for rice-cotton system (Fig. 3b). Overall RT had the lowest CF in rice-based cropping system. The contribution to CF for both rice-rice and rice-cotton were in the following order: N_2O and CH_4 emission > agricultural inputs > SOC sequestration for all treatments. Irrespective of the cropping system, the CF was in the order: RT > ZT > CT.

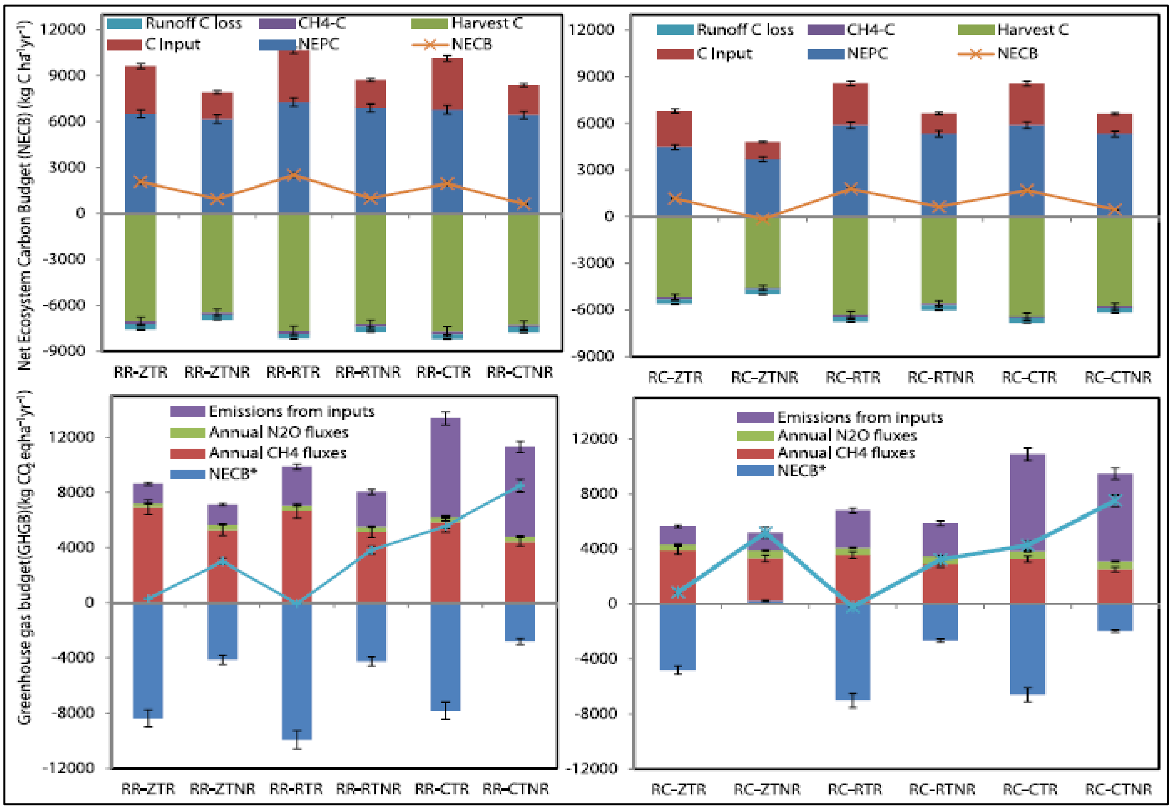

Fig 3a: Net ecosystem carbon budget (NECB) and greenhouse gas budget (GHGB) under different tillage and residue treatments in rice-rice (RR) and rice-cotton (RC) systems. ZTR, Zero tillage with residue; ZTNR, Zero tillage with no residue; RTR, Reduced tillage with residue; RTNR, Reduced tillage with no residue; CTR, Conventional tillage with residue; CTNR, Conventional tillage with no residue [Source: Mandal *et al*., 2021] [32].

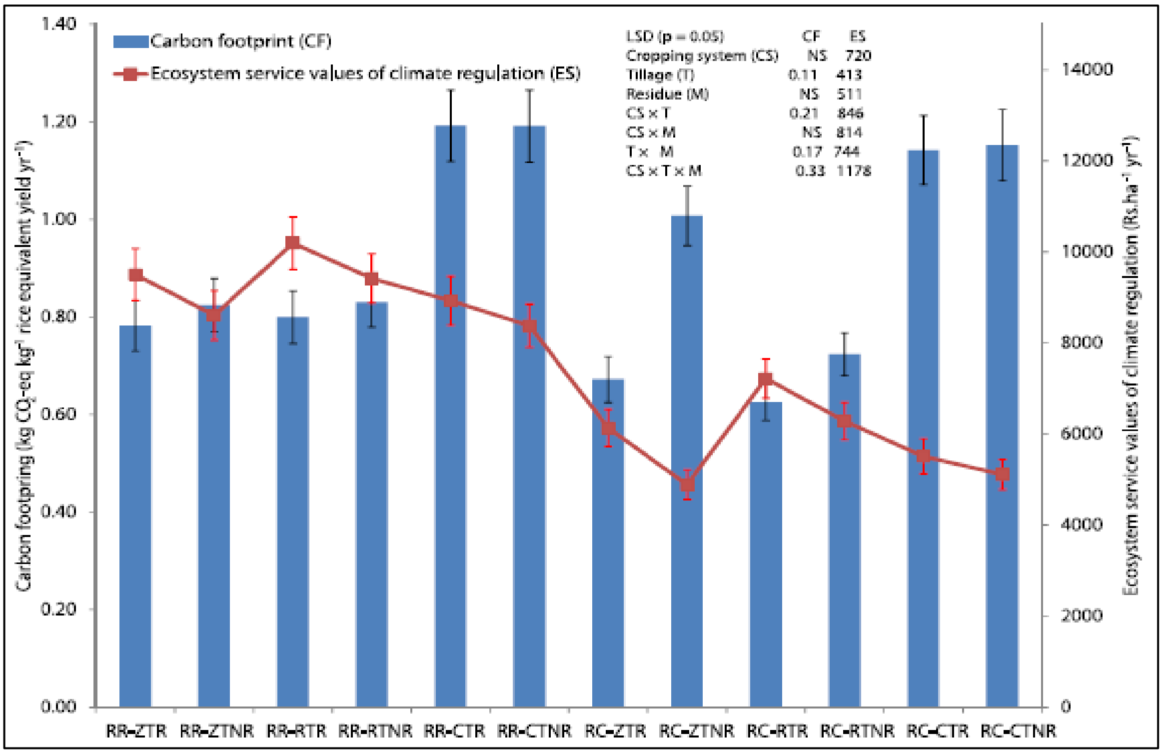

Fig 3b: Carbon footprint (CF) and ecosystem service of climate regulation (ES) under different tillage and residue treatments in rice-rice (RR) and rice-cotton (RC) systems [Source: Mandal *et al*., 2021] [32].

Naresh *et al*. (2021) [39] reported that over six years, the T9 cropping system (spring-sown sugarcane with PLL) had the lowest greenhouse gas emissions (0.24 kg CO_2 eq ha^{-1} year^{-1}), while the T_{12} cropping system (late sown spring sugarcane under TLL) had the highest greenhouse gas emissions (0.97 kg CO_2 eq ha^{-1} year^{-1}) (Table 1). The total CO_2-equivalent emissions were lower in cropping systems which included potato, as relatively more potassium fertilizer than nitrogen fertilizer was applied in these systems: excess or poorly timed nitrogen fertilizer is a key source of agricultural greenhouse gas emissions (Chai *et al*., 2021). Crop residues increased SOC, soil health and thereby reduce the green-house emissions in the top 20-cm soil layer. Further higher SOC stocks offset the input-induced greenhouse gas emissions. Under TLL, farmers till the field at least thrice and plank it once, which results in approximately 4.5 h' per hectare tractor usage to sow two crops each year. Under PLL, the tractor time required to sow each crop is reduced by 2.25 h' per hectare, which saves approximately 19,536 MT CO_2 emissions per annum across western Uttar Pradesh (Jat *et al*., 2015) [27].

Table 1: Average emissions and the Carbon footprint under alternative cropping systems with leveling options from 2009–2015 (Source: Naresh *et al*., 2021) [39]

Crop Sequences	Average Emissions (Kg CO_2 kg^{-1})	Carbon Footprint (kg CO_2 kg^{-1})	Build-Up of C%	Rate of C Build-Up (Mg C ha^{-1} year^{-1})	Sequestrated Carbon (Mg C ha^{-1})
T_1	1565.37	0.51	36.6 ± 0.6	1.46 ± 0.09	8.6 ± 0.8
T_2	3590.63	0.85	33.8 ± 1.8	1.36 ± 0.07	7.9 ± 0.3
T_3	1223.34	0.45	41.0 ± 2.2	1.63 ± 0.09	9.3 ± 0.2
T_4	3119.88	0.75	40.7 ± 2.4	1.82 ± 0.006	8.7 ± 0.8
T_5	944.19	0.24	43.6 ± 0.09	1.88 ± 0.001	9.6 ± 0.7
T_6	2475.63	0.68	40.1 ± 2.31	1.74 ± 0.10	9.1 ± 0.2
T_7	1746.44	0.55	39.3 ± 1.81	1.13 ± 0.021	6.8 ± 0.5
T_8	4275.56	0.86	37.5 ± 3.1	1.02 ± 0.006	6.3 ± 0.8
T_9	1056.73	0.36	39.3 ± 1.8	1.96 ± 0.09	9.4 ± 0.8
T_{10}	3292.35	0.76	37.3 ± 0.06	1.73 ± 0.021	8.5 ± 0.5
T_{11}	1949.04	0.64	34.2 ± 1.8	1.36 ± 0.07	8.2 ± 0.1
T_{12}	5249.33	0.97	31.8 ± 0.6	1.33 ± 0.04	7.6 ± 0.8

SOC fractions under different tillage and nutrient supply options

Das *et al*. (2016) [13] reported that the SOC stock of the 0–60 cm profile ranged from 67.9 to 83.1Mgha^{-1} under different nutrient management options (Fig. 4a). Unfertilized control had the lowest SOC stock, which was statistically at par with sole fertilizer treatments or two IPNS treatments (NPK +GR and NPK + CR). The SOC stock under NPK+ SPM treatment was significantly greater compared with control, and increased further in the NPK +FYM and NPK +GR +FYM treatments.

However, averaged across soil depths, the contribution of C_{VL}, C_L, C_{LL} and C_{NL} towards TOC under different treatments was in the range 6.6–16.5%, 11.6–24.4%, 4.04–11.8% and 53.5–70.8% respectively. The passive pool (C_{LL}+C_{NL}) contributed a relatively higher proportion (70.1%) than the active (C_{VL} + C_L) pool (29.9%; Fig. 4b). Majumder *et al.* (2007) [31] also recorded a similar contribution of passive pool of SOC towards TOC under NPK and FYM treatments. Conjoint use of FYM, GR or SPM along with fertilizers increased the proportion of the active pool, especially in the top two soil layers, whereas the use of sole fertilizers or NPK + CR contributed more towards the passive pool of OOC, especially C_{LL} at all soil depths.

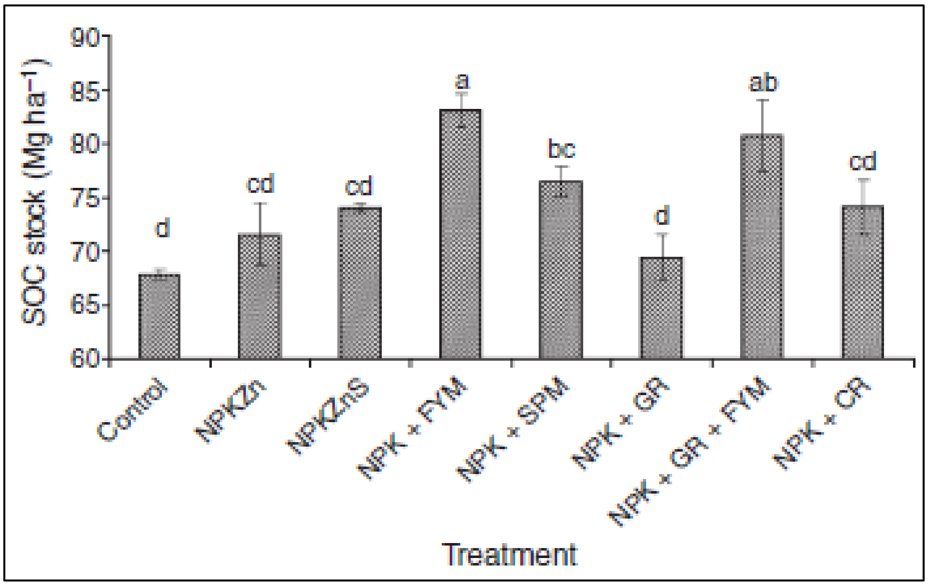

Fig 4a: Effects of long-term fertilization and manuring on soil organic carbon (SOC) stock (0–60 cm soil depth) in the rice–wheat system [Source: Das *et al.*, 2016] [13]

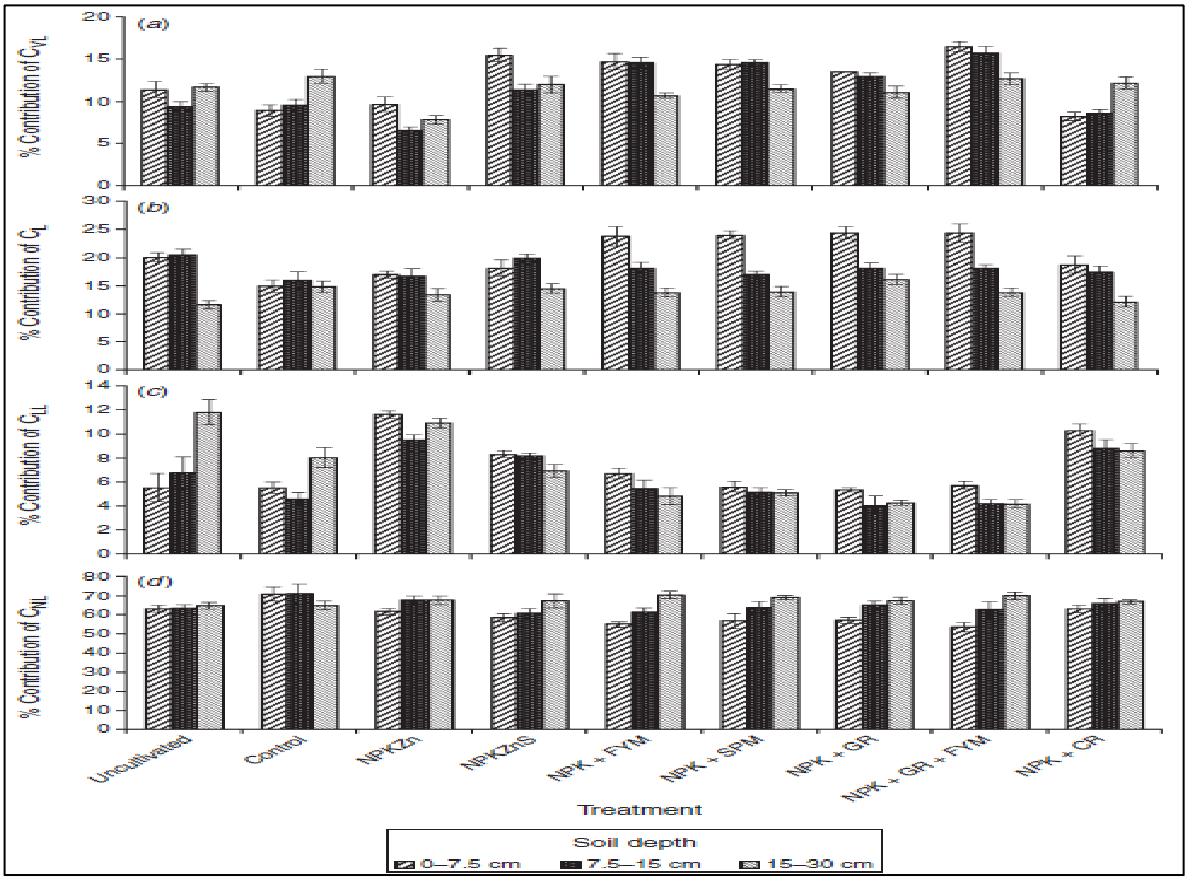

Fig 4b: Contribution of (*a*) very labile C (C_{VL}), (*b*) labile C (C_L), (*c*) less-labile C (C_{LL}) and (*d*) non-labile C (C_{NL}) to total organic carbon under different nutrient supply options and soil depths. Control, unfertilized plots; FYM, farmyard manure; SPM, sulfitation pressmud; GR, green gram residue; CR, cereal residue [Source: Das *et al.*, 2016] [13]

Bhardwaj *et al.* (2019) [4] revealed that Oxidizable C was the maximum in FYM followed by GM and crop residue (WS, RS) treatments in the surface 0.15 m soil. At the lower depths (0.15–0.30 m), there was no significant difference in the oxidizable C for any management. At both depths O and F accumulated least oxidizable C. VLc (very labile C) and LLc (less labile C) fractions constituted a major part of soil organic C, for all managements. All integrated nutrient management (INM) accumulated a similar amount of VLc fraction for all measured depths. GM accumulated the maximum Lc fraction at the surface 0–0.15 m. The LLc fraction was maximum in FYM which was followed by all other integrated nutrient managements. Management O had least LLc fraction in surface 0.15 m. There was no difference in NLc fraction for any of the treatments, for any measured depth. There was 46 to 65% decrease in oxidizable C, from the surface (0–0.15 m) to lower layer (0.15–0.30 m). Change in soil C content was directly related to the C input to the soil (Fig. 5a). In general, the most increases were in the VLc and the LLc fractions of soil C in all management. With an increase in C input, the most significant increase was noticed in the Lc (labile C) and the LLc (less labile C) fractions. Management FYM had maximum contributions to the LLc and the VLc fractions while GM had a maximum contribution to Lc. Non-labile (NLc) C fraction changed little with increased total C input to the soil in different treatments. Moreover, significantly higher carbon sequestration potential (CSP) was noted for FYM, GM and WS management, for shallower depths (0–0.15 m) (Fig. 5b). For lower depths (0.15– 0.30 m), there were no significant differences amongst management. Different managements and C inputs led to significant variation in bulk density only for surface 0.15 m soil. LE and GM had the least bulk density at this depth while there were no significant differences at 0.15–0.30 m. Consequent of C inputs and bulk density changes; soil C stock was maximum in FYM, GM, and WS for 0.15 m. For all depths, O had the least organic C stock.

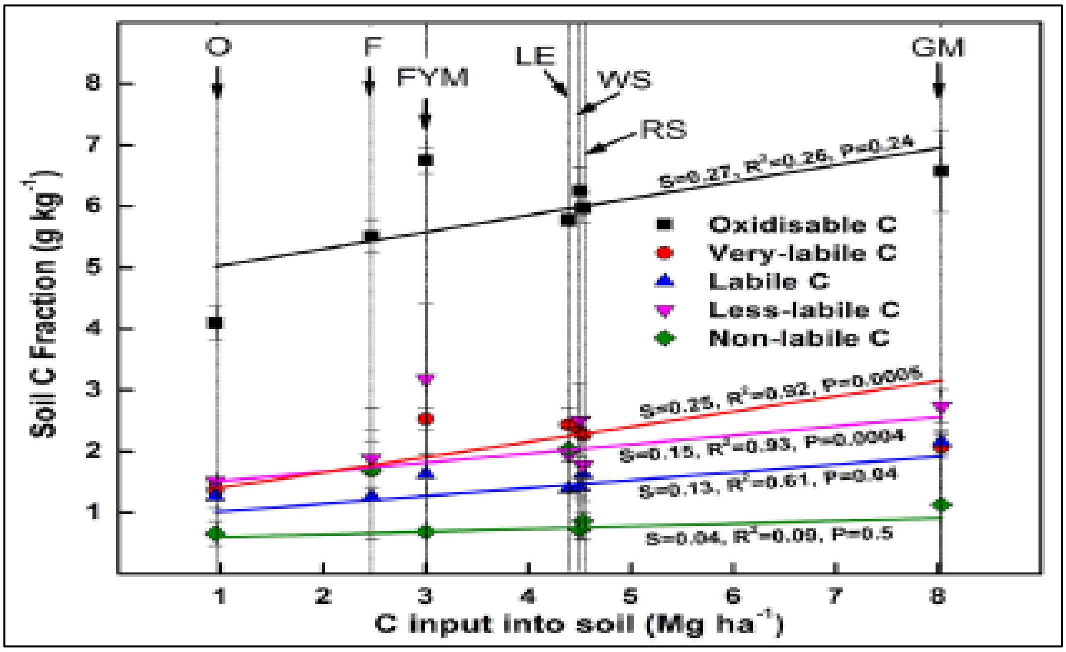

Fig. 5a: Relationship between carbon (C) input into the soil and soil C fractions under different nutrient management. O = no fertilizer, F = 100% inorganic fertilizers, LE = opportunity legume crop (*Vigna radiata*), GM = green manuring, FYM = farmyard manure, WS = wheat stubble, RS = rice stubble [Source: Bhardwaj *et al*., 2019] [4]

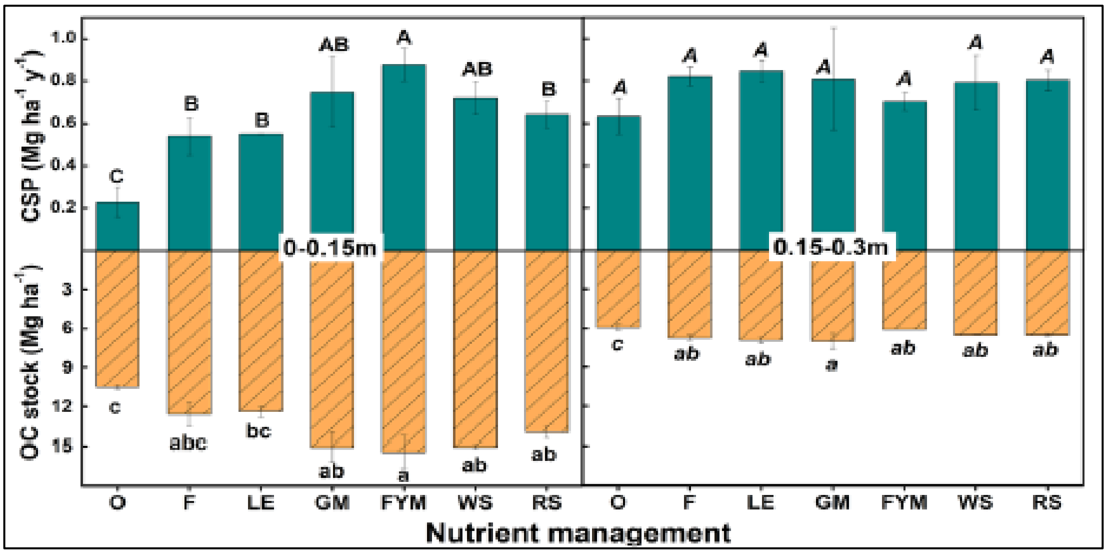

Fig.5b: Carbon (C) sequestration potential (CSP) and soil C stock under different nutrient management after 10 years of initiation (2005–2015). O = no fertilizer, F = 100% inorganic fertilizers, LE = opportunity legume crop (*Vigna radiata*), GM = green manuring, FYM = farmyard manure, WS = wheat stubble, RS = rice stubble, OC = organic carbon, CSP = carbon sequestration potential [Source: Bhardwaj *et al*., 2019] [4]

Yan *et al*. (2013) [51] observed that particulate organic C was found stratified along the soil depth. A higher POC was found in surface soil decreasing with depth. At the 0–20 cm, POC content under NP+FYM, NP+S and FYM were 103, 89 and 90% greater than under CK, respectively. In 20–40 cm and 40–60 cm soil layers, NP+FYM had maximum POC which was significantly higher than NP+S and FYM treatments. Even though POC below 60 cm depth was statistically similar among fertilization treatments, the general trend was for increased POC with farmyard manure or straw application down to 100 cm soil depth. Guo *et al*. (2016) [24] reported that in the 0−5 cm soil layer, NT treatments significantly increased SOC concentration by 5.8%, 6.8%, and 7.9% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate, respectively, compared with CT treatments. NT treatments significantly increased MBC of bulk soil, >0.25 mm and <0.25 mm aggregates by 11.2%, 11.5% and 20.0%, respectively, compared with CT treatments. DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under NT treatments were 15.5%, 29.5%, and 14.1% higher than those under CT treatments, respectively. In comparison with NS treatments, S treatments significantly increased SOC concentrations of bulk soil by 12.8%, >0.25 mm aggregate by 11.3%, and <0.25 mm aggregate by 14.1%. In addition, MBC of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under S treatments were 29.8%, 30.2%, and 24.1% higher than those of NS treatments, respectively. S treatments exhibited 25.0%, 37.5%, and 23.2% higher DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate compared with NS treatments, respectively. In the 0−5 cm soil layer, there were significant interactions of tillage and straw returning on SOC concentration of >0.25 mm and <0.25 mm aggregates, MBC of bulk soil and <0.25 mm aggregate, and DOC concentration of >0.25 mm aggregate. Conservation tillage significantly increased SOC concentration of bulk soil in the 0−5 cm soil layer. This increase in SOC concentration can be attributed to a combination of less soil disturbance and more residues returned to the soil surface under conservation tillage.

Naresh *et al*. (2016) [37] also found significantly higher POC content was probably also due to higher biomass C. Results on PON content after 3-year showed that in 0-5 cm soil layer of CT system, T1, and T5treatments increased PON content from 35.8 mgkg-1in CT (T9) to 47.3 and 67.7 mg·kg-1without CR, and to78.3, 92.4 and 103.8 mgkg^{-1} with CR @ 2, 4and 6 tha^{-1}, respectively. The corresponding increase of PON content under CA system was from 35.9 mgkg-1in CT systems to 49 and 69.6 mgkg-1 without CR and 79.3, 93.0 and 104.3 mgkg^{-1} with CR @ 2, 4 and 6 tha^{-1}, respectively. Small improvement in PON content was observed after 4 years of the experiment. Xie *et al*., (2018) revealed that the largest percentage, which ranged from 52.0 to 60.7% at a depth of 0–10 cm and from 63.2 to 73.4% at 10–20-cm depth, followed by micro-aggregates occluded in the macro-aggregate fraction (24.5–34.6 and 21.0–28.9%, respectively). The cPOC fraction had the smallest percentage (11.0–17.0% and 5.5–10.0%, respectively) at the two soil depths for all treatments. Within the micro-aggregate occluded in macro-aggregate fraction, the mass proportion of the s+c- m fraction was the largest (10.2–27.5% at a depth of 0–10 cm and 11.9–19.8% at 10–20 cm), followed by the iPOC fraction (6.3–13.6 and 7.5–11.5%, respectively), and the smallest fraction was fPOC, with only 0.3–2.1% at 0–10 cm and 0.2–0.4% at 10–20 cm. Kan *et al*. (2020) also found that the macro-aggregates size classes were the most abundant for all tillage practices throughout the 0–50 cm layer, accounting for 52.9% (CT)-59.1% (NTS) in the LM>2 size class and 24.6% (CT)-28.0% (NTS) in the SM0.25-2 size class. In the LM>2 size class, the highest value was observed under NTS, higher than CT (lowest) by 40.7, 35.0, and 20.3% at 0–5, 5–10, and 10–20 cm layers, respectively.

Awanish, (2016) [3] reported that the greater variations among carbon fractions were observed at surface layer (0-5 cm).F_1= very labile, F_2=labile, F_3= less labile and, F_4=non-labile. At this depth, C fraction in vertisols varied in this order: $F_4>F_1>F_2=F_3$. Below 5 cm, the carbon fraction was in the order: $F_4>F_1>F_3>F_2$. For 15-30 cm depth it was in the order $F_4>F_1>F_2>F_3$. At lower depth, almost similar trend was followed as that of 30-45 cm. Regardless of tillage system, contribution of different fractions of carbon (C) to the TOC varied from, 33 to 41%; 9.30 to 30.11%; 8.11 to 26%; 30.6 to 45.20% for very labile, labile, less labile and non-labile fractions, respectively at 0-5cm depth. For subsurface layer (5-15cm), contribution of different fractions to the TOC varied from 27.8 to 40%; 7.80 to 12.40%; 11.11 to 19.0%; 38.0 to 50.0% for very labile, labile, less labile and non-labile fraction, respectively. In general, C contents decreased with increasing depth, mainly for very labile faction (F_1) which was contributing around 40% or more in surface and surface layers (0–5 and 5–15 cm) as compared to deeper layers (15–30 and 30–45 cm). Moreover, less labile and non-labile fractions contribute more than 50% of TOC, indicating more recalcitrant form of carbon in the soil.

Du *et al*. (2013) [16] reported that the NT system did affect the SOC stock distribution in the soil profile but not the total quantity. Tillage regimes obviously influenced soil aggregation distribution in the soil profile. In the upper 0.00-0.05 and 0.05-0.20 m layers, the NT system improved the formation level of the >2 mm aggregate but reduced the formation level of <0.053 mm aggregates, compared to the MP system suggesting that mechanical operation reduced large-macro-aggregate formation and disrupted soil macro-aggregates into individual particles. The aggregate-associated SOC concentration in different soil layers was influenced by tillage systems. In the 0.00-0.05 m layer, SOC concentration in macro-aggregates showed the order of NT+S>MP+S = NT-S>MP-S, whereas the NT system was superior to the MP system. However, the NT system significantly reduced the SOC concentration in the 2.00-0.25 mm fraction in the 0.05-0.20 m layer. A similar trend was observed in the 0.25-0.053 mm fraction in the 0.20-0.30 m layer. Across all the soil layers, there was no difference in the <0.053 mm fraction between NT-S and MP-S, as well as between NT+S and MP+S, indicating that the NT system did not affect the SOC concentration in the silt + clay fraction. In average across the soil layers, the SOC concentration in the macro-aggregate was increased by 13.5% in MP+S, 4.4% in NT-S and 19.3% in NT+S, and those in the micro-aggregate (<0.25 mm) were increased by 6.1% in MP+S and 7.0% in NT+S compared to MP-S. For all the soil layers, the SOC concentration in all the aggregate size classes was increased with straw incorporation, by 20.0, 3.8 and 5.7% under the MP system, and 20.2, 6.3 and 8.8% under the NT system. The higher proportion of >2 mm aggregates and lower proportion of <0.053 mm aggregates under NT systems might be the result of the higher soil hydrophobicity, low intensity of wetting and drying cycles, higher soil C concentration or the physical and chemical characteristics of large macro-aggregates making them more resistant to breaking up (Vogelmann *et al*., 2013) [49].

Dhaliwal *et al*. (2018) [15] revealed that the mean SOC concentration decreased with the size of the dry stable aggregates (DSA) and water stable aggregates (WSA). In DSA, the mean SOC concentration was 58.06 and 24.2% higher in large and small macro-aggregates than in micro-aggregates, respectively; in WSA it was 295.6 and 226.08% higher in large and small macro-aggregates than in micro-aggregates, respectively in surface soil layer. The mean SOC concentration in surface soil was higher in DSA (0.79%) and WSA (0.63%) as compared to bulk soil (0.52%).

Naresh *et al*. (2021) [39] revealed that average SOC stocks in the top 400 kg of soil dropped from 5.92 to 5.41 kg C m^{-2} (Table 2). Between 2009 and 2015, changes in important treatments were -1.88 ± 0.04 kg C m^{-2} in T8 (i.e., 5.41 to 4.89 kg C m^{-2}); -0.68 ±0.2 kg C m^{-2} in T10 (i.e., 5.93 to 5.28 kg C m^{-2}); -0.82 ±0.09 kg C m^{-2} in T_4 (i.e., 5.92 to 5.22 kg C m^{-2}); and -0.700 ±0.09 kg C m^{-2} in (i.e., 5.48 to 5.05 C m^{-2}). PLL-treated plants stored larger fractions of atmospheric carbon and, in certain circumstances, established equilibrium of C imports and exports. SOC stocks decreased after six years in TLL therapy. Over the six-year trial, similar trends in soil C content were seen in lower soil layers (i.e., 400–800 and 800–1200 kg of soil m^{-2}): the average over all PLL treatments was -0.070 ±0.06 and -0.020 ± 0.02 kg C m^{-2} in the 400–800 and 800–1200 kg of soil^{-2} intervals, respectively. This approximates an average yearly rate of change of -6.9 and -5.6 g C m^{-2} $year^{-1}$ for the mid and lower soil layers, respectively (Table 2). Due to associated errors during its calculation, SOC estimates in the 400–800 and 800–1200 kg m^{-2} layers were small. Over the entire 0 to 1200 kg m^{-2} soil depth, SOC stocks did not vary greatly under different land leveling treatments (Table 2). Under T_5, SOC increased from 22.33 to 24.31 kg C m^{-2} between 2009 and 2015. Changes were also observed in T11 (20.89 to 21.86 kg C m^{-2}), T7 (14.96 to 14.13 kg C m^{-2}), and T8 (13.08 to 12.35 kg C m^{-2}). Archived samples exposed that decomposition degree of SOC under T5, T8, and T7 was 1.5 times greater and significantly higher than that of R-W-S-R-WPLL with PLL and hence to evaluate the effect of applied treatments on SOC, previous year samples are certainly important (Potter, 2006) [40].

Between 2009 and 2015, the average SOC in 0–1200 kg m^{-2} of soil (i.e., around 1 m soil depth) in T8 treatments declined by -1.97+0.06 kg m^{-2}, from 13.08 to 12.35 kg C m^{-2}. SOC stocks in 0–1200 kg m^{-2} of soil grew by +1.98 kg m^{-2} (i.e., from 22.33 to 14.13 kg m^{-2}) in T5 (i.e., from 22.33 to 24.31 kg m^{-2}) and +0.83 ±0.3 kg m^{-2} in T7 (i.e., from 14.96 to 14.13 kg m^{-2}) in T5 (i.e., from 22.33 to 24.31 kg m^{-2}.

Table 2: Annual rate of change in multiple soil mass intervals and variations in SOC stocks from 2009 and in 2015 [Source: Naresh *et al*., 2021] [39]

Soil Organic Carbon												
Crop Sequence	**0-400 kg of Soil m^{-2} (Approx. 0-30 cm)**			**SOC Change Rate g of Cm^{-2} $year^{-1}$**	**400-800 kg of Soil m^{-2} (Approx. 0-30 cm)**			**Annual SOC Change Rate g of cm^{-2} $year^{-1}$**	**800-1200 kg of Soil m^{-2} (Approx. 0-30 cm)**			**SOC Change Rate g of Cm^{-2} $year^{-1}$**
	2009	**2015**	**Difference**		**2009**	**2015**	**Difference**		**2009**	**2015**	**Difference**	
T_1	8.12	9.11*	0.99 ± 0.2	46.2	5.47	5.57	0.10 ± 0.09	7.1	3.38	3.47	0.01 ± 0.11	4.4
T_2	5.48	5.05	-0.70 ± 0.09	-23.3	3.85	3.18	-0.09 ± 0.06	-6.1	2.92	2.57	-0.02 ± 0.02	-5.4
T_3	8.81	8.75	0.06 ± 0.05	25.7	5.82	5.31*	0.51 ± 0.2	4.5	2.93	2.67	0.26 ± 0.02	5.7
T_4	5.92	5.22	-0.82 ± 0.09	-21.4	4.05	3.98	-0.07 ± 0.09	-5.5	2.42	2.37	-0.05 ± 0.02	-4.2
T_5	9.18*	9.87	-0.69 ± 0.2	82.1	7.62	7.64	0.02 ± 0.2	8.8	5.04	5.08	0.04 ± 0.01	7.2
T_6	6.62	6.18	-0.79 ± 0.2	-13.6	5.36	5.27	-0.46 ± 0.07	-4.8	3.56	3.28	-0.18 ± 0.02	-1.8
T_7	7.46	7.15*	0.31 ± 0.03	28.2	5.39	5.65	0.26 ± 0.09	3.9	4.14	4.12	0.02 ± 0.01	1.8
T_8	5.41	4.89	-1.88 ± 0.04	-67.8	3.35	3.08	-0.07 ± 0.06	-6.9	2.72	2.37	-0.02 ± 0.02	-5.6
T_9	8.98*	9.77	0.79 ± 0.2	57.4	7.03	7.11	008 ± 0.2	1.5	3.72	3.81	0.09 ± 0.11	5.1
T_{10}	5.93	5.28	-0.68 ± 0.2	-19.4	4.05	3.98	-0.07 ± 0.09	-5.5	2.42	2.37	-0.05 ± 0.02	-3.9
T_{11}	9.15	9.29	0.14 ± 0.9	19.6	5.72	5.88	0.16 ± 0.09	7.3	4.57	4.58	0.01 ± 0.01	0.6
T_{12}	6.01	5.75	-0.70 ± 0.09	-16.3	4.85	4.18	-0.31 ± 0.09	-5.1	3.42	3.37	-0.15 ± 0.02	-2.4

Dai *et al*. (2020) [14] reported that the WSOC contents were higher in NPKS2 than in NPK in the 0–5, 5–10, and 10–20 cm soil layers and in CK in all soil layers (Fig.6). WSOC was 0.53 to 1.04% of the total SOC in all soil layers, and WSOC/SOC of NPKS2 was higher than other treatments in the 0–10 cm layer. The HWSOC, EOC, and POC contents were higher in NPKS2 than in NPK and CK in all soil layers (Fig. 6). HWSOC comprised 2.83 to 4.25%, EOC from 17.34 to 33.81%, and POC from 21.49 to 38.26% of total SOC. The HWSOC/ SOC ratios were highest in NPKS2 in 0–5 cm soil layer, and the ratios were higher in NPKS2 and NPKS1 than in NPK and CK in the 5–10 soil layer. The EOC/SOC ratios were higher in NPKS2 and NPKS1 than in CK in all layers and the POC/SOC ratios were higher in NPKS2 and NPKS1 than in CK in 0–5 and 5–10 soil layers. The MBC contents were higher in NPKS2 than in NPK in the 0–5, 5–10, and 10–20 cm soil layers and in CK in all soil layers (Fig. 6). Similarly, the LFOC contents were higher in NPKS2 than in NPK in the 10–20 and 20–30 cm soil layers and in CK in all soil layers. MBC constituted 2.21 to 2.72% and LFOC from 7.37 to 17.60% of total SOC. The MBC/SOC and LFOC/SOC ratios were higher in NPKS2 and NPKS1 than in CK in the 0–5 and 5–10 cm soil layers and the LFOC/SOC ratio was higher in NPKS2 than in CK in the 10–20 cm soil layer.

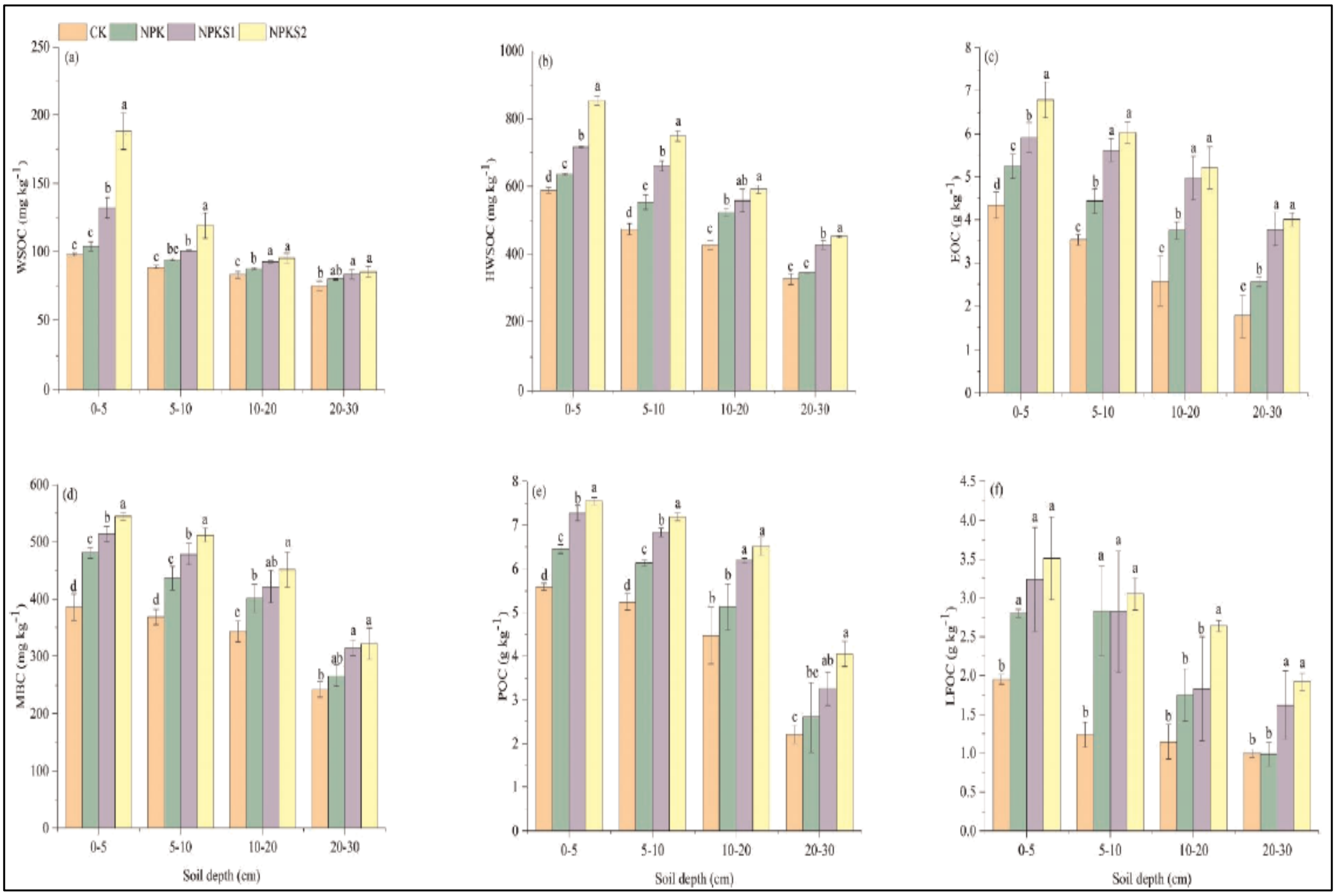

Fig 6: The effects of straw incorporation on labile organic C fractions (WSOC, water soluble organic C; HWSOC, hot-water soluble organic C; EOC, easily oxidizable C; MBC, microbial biomass C; POC, particulate organic C; LFOC, light fraction organic C) in the soil layers of 0–5, 5–10, 10–20, and 20–30 cm. CK: unfertilized control; NPK: N, P, and K fertilizers; NPKS1: wheat straw incorporated at a moderate rate of 3000 kg ha^{-1} plus NPK fertilizers; NPKS2: wheat straw incorporated at a high rate of 6000 kg ha^{-1} plus NPK fertilizers [Source: Dai *et al*., 2020] [14].

Mandal *et al*. (2021) [32] also found that the SOC pool in different layers (0- 5 cm, 5- 20 cm, 20 - 40 cm, 40 - 60 cm, 60 - 80 cm and 80 - 100 cm) differed among tillage and residue treatments (Fig. 7a). The initial SOC pool in surface 0 - 20 cm was 15.24 Mg ha^{-1} and increased to 18.20, 18.17, 17.18 Mg ha^{-1} in ZT, RT and CT with R and 16.07, 16.4 and 15.98 Mg ha^{-1} in NR plots. The beneficial effect of no-tillage and residue effect on SOC pool did not percolate to the sub-surface soil layers. The SOC pool in 0 -100 cm depth was increased by 4.1%, 6.5% and 6.3% in ZT, RT and CT, respectively over that of the initial value of SOC during 2012. The application of residue increased the SOC pool by 9.2% over the initial pool whereas it was just 2.1% increase in NR plots. SOC pools increased 7.4% and 3.9% over the initial value in rice-rice and rice-cotton system, respectively.

The intensity of tillage and the quantity of residue retained on the surface govern the SOC dynamics (Srinivasarao *et al*., 2012). In CTR, the surface layer SOC pool was lower than in RTR and ZTR with residue as intensive tillage practices promote rapid oxidation of organic matter and breakdown of soil aggregates lowering physical protection, which ultimately causes loss of C as CO_2 (Alvarez *et al*., 2014) [1] as well as release and depletion of nutrients (Hassan *et al*., 2016) [25]. Under CTR, the high SOC content and pool in sub-soil (20–40 and 40–60 cm) layers in comparison to ZTR could be on account of the incorporation of C rich crop residues under the CTR systems (Hassan *et al*., 2016) [25] and it was distributed almost uniformly in the various soil layers. Blanco-Canqui *et al*. (2011) [6] and Munoz-Romero *et al*. (2017) [34] have also reported that under CT the sub-soil layer had higher SOC content than that in the ZT system. In ZTR, the positive effects of mulching on the concentration and pools of SOC observed only within the top 20 cm soil layer could be due to majority of the released C through decomposition and mineralization being limited mostly in the surface layer (Fontaine *et al*., 2007). Consequently, the influence of mulches applied on the surface on soil properties was less in the sub-soil (below 20 cm depth).

Dai *et al*. (2020) [14] observed that the SOC content decreased with the increasing soil depth in every treatment (Fig. 7b). The SOC contents were higher in NPKS2 than in NPK in the 20–30 cm soil layer and in CK in all soil layers.

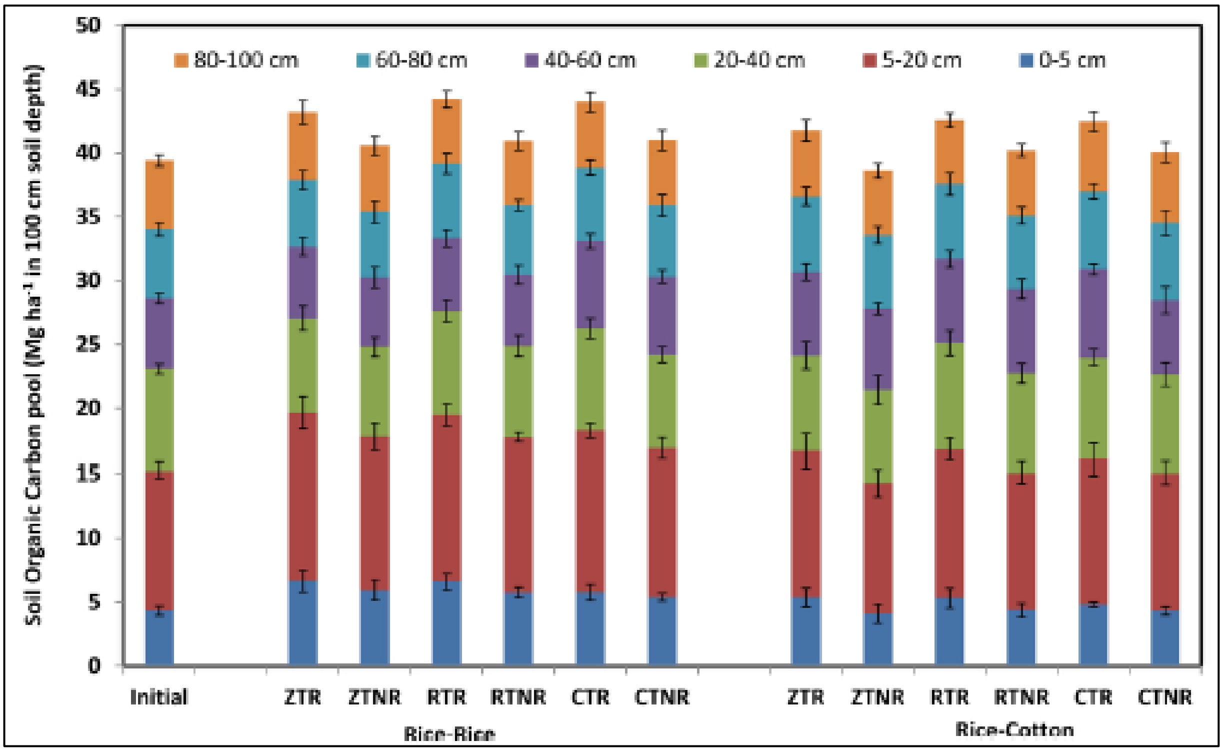

Fig 7a: Depth distribution of soil organic carbon (SOC) pool under different tillage and residue treatments in rice-rice and rice-cotton systems. ZTR, Zero tillage with residue; ZTNR, Zero tillage with no residue; RTR, Reduced tillage with residue; RTNR, Reduced tillage with no residue; CTR, Conventional tillage with residue; CTNR, Conventional tillage with no residue [Source: Mandal *et al*., 2021] [32]

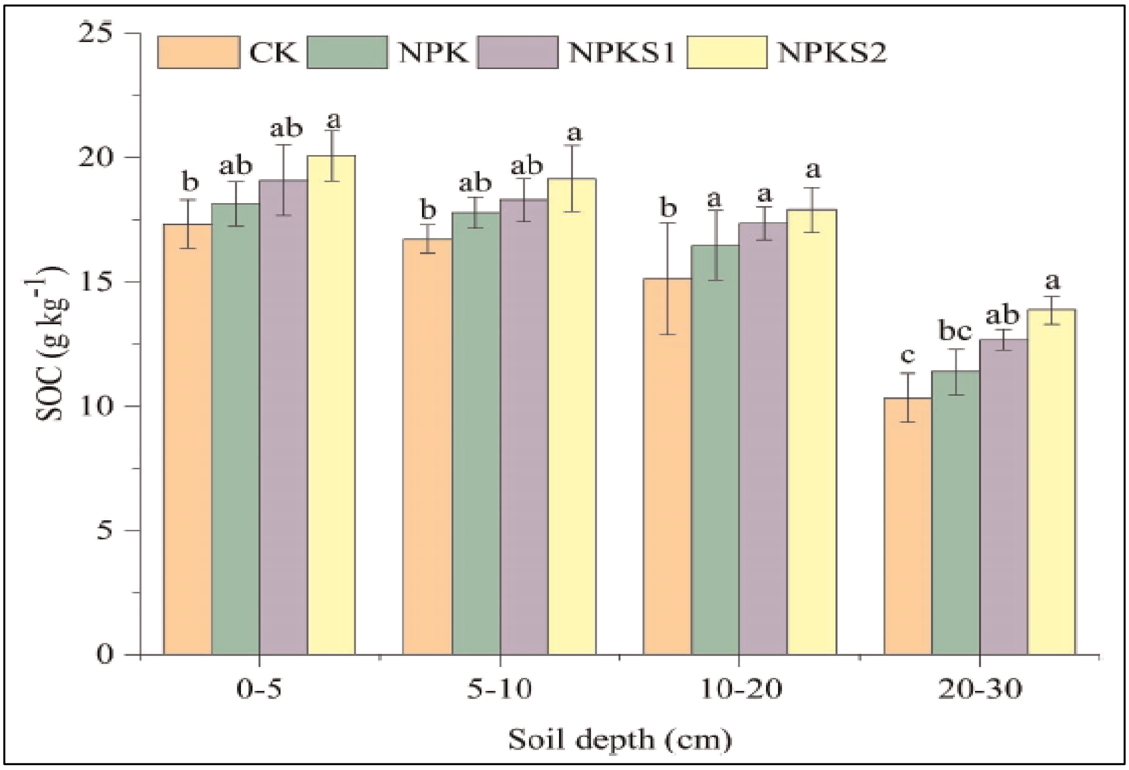

Fig 7b: The effects of straw incorporation on SOC in the soil layers of 0–5, 5–10, 10–20, and 20–30 cm. CK: unfertilized control; NPK: N, P, and K fertilizers; NPKS1: wheat straw incorporated at a moderate rate of 3000 kg ha^{-1} plus NPK fertilizers; NPKS2: wheat straw incorporated at a high rate of 6000 kg ha^{-1} plus NPK fertilizers [Source: Dai *et al*., 2020] [14].

Awale *et al*. (2017) [2] observed that proportions of labile C and N pools in SOM showed variation among treatments, with significant differences observed for POXC/SOC, Cmin/SOC, and POM-N/TN. POXC/ SOC was lower under GP than under cultivated treatments. Cmin/SOC was significantly lower under FP than under DT/CT and SP treatments, while GP and NT had intermediate levels of Cmin/SOC. POM-N/TN was higher under NT and DT/CT treatments compared to plow-tillage treatments and GP. In general, POM-C/SOC and MBC/SOC were lower, while N-pools in TN were higher under GP than under cultivated treatments, although such differences were not statistically significant ($P > 0.05$). On average, SOC had 22.8% POM-C, 3.6% POXC, 0.9% WEOC, 2.9% MBC, and 3.3% Cmin. Similarly, TN constituted about 17.1% PON, 1.9% TDN, and 4.9% MBN, and 1.1% KEN.

Naresh *et al*. (2017) [37] reported that the WSC was found to be 5.48% higher in surface soil than in sub-surface soil. In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to CT, FIRB and ZT coupled with 6tha-1 CR increased 35.6% WSC in surface soil and 33.1% in sub surface soil. Among all the treatments, T_6 had significantly higher (19.73%) proportion of WSC than the other treatments compared. Irrespective of tillage practices, residue retention resulted in 22.56% and 25.61% higher WSC as compared to the non-residue treatments in surface and subsurface soil, respectively. The microbial biomass carbon (MBC) is an important component of the SOM that regulates the transformation and storage of nutrients. The soil MBC regulates all SOM transformations and is considered to be the chief component of the active SOM pool. It is evident that the MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 100% RDN as CF+ VC @ 5tha^{-1} (F_5) and 75% RDN as CF+ VC @ 5tha^{-1} (F_4) treated plots compared to 100% RDN as CF (F_2) fertilizer and unfertilized control plots. The values of MBC in surface soil varied from 116.8 mgkg^{-1} in unfertilized control plot to 424.1 mgkg^{-1} in integrated nutrient use of 100% RDN as CF+ VC @ 5tha^{-1} plots, respectively; while it varied from 106.6 mgkg^{-1} (control) to 324.9 mgkg^{-1} (100% RDN as CF+ VC @ 5tha^{-1} F_5) in subsurface (15-30 cm) soil layer. The values of MBC increased by 72.5 and 58.4% under 100% RDN as CF+ VC @ 5tha^{-1} (F_5) and 75% RDN as CF+ VC @ 5tha^{-1} (F_4) treatment in surface soil over control. The values of LFC in surface soil (0-15 cm) were 81.3, 95.7, 107.8, 128.8, 155.2, 177.8 and 52.7 mgkg^{-1} in ZT and FIRB without residue retention, ZT and FIRB with 4 and 6 tha^{-1} residue retention and CT treatments, respectively.

Naresh *et al*. (2021) [39] also found that after six years, more SOC stores were discovered in the surface 400 kg of soil m^{-2} under T_9 or T_5 compared to T_8. T_8 lost more SOC than T_9 or T_5 with PLL, despite the fact that the temporal difference was not judged significant. Given the parameters of this experiment, it is likely that more than 06 years will be necessary to identify variations between the examined cropping systems and land levelling procedures in the surface 400 kg of soil m^{-2} (approx. 30 cm). SOC stores in the 400–800 kg soil m^{-1} range were found to diminish after only 06 years under T_8, but remained constant under T_9 and T_5. Leveling choices have no effect on SOC stores in the 800–1200 kg of soil m^{-2} range. Comparison between old and fresh soil samples revealed that higher fraction of carbon was recorded in the T_9 and T_5 plots where PLL followed than T_8 plots where TLL was practiced. Further, plots under TLL with time lost the SOC. The yearly SOC change rate (g of cm^{-2} year^{-1}) under both alternative cropping systems and precision land leveling practices indicated that rice-black gram-autumn sugarcane-ratoon sugarcane-wheat, maize-autumn sugarcane-ratoon sugarcane-wheat, rice-potato-spring sugarcane-ratoon sugarcane-wheat, rice-mustard-spring sugarcane-ratoon sugarcane-wheat, rice-pea-spring sugarcane-ratoon sugarcane-wheat, and rice-wheat-late spring sugarcane-ratoon sugarcane wheat under precision laser leveling showed the positive SOC than traditional laser leveling (Fig. 8a)

Wankhede *et al*. (2020) also found that SOC mineralization from macro- and micro- aggregates was 34 and 28% higher than s + c across the treatments. The s + c fraction of NPK + FYM had ~ 41, 40 and 24% higher C decay rate than NPK plots at 25, 35 and 45 °C, respectively (Fig. 8b).

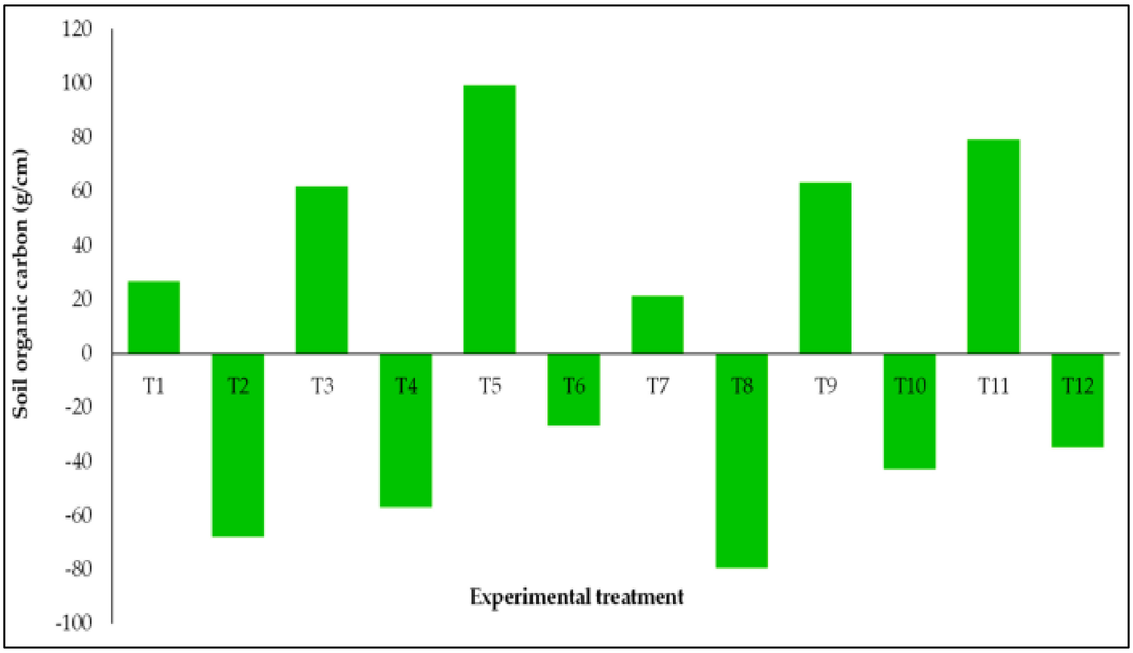

Fig. 8a: Yearly SOC change rate (g of cm^{-2} year^{-1}) under alternative cropping systems and precision land leveling practices [Source: Naresh *et al*., 2021) [39].

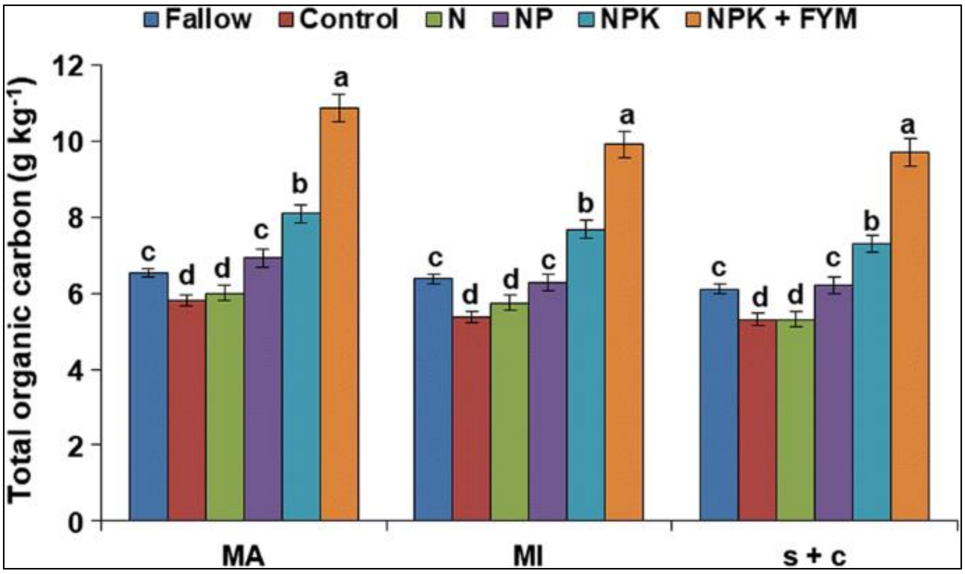

Fig 8b: Soil organic carbon quality or quantity govern relative temperature sensitivity in soil aggregates [Source: Wankhede *et al*., 2020]

Distribution of organic carbon pool, sequestration and retention efficiency

Mandal *et al*. (2021) [32] reported that the SOC concentration differed significantly among treatments and depths. Rice-rice system recorded more SOC than rice-cotton system. All plots receiving crop residue amendments had higher SOC concentration in the surface and sub-surface soil compared with those where no residue was added. Highest SOC concentration of 0.969% in the surface layer (0-5 cm) was observed in the ZTR under rice-rice system. With the increase in depth, the SOC level decreased. After seven years of experimentation, SOC was maximum in ZT followed by RT and CT and in the surface soil layer (0- 20 cm depths) it increased 13.6, 12.6 and 8.9% in ZT, RT and CT respectively over the initial SOC level during 2012. The increase was more in R than NR plots. Saurabh *et al*. (2021) [41] reported 18% increase of SOC in 0-10 cm soil depth under ZT over CT. In contrast, SOC was higher in RT and CT than ZT in soils below 20 cm of soil depth. The weighted average profile SOC concentration in 0- 100 cm soil depth increased from 2.64 g kg^{-1} in 2012 to 2.91, 2.94 and 2.94 g kg^{-1} in ZT, RT and CT with R plots and 2.66, 2.72 and 2.72 g kg^{-1} in NR plots, respectively.

Naresh *et al*. (2018) [38] reported that SOC concentrations in both NPK and NPK+FYM treatments were higher than the control treatment. Compared to the RDF treatment also, the NPK+FYM treatment had higher SOC concentration in all the TCE. The highest increase in SOC in the NPK+FYM treatment was observed in F_6 with TCE T_6. In comparison with the control, the mean rate of SOC build-up during the 16 years of cropping was the highest in F_6 with T_6 (50.63%) and the lowest in F_1 with T_7 (9.79%). It was estimated that 30 per cent of applied C through FYM was stabilized, and the rest (70 per cent) was lost through oxidation. However, highest carbon sequestration potential change (88.2%) was found in T^3 zero tillage with 6tha^{-1} residue retained plots followed by T_2 zero tillage with 4tha^{-1} residue retained plots (84.7%) and T_6 permanent raised beds with 6tha^{-1} residue retained plots (80.1). The use of T_1 zero tillage without residue retained and T_4 permanent raised beds without residue retained for sixteen crop cycle increased carbon sequestration potential by 24.4% and 23.1% more than that of T_7 conventional tillage, respectively. The final SOC concentrations in both NPK and NPK+FYM treatments were higher than the control treatment. Compared to the NPK treatment also, the NPK+FYM treatment had higher SOC concentration in all the nutrient management practices. The highest increase in SOC in the 50% NPK by CF+50% NPK by FYM treatment was observed.

Das *et al*. (2014) [12] reported that CT significantly reduced soil bulk density and enhanced organic carbon content, microbial biomass C, and sustained the activity of the soil organisms. Mutema *et al*. (2013) [35] also demonstrated that conservation tillage practices with reduced tillage and crop cover enhance macro-fauna activities, their abundance, and diversity. Reduced risk of soil erosion; better soil quality (through enhancing organic matter content); improved fertility status; water infiltration rate and storage capacity; flora and fauna populations; stability of agro-ecosystem; energy use efficiency; and improved crop yield are also reported as a positive influence of CT practices (Iqbal *et al*., 2005) [26]. Under a no-till system, a substantial amount of C is added to the soil when crop residues are left on the surface of the soil, while minimum tillage reduces soil disturbance, thereby slowing the residues' incorporation and lowering the susceptibility to physical disruptive forces, which in turn reduce the mineralization rates of organic matter. Similarly, under a reduced tillage system, the retention of crop residues (including stubbles and root biomass) increases SOC, which in turn creates a physical barrier between the substrates and soil microbes to form the stable micro-aggregates and macro-aggregates that protect the microbial decomposition (Tripathi *et al*., 2014) [46].

Conclusions

The conjoint use of NPK and organics, particularly FYM and GR, had positive effects on labile fractions (PmOC, MBC, C_{VL}, C_L) compared with stabilized fractions of SOC. Conversely, continuous incorporation of CR led to accumulation of relatively stable passive fractions (C_{LL} and C_{NL}). Labile fractions of SOC showed far more consistent positive relationships with crop yields than stabilized fractions of SOC. Among the SOC fractions, MBC, C_{VL} and C_{LL} appeared to be more sensitive to changes in nutrient management. Soil management through the use of different tillage systems affects soil aggregation directly by physical disruption of the macro-aggregates, and indirectly through alteration of biological and chemical factors. Crop residue plays an important role in SOC sequestration, improving soil organic matter. Tillage reduction and residue retention both increased the proportion of soil organic matter as microbial biomass.

Conventional tillage decreased the stocks of carbon organic soil and its labile fractions in both the top and the subsoil (20-100 cm). The reduction of POC in topsoil was mainly motivated by a decrease in fine POC, while DOC was mainly reduced in the subsoil. The LOC fractions also decreased to SOC ratios, suggesting a decline in carbon efficiency as a result of tillage and residue management. Reduced LOC fractional stocks in the subsoil may be partly explained by the decline in subsoil fine root biomass, with implications for SOC stocks.

Treatment involving 50 per cent recommended dose of N supplied through chemical fertilizers and another 50 per cent through FYM reduced the depletion of SOC stocks. However, most ≥ (7 per cent) of the C supplemented through FYM in this climate was mineralized and only a small fraction ≥ (23 per cent) was stabilized into SOC stock. The rate of addition of organic amendments should be at least doubled to reduce SOC depletion and increased considerably to enhance the SOC stock. Increased SOC stock in the surface 50 kg m^{-2} under ZT and PRB was compensated by greater SOC stocks in the 50-200 and 200-400 kg m^{-2} interval under residue retained, but SOC stocks under CT were consistently lower in the surface 400 kg m^{-2}. Thus, conjunctive use of 50% FYM+50% RDF is viable option for curbing SOC depletion and sustaining soil health. Thus, the review study infers that nutrient supply options involving FYM, FYM+GR or SPM along with NPK would support higher nutrient availability of RWS in the IGP. In view of the scarcity of organic manure and reluctance on the part of farmers to use conventional (*Sesbania aculeata* L.) green manure in the northwest IGP, raising short-duration green gram after the wheat harvest and recycling the GR after pod picking may prove an ideal IPNS practice to improve soil health.

The need for drawdown solutions is progressively urgent and soil C sequestration through agricultural management practices warrants far better consideration from climate experts. Most, if not all, of the agricultural management practices that promote carbon sequestration also improve soil aggregate stability, water retention capacity, and soil fertility. These noteworthy co-benefits should serve as incentives for augmented action. The significant discussion over the potential of soil CS will remain a bridge to the future. The protection dynamics along with soil C cycles are still not fully demonstrated in all locations on the globe, and variable patterns of land management make it difficult to predict the adoption of agricultural management practices that can sequester C. Nevertheless, a comprehensive understanding of soil C and the sequestration potential should not be a prerequisite for action. Recently, various research on different agricultural management practices has introduced numerous strategies to increase the sequestering of atmospheric C. Compared to a number of other atmospheric drawdown strategies, the adaptation of conservation tillage practices is relatively more effective and could be adapted in the near future. In this system, the risks are minimal while the known benefits of improving soil quality and sequestering C are numerous.

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