Climate Smart agricultural practices improve soil quality through organic carbon enrichment and lower greenhouse gas emissions in farms of bread bowl of India

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Abstract

Potential impacts of “Climate Smart” agricultural practices were studied on working farms in Karnal, Haryana, India. Practices included zero tillage, crop residue retention, and crop diversification . Impacts considered were soil physical and chemical properties and greenhouse gas emissions (estimated by the Climate Change Agriculture and Food Security- Mitigation Option Tool). Farmers following either practices of Climate Smart agriculture or conventional agriculture were surveyed. Soil samples were collected at 0 – 20 cm depth under wheat grown in the winter season. Of the 70 farmers surveyed, 22 followed Climate Smart agriculture while 48 farmers used conventional practices. For Climate Smart agriculture compared to conventional practices, soil pH was lower (7.76 compared to 7.99), and soil carbon was enriched (Walkley-Black carbon is 0.19% higher compared to 0.13%, total organic carbon stock is 32.03 Mg ha^{-1} compared to 25.26 Mg ha^{-1} and total carbon is 0.24% compared to 0.16%). Significant interactions between farming type, pH and organic carbon, gravimetric and volumetric water content were observed. Conservation agriculture registered ~31% higher soil quality index over conventional practice. Total organic carbon stock, inorganic carbon and gravimetric water content were identified as key soil quality indicators. Higher wheat grain yield (5.99 t ha^{-1}) was observed under conservation agriculture over conventional (5.49 t ha^{-1}). Greenhouse gas emissions were estimated to be 63% higher from conventional practices than from Climate Smart agriculture. We conclude that Climate Smart agricultural practices improve soil properties through enrichment in soil organic carbon at the same time as reducing emissions of greenhouse gases.

Keywords: Conservation agriculture, soil properties, soil organic carbon, CCAFS-MOT

Introduction

Human civilization is currently at risk due to climate change and food insecurity; both of these issues are linked to earth’s carbon (C) cycle (Mandal 2011). The atmospheric concentration of carbon dioxide (CO_2) has already reached 400 ppm (Datta *et al.* 2015). Climate change is linked to extreme weather events, such as droughts and floods, and these can cause crop failure (Iizumi and Ramankutty 2015). As a result of this, large-scale migration of people is likely to occur in the near future; a recent study conducted in sub-Saharan Africa, South Asia and Latin America by the World Bank suggested that climate change will result in large scale within country and cross-border migration, creating "hotspots" where large numbers of people live in crowded slums (Rigaud *et al.* 2018). More than 140 million people in three regions of the developing world, accounting for 55% of the population, are likely to be internally displaced between now and 2050; 86 million people in Sub-Saharan Africa, 40 million in south Asia and 17 million in Latin America (Rigaud *et al.* 2018). Such large scale movements of people could cause huge disruption to governance and economic and social development.

The World Bank suggested that it is still possible to avoid the worst effects of this migration. Although climate driven migration in the near future is unavoidable, a crisis could be avoided if strong and bold action is taken now. The World Bank suggested three key actions points for governments; accelerated reduction of greenhouse gas (GHG) emissions, incorporation of climate change migration into national development planning, and investment in further data and analysis for use in planning and development. The predicted 140 million migrants by 2050 follows current trends, but this could be reduced if these changes are made. In addition to more inclusive economic development and strong action is taken on GHG emissions, this number may be reduced to between 30 million and 70 million (Rigaud *et al.* 2018).

Climate change is likely to have most impact on the poorer and more vulnerable people of the world, making agriculture difficult in many areas, reducing availability of water while also increasing the likelihood of floods, droughts and heatwaves, with rising sea levels and storm surges hitting low lying coastal areas, such as Bangladesh (Rigaud *et al.* 2018). Nevertheless, Rigaud *et al.* (2018) suggested that there is an opportunity to plan now and act for emerging climate change threats.

In India, the harmful effects of climate change are already visible. Government of India (2018) observed that the impacts of changes in temperature and rainfall are only a problem under extreme conditions, but this is already apparent in long-term trends of rising temperatures, declining average precipitation and increasing extreme precipitation events. In India, there is likely to be significantly more adverse impacts of climate change in areas without irrigation where rain-fed crops are grown, than in irrigated areas which usually grow cereals (Economic survey of India 2018). Projected long-term weather patterns suggests that annual agricultural incomes could be reduced due to climate change by an average of 15 to 18% in irrigated areas, and up to 20 to 25% for non-irrigated areas (Economic survey of India 2018).

The Food and Agriculture Organization defines Climate Smart agriculture (CSA) as "agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces/removes GHGs (mitigation) where possible, and enhances achievement of national food security and development goals" (https://csa.guide/csa/what-is-climate-smart-agriculture). Recently CSA practices based on conservation agriculture (CA) principles have become popular among the farmers of North West India; because of that the Government of India is encouraging the adoption of CSA practices to cope with extreme weather events. Climate Smart agriculture addresses the impacts of limitations due to weather, nutrients, water, carbon (C), knowledge, and information and communication technologies (CIMMYT-CCAFS 2014).

Climate Smart agriculture is based on the three interlinked pillars of productivity, adaptation, and mitigation (http://www.fao.org/3/a-i3325e.pdf), using management practices, such as residue retention, zero tillage, water and nutrient management, and crop diversification, as an alternative to conventional (business as usual) practices to achieve sustainable intensification. Significant quantities of farmyard manure (FYM) are used by the farmers for fuel purposes (on average 40%, Datta *et al.* Unpublished), thereby reducing the organic inputs to soil. In these circumstances, zero tillage with residue retention may serve as an alternative to FYM for maintaining soil C.

Since, 2010, with support from the Consultative Group on International Agricultural Research (CGIAR) research programme on Climate Change Agriculture and Food Security (CCAFS), 25 Climate Smart villages were established in Karnal district, Haryana, India. Technical guidance on CA based practices was provided to the farmers. Many studies have been done in controlled experiments to look at the improvement in soil quality with CSA practices (Jat *et al.* 2018a; Choudhary *et al.* 2018*a*,*b*), water use efficiency (Kakraliya *et al.* 2018*b*), C sequestration (Powlson *et al.* 2014), energy efficiency (Parihar *et al.* 2017) and overall sustainability (Jat *et al*. 2018b). Aryal *et al.* (2016) studied the adaptability of CA based wheat to cope with extreme weather events, particularly focussing on untimely excess rainfall. More recently, Aryal *et al.* (2018) studied the adoption behaviour of multiple CSA practices by farmers in Gangetic plains of Bihar, India.

To maintain global food and environmental security, it is important to understand the dynamics of organic C in agricultural soils. About 25% of the world's population and more than 22% of the global wheat area is in South Asia (Jat *et al.* 2018b). Wheat is grown in an area of 30 M ha in India. To feed the rising population, demand for wheat is expected to increase over the coming decades, particularly in the developing world. South Asia is likely to be worst affected by climate change in the 21st century, and large declines in yield are predicted for most crops (Jat *et al.* 2018b). During the wheat growing season

(November to March) in South Asia, it is predicted that there will be severe reductions in absolute precipitation and the mean annual temperature will increase to over 2°C above the late-20th-century baseline. Temperature, precipitation and atmospheric CO_2 levels can affect the wheat crop, both directly at plant level and indirectly through changes in soil processes, nutrient transformations and incidence of disease pests (Jat *et al.* 2018b). As a result, in substantial areas of India, the yield of both irrigated and rainfed wheat are predicted to be reduced (Nelson *et al.* 2009; Ortiz *et al.* 2008).

The CSA practices have been scaled-out from experimental plots to farmer's field, but no study has yet been completed of the effect of those CSA practices on soil physical and chemical properties as well as overall soil quality, the organic and inorganic C content of soils, and GHGs emissions. Recently Somasundaram *et al.* (2020) also emphasized the importance of quantifications of organic carbon storage and other tangible and intangible benefits of conservation agriculture in farmer's fields. We hypothesised that soils under CA would have improved soil quality with higher soil organic C contents and lower GHG emissions than soils under conventional tillage. Here we report measurements of the impact of CSA practices on physical and chemical properties and soil C, soil quality indices and estimates of GHG emissions provided by the Climate Change Agriculture and Food Security - mitigation option tool (CCAFS-MOT) for farmers' fields in villages of Karnal.

Methods

Site description

Karnal (29.7820°N and 76.9182°E) is one of the 22 districts of Haryana (Fig. 1). The area is about 2520 km^2, with a population of little over 1.5 million (2011 Census). It has five tehsils/subdivisions, namely Karnal, Nilokheri, Indri, Gharaunda and Assandh. Approximately 73% of the population lives in rural villages and primarily depends on agriculture for their livelihoods. The region is a hot semi-arid eco-region, receiving a mean annual rainfall of 847 mm, and mean annual minimum and maximum temperatures of 10.5 and 41.6°C, respectively. The weather data for the last ten years is presented in Supp. Table 1. The soil of the studied villages is silty clay loam (hyperthermic, Typic Haplustept; Sachdev et al. 1995).

Soil and crop management systems

We surveyed 70 farmers of 12 villages of Karnal district, Haryana. Information on crops grown, management practices followed was collected through meetings with groups of farmers from each of the villages. The district lies on the bank of river Yamuna. The survey showed that wheat was the main crop grown in the *rabi* season (crops sown in winter and harvested in the spring). We collected soil samples after harvesting of *rabi* season crops namely wheat, mustard, chickpea, sugarcane, garlic and berseem (Table 1) from farmers fields (Fig. 1). For comparison purpose, wheat crop was selected and found that 22 farmers followed CA based wheat and 48 farmers followed conventional tillage based wheat crop. CA has been used by the farmers for at least 8-10 years.

In conventionally grown wheat, farmers generally prepared the land using an average of 2 passes of the harrow and one pass of the cultivator, followed by planking and broadcasting of seeds. A further tillage was then done with a cultivator to press the seeds into the soil followed by planking. Farmers usually applied 125 kg ha^{-1} DAP (18% N, 46% P_2O_5), and 62 kg ha^{-1} muriate of potash (MOP) (60% K_2O) as a basal dressing, and 375 kg ha^{-1} urea (46% N) by broadcasting in three equal split applications between 20-25, 35-40 and 50-55 days after sowing. In CA, a Turbo seeder (Happy seeder) was used to sow wheat seeds into the rice residues without ploughing the land, and a basal dressing of 125 kg ha^{-1} inorganic fertiliser (diammonium phosphate (DAP); 18% nitrogen (N), 46% P_2O_5) was applied, followed by a further 312 kg ha^{-1} urea, applied by broadcasting, equal split applications between 20-25, 35-40 and 50-55 days after sowing. In addition, in both cultivation systems, 7.5 kg ha^{-1} sulphur was applied 20-25 days after sowing, and two treatments of herbicides for grasses like *Phalaris minor* (Topik - 240 g dm^{-3} Clodinafop-Propargyl 15 WP, 60 g dm^{-3}) and broadleaf weeds (Metsulfuron methyl 20% WG) were applied once after 25-30 DAS by mixing both the herbicides and later based on the weed population. In garlic, rice residues were used as mulch, which not only served to maintain the soil temperature, but also supplied additional organic C and nutrients to the crops. In sugarcane, huge quantities of trash were retained in the field (Fig. 2) while the top portion of the cane was used as a fodder.

Soil sampling and analysis

Three replicated soil samples from each field were collected at 0-20 cm soil depth after harvesting of each of the crops from all the farms in winter-spring *rabi* season of 2018. Samples were dried, ground and sieved with a 2.0 mm sieve and stored. Soil samples were collected using a metal core sampler for bulk density (BD) analysis (Black and Hartge 1986). Gravimetric water content (GWC) and volumetric water content were measured by following Black (1965).

GWC (g water/g of soil) = (Wt. of moist soil – wt. of dry soil)/wt of dry soil

Volumetric water content (cm^3 of water/cm^3 of soil) = GWC × bulk density

Soil pH (soil: water 1:2 by volume) and electrical conductivity (EC) (soil: water 1:2 by volume) were determined using standard methods (Jackson 1973).. Inorganic C was calculated by multiplying the $CaCO_3$ concentration as determined by a manometric method using Collin's calcimeter by the proportion of C in $CaCO_3$ (0.12) (Chandel *et al.* 2021). Organic C content of the soils was determined following the Walkley Black method (Walkley and Black 1934). Total organic C was estimated by multiplying by 1.28, the Walkley Black correction factor for soils of semi-arid regions of India (Bhattacharyya *et al.* 2015). Total organic C and inorganic C were summed to determine total C.

Soil quality indexing

Soil quality indexing was done for the soils collected from fields of farmers following CA (22) and CT (48) based wheat separately. For soil quality indexing purposes few steps were followed. Firstly, minimum data set (MDS) of soil quality indicators were selected through principal component analysis (PCA) which best represent the soil function. Then scoring of the MDS indicators based on their performance of soil function, and lastly integrating the indicator scores into a comparative index of soil quality (Sharma *et al.* 2005; Choudhary *et al.* 2018a). Through PCA the dataset (of 10 attributes) was reduced to a minimum dataset of soil quality indicators (Andrews *et al.* 2002). The principal components with higher eigen values and variables with higher factor loading were assumed to be the variables which best represented system attributes. Therefore, we examined only the PCs with eigen values > 0.9 and those that explained at least 5% of the variation in the data. The highly weighted factors within each PC were retained for MDS. Highly weighted factor loadings were defined as having absolute values within 10% of the highest factor loading. In a single PC, when more than one factor were retained, multivariate Pearson's correlation coefficients were employed to check the redundant variables and therefore dropped from the MDS (Andrews and Carroll, 2001; Andrews *et al.* 2002). After finalization of the MDS indicators, each observation of MDS indicators was transformed to standardize its value using the non-linear scoring method of Bastida et al. (2006) by following the formula:

$y = a/ (1+(X/X_0)^{-b})$

where, a is the maximum value reached by the function, in our case, a =1, X is the unknown of the equation, corresponding to the value of the parameter in question in each case, X_0 is the mean value of each parameter corresponding to the soils of different treatments, b is the value of the slope of the equation. We obtained curves that fit a sigmoidal tending to 1 for all the proposed parameters using different values of b for different selected parameters. The above value (*y*) provides curves that vary between 0 and 1. The b value in the equation was optimized for different selected indicators to get an "S" shaped curve.

Using the PCA results the MDS variables for each observation were weighted. In the total data set, each PC explained a certain amount of variation (%). Dividing this variation by the total percentage of variation explained by all PCs with eigen vectors > 0.9, provided the weighted factor for variables chosen under a given PC. The MDS variables with weighted scores for each observation were then added using the following equation:

$$SQI = \sum_{i=1}^{n} W_i S_i$$

where S= indicator score, W= the weighing factor obtained from PCA.

Better soil quality or greater performance of soil function was associated with higher index scores.

Data such as wheat grain yield, amount of crop residue retention of previous rice crop and input use, input costs and farmers' perceptions regarding the impacts of CA on crop yield and resource use were collected during the meetings and discussions with the farmers.

Greenhouse gases estimation

The Climate Change, Agriculture and Food Security-Mitigation Option Tool (CCAFS-MOT) was used to estimate GHG emissions (Feliciano *et al.* 2015). Under different production systems, different combinations of empirical models are used to estimate GHG emissions. Site specific factors influencing GHGs emissions, such as soil properties, climatic characteristics, production inputs and other crop management practices, were entered into the CCAFS-MOT. Multivariate empirical models are used within CCAFS-MOT to estimate the background and fertilizer-induced emissions. The empirical models of Bouwman *et al.* (2002) and FAO/IFA (2001) are used to calculate N_2O (nitrous oxide) and NO (nitric oxide) emissions, and NH_3 (ammonia) emissions, respectively. The IPCC

N_2O Tier 1 emission factors are used to estimate emissions due to crop residue management. Emissions from production and transportation of fertilizers, are estimated using the Ecoinvent database (Ecoinvent Center 2007). The IPCC methodology was used to calculate changes in soil C due to tillage, FYM and crop residue management (Ogle *et al.* 2005; Smith *et al.* 1997). The IPCC methodology was also used to estimate CO_2 emissions from soil resulting from urea application (IPCC 2006). A global warming potential (GWP) of 34 and 298 times for CH_4 and N_2O, respectively, was used to estimate the overall GWP of the production systems (IPCC 2013) including emissions from the soil, operations such as tillage, inputs such as fertilizers, crop residue management and FYM applications. The GHG emission intensity was then obtained by dividing the total GWP by grain yield.

Statistical analysis

The normality of the data was tested using the Shapiro-Wilk test ($P<0.05$) for Normality using SAS software package 9.2 (SAS Institute 2010). The data were subjected to analysis of variance (ANOVA). A general linear model (GLM) was fitted using the GLM procedure from SPSS Windows version 16.0 (SPSS Inc., Chicago, USA). Treatment (CA and conventional) means for different parameters were separated by Independent sample T test using SPSS 16.0 software. Descriptive statistical analysis was carried out in MS Excel to determine the mean, median and standard error of the mean.

Results and discussion

Soil pH and electrical conductivity

Significant differences in soil pH and EC were observed between conventional and CA practices. Across all crops grown in the 70 farmers' fields, at 0-20 cm soil depth, EC was not normally distributed, with median value of 0.50 (±0.08) dS m^{-1} (standard error given in brackets), whereas soil pH was normally distributed, and was neutral to slightly alkaline with an average of 7.92 (±0.04) (Table 2). For crops grown using conventional practices, EC was also not normally distributed, with median value of 0.49 (±0.10) dS m^{-1}, whereas soil pH was normally distributed, and was neutral to slightly alkaline with an average of 7.99 (±0.05) (Table 2). In CA based crops, EC was also not distributed normally, with median value of 0.50 (±0.11) dS m^{-1}, whereas soil pH was normally distributed, and was neutral to slightly alkaline with an average of 7.76 (±0.07) (Table 2).

A significant interaction ($p<0.05$) between soil pH and farming type was observed, indicating significant differences in the soil pH of conventional and CA fields (Table 3). On average, soil pH in CA based wheat crop was 0.23 units lower than in a conventional wheat crop. In CA based practices, farmers leave rice crop residues (on average 8.1 t ha^{-1}, Supp. Table 2) on the soil surface and wheat is sown by the Happy seeder machine (Fig. 3). Upon decomposition of crop residues, organic acid are produced, thereby reducing the soil pH (Jat *et al.* 2018). Paul *et al.* (2003) showed that 4.25 t ha^{-1} residues added to the top 2.54 cm can reduce soil pH by 0.02 units. In some instances under conventional wheat crop, reduction in soil pH might also occur due to the incorporation of crop residues and FYM in soils. Singh *et al.* (2005) also reported a decrease in soil pH under crop residue incorporation in rice-wheat cropping systems. Somewhat higher soil pH was observed in soils where arable crops, such as mustard, chickpeas and berseem without crop residue retention or incorporation were included in the rotation (data not shown).

The difference in electrical conductivity was non-significant between CA based and conventionally grown wheat and other crops fields; the median value was similar in both systems. Soil is covered with crop residues in CA based fields and undisturbed, thereby potentially facilitating the accumulation of salts at the soil surface, although in controlled experiments, Jat *et al.* (2018) also observed that EC remained below harmful levels. In conventional wheat and other crops, tillage and incorporation of crop residues favours leaching of the salts with irrigation water resulting lower EC.

Bulk density

Values of BD were normally distributed in all the management practices. There was no significant difference between the average soil BD of conventionally grown and CA based wheat crops; the average BD of the soil samples was 1.34 (±0.01) Mg m^{-3} at 0-20 cm soil depth (Table 2).

In controlled experiments, Jat *et al.* (2018) also reported a non-significant change in BD under CA based practices compared to conventional practices. McVay *et al.* (2006) suggested a higher BD in surface soils of conventional practices occur due to machine induced compaction. Similarly, incorporation of crop residues in soil can result in lower BD in rice-wheat cropping systems (Singh *et al.* 2005). Soils with higher SOC are less prone to compaction (McVay *et al.* 2006), which may help explain why so little change in BD occurred in the CA-based scenarios studied here.

Soil moisture content

Gravimetric and volumetric water content were normally distributed irrespective of management practices. Significant variation in gravimetric and volumetric water content of soil was observed between CA and CT based wheat. Gravimetric water content in soil was significantly higher under CA system (0.27±0.02 g water per g soil) over CT system (0.21±0.02 g water per g soil) (t=2.06, p<0.05). CA based system also recorded significantly higher volumetric water content (0.35±0.02 cm^3 water per cm^3 soil) over CT system (0.28±0.02 cm^3 water per cm^3 soil) (t=2.09, p<0.05). Significant interactions (p<0.05) were observed between the water contents and farming types (Table 3).

Higher moisture content in soil under CA might be due to crop residue retention of previous rice which checks evaporation loss and conserves moisture in soil (Jat *et al.* 2018a). The amount of rice crop residues retained before wheat sowing ranged from 6.56 to 9.45 t ha^{-1} irrespective of farmers following CA based wheat (Suppl. Table 2). In addition, crop residues upon decomposition added organic carbon to soil thereby improving soil structure which further enhances water holding capacity of soil (Pisani *et al.* 2016). Malecka *et al.* (2012) reported that higher volume of medium sized pores and lower volume of macro pores under CA system might have facilitated higher moisture content in soils under CA compared to CT system. Jat *et al.* (2018a) observed about 7-9% higher volumetric water content at 0-15 cm soil depth compared to conventional tillage system in a controlled experiment.

Soil carbon

Soil organic carbon - Over all crops and for conventionally grown and CA based wheat crops taken separately, oxidisable organic C (Walkley and Black C: WB-C), total organic carbon (TOC) and TOC stock were normally distributed. Over all crops, WB-C, TOC and TOC stock were 0.79 (±0.03) %, 1.01 (±0.03) % and 27.38 Mg ha^{-1} at 0-20 cm soil depth, respectively (Table 3). In soils under conventionally grown wheat, WB-C was 0.73 (±0.03) %, whereas under CA it was significantly (p<0.05) higher at 0.92 (±0.04) % (Table 3). The TOC under conventionally grown wheat was 0.94% (±0.04), whereas under CA it was 1.18% (±0.05) (Table 3). TOC stock was 25.26 Mg ha^{-1} under conventionally grown wheat, whereas it was 32.03 Mg ha^{-1} under CA (Table 2). On average, the CA based wheat crop recorded higher WB-C (0.13 and 0.19%), TOC (0.17 and 0.24%) and TC (0.16 and 0.24%) than over all crops and conventional wheat crops, respectively (Table 2). Significant interactions ($p<0.05$) between WB-C, TOC concentration and stock with farming type was observed (Table 3).

The significantly higher organic C in soils under CA based wheat crop was due to addition/retention of crop residues (on average 8.1 t ha^{-1} rice residues, Supp. Table 2) leading to higher C inputs to the soil. Minimum soil disturbance (through zero tillage) also facilitates lower decompositon of organic matter in CA based practices. This is consistent with the findings of Jat *et al.* (2018a), and Choudhary *et al.* (2018a,b) in north west India, who observed higher organic C in soils at 0-15 cm soil depth under CA based practices of cereal systems than under conventionally grown wheat. An increase in organic C content in surface soil under CA compared to conventionally grown crops was also observed in other studies (Lopez-Fando and Pardo 2009; Malecka *et al.* 2012). In semi-arid Spain, Lopez-Fando and Pardo (2009) observed that after 5 years of no till in a grey pea-barley cropping system, SOC concentration had increased by 2.0 Mg ha^{-1} at 0–5 cm soil depth. After 7 years of no tillage in Poland, Malecka *et al.* (2012) also reported increased SOC (10.2 g kg^{-1}) at 0–5 cm soil depth. Du *et al.* (2010) and Dikgwatlhe *et al.* (2014) suggested that the higher SOC concentrations in the surface layer under CA based wheat was due to higher quantities of residue additions (both above and below ground) and slow decomposition due to less soil disturbance. Gathala *et al.* (2011) suggested that zero tillage decreases SOC decomposition by minimizing breakdown of macroaggregates, so maintaining protection of SOC within the aggregate.

Soil inorganic carbon - Over all crops and for conventionally grown and CA based wheat crops, inorganic carbon (IC) content was normally distributed. Similar inorganic carbon content (0.22±0.01%) was observed in over all crops, conventionally grown and CA based wheat at 0-20 cm soil depth (Table 2).

Total soil carbon - Total C (TC) values were distributed normally for overall crops, conventionally grown and CA based wheat crops. Over all crops and conventionally grown wheat crop, TC concentration was 1.24% (±0.04) and 1.16% (±0.05), respectively. In CA based wheat crop, TC was significantly ($p<0.05$) higher at 1.40% (±0.04) at 0-20 cm soil depth (Table 2). About 17.1% higher TC was observed in CA based wheat than conventionally grown wheat. Higher TC in CA based system may be due to zero tillage, resulting in less soil disturbance. In controlled experiments, Jat *et al.* (2018a) also reported

65% higher TC in soils after 4 years of CA in cereal based systems of North West India. Our findings are also consistent with the findings of Choudhary *et al.* (2018a, b) and Parihar *et al.* (2018) who also observed significantly higher TC under CA based practices.

Developing soil quality indices for CA and CT practices followed in wheat

Soil quality index under CA

In the PCA of 10 variables, three PCs were extracted with eigen values> 0.9 and explained 83.04% of the variance (Fig. 4, Supp. Table 3). WB-C concentration, TOC concentration and stock, and total carbon concentration were the highly weighted variables in PC1 (40.77% of total variance). Minimum variables need to be selected to avoid redundancy. So correlations study (Pearson's correlation) was performed for all the 4 variables. Among the four variables in PC1, TOC stock was chosen for the MDS. In PC2 (29.28% of total variance) and PC3 (12.99% of total variation), GWC, IC and soil BD were considered highly weighted eigen vectors and therefore were selected in the MDS. Therefore, TOC stock, GWC, IC and BD were included in the final MDS.

The four parameters (TOC stock, GWC, IC and BD) with most weights as obtained from PCA were selected for SQI estimation and therefore qualified as key soil quality indicators. We used b value of -12.5 for all the parameters to obtain a sigmoidal curve using the non-linear equation of Bastida et al. (2006). In the present study, as all the indicators except BD that were retained in the minimum data set were considered good when in increasing order, they were scored, as “more is better” whereas BD was scored as “less is better”. Elliott and Coleman (1988) used ‘more-is-better’ function for SOC, while ‘less is-better’ function was used for BD (Grossman *et al.* 2001). After scoring, each score was multiplied by the respective weight as obtained during PCA analysis. Then summation of these values provided the soil quality indices for each soil collected from farmers field (Supp. Table 5):

SQI = $\sum$ (TOC stock score × 0.49) + (GWC score × 0.35) + (soil IC × 0.35) + (soil BD score × 0.16)

Soil quality index under CT

In the PCA of 10 variables, four PCs were extracted with eigen values> 0.9 and explained 91.23% of the variance (Fig. 5, Supp. Table 4). Similar to CA system, TOC stock was the highly weighted variables in PC1 (46.35% of total variance) and selected for the MDS. In PC2 (23.89% of total variance), GWC was selected and in PC3 (11.66% of total variation), IC was considered highly weighted eigen vectors and therefore were selected in the MDS. Though soil EC had higher factor loadings in PC4 (9.33% of total variance), it was not retained in the MDS as EC did not have any effect on crop growth in nonsaline soils. Therefore, TOC stock, GWC, and IC were included in the final MDS.

The three parameters (TOC stock, GWC and IC) with most weights as obtained from PCA were selected for SQI estimation and therefore qualified as key soil quality indicators. We used b value of -12.5 for all the parameters to obtain a sigmoidal curve using the non-linear equation of Bastida et al. (2006). In the present study, as all the indicators that were retained in the minimum data set were considered good when in increasing order, they were scored, as "more is better". Elliott and Coleman (1988) used 'more-is-better' function for SOC. After scoring, each score was multiplied by the respective weight as obtained during PCA analysis. Then summation of these values provided the soil quality indices for each soil collected from farmers field (Supp. Table 6):

$$SQI = \sum (\text{TOC stock score} \times 0.508) + (\text{GWC score} \times 0.262) + (\text{soil IC} \times 0.128)$$

Results showed significant ($p<0.05$) difference in SQI between CA and CT cultivation methods. The mean SQI under CA and CT was 0.67 (SEm ±0.03) and 0.46 (SEm ±0.04), respectively (Fig. 6). CA based wheat registered ~31% higher SQI over CT. Lower SQI under CT over CA based wheat was due to improved soil physico-chemical properties with higher TOC in CA based managements (Choudhary *et al.* 2018a). Higher soil quality indices under CA based management practices over conventional method of cultivation were also reported by Choudhray *et al.* (2018a, b) in controlled experiments. Contribution of different key soil quality indicators to SQI under CA and CT based wheat were also calculated (Supp. Fig. 1, 2). Among the key soil quality indicators, TOC stock contributed significantly to SQI in both the methods of cultivation thereby reiterating the importance of organic carbon in soil health maintenance (Somasundaram *et al.* 2017).

Wheat grain yield

Results showed significant ($p<0.05$) difference in wheat crop yield between CA and CT methods (Supp. Table 5). The mean wheat grain yield under CA and CT was 5.99 t ha^{-1}(SEm ±0.05) and 5.49 t ha^{-1} (SEm ±0.03), respectively (Fig. 6). CA registered 8.35% higher wheat grain yield over CT. This was probably due to better soil quality as evidenced from higher SOC and reduced GHG emissions under CA over CT in wheat. Oldfield *et al.* (2019) also observed positive relationship between wheat grain yield and

SOC up to maximum 2% SOC content in a global meta-analysis. In another controlled green house study, Oldfield *et al.* (2020) showed greater productivity of wheat with higher concentration of SOM up to a threshold of 5% SOM which was due to improved soil health indicators with increasing SOC. Jat *et al.* (2019) also reported 11 and 16% higher rice equivalent yield in rice and maize based system after four years of CA in a controlled experiment. Higher soil quality in CA over conventional practices can help to sustain the crop productivity, maintain natural resources by making the system resilient towards extreme climate events and secure livelihood of the farmers and thereby have the capability to avoid migration in the years to come.

Relationships among the soil properties, crop yield and SQI

Pearsons correlation matrix was constructed among the soil properties, wheat grain yield and SQI values irrespective of cultivation method (Table 4). Soil BD was significantly negatively correlated with EC ($r=-0.28$, $p<0.05$) of soil. Soil pH was positively and negatively correlated with IC ($r=0.45$, $p<0.01$) and VWC ($r=-0.24$, $p<0.05$) of soil, respectively. WB-C and TOC content were significantly positively correlated with TOC stock ($r=0.97$, $p<0.01$, $r=0.97$, $p<0.01$), TC ($r=0.93$, $p<0.01$, $r=0.89$, $p<0.01$), GWC ($r=0.34$, $p<0.01$, $r=0.34$, $p<0.01$) and VWC ($r=0.36$, $p<0.01$, $r=0.36$, $p<0.01$) of soil. More interestingly wheat grain yield was significantly positively correlated with WB-C ($r=0.35$, $p<0.01$), TOC content ($r=0.34$, $p<0.01$), TOC stock ($r=0.36$, $p<0.01$), total carbon ($r=0.29$, $p<0.05$) and GWC ($r=0.24$, $p<0.05$) and VWC ($r=0.25$, $p<0.05$) of soil and overall SQI ($r=0.29$, $p<0.05$). Soil bulk density was significantly positively correlated with GWC ($r=0.39$, $p<0.01$), VWC ($r=0.43$, $p<0.01$) and SQI ($r=0.52$, $p<0.01$). SQI was significantly positively correlated with organic carbon pools, BD and soil moisture content. Higher EC soils possess good soil structure leading to higher porosity thereby explaining lower BD in soil (Jung *et al.* 2005; Chaudhari *et al.* 2014). Datta *et al.* (2015) reported positive correlations among the soil carbon pools which were also responsible for higher soil moisture content. Yost and Hertemink (2018) observed significant positive correlations between soil carbon and volumetric water content in USA. Henderson et al. (1988) observed positive relationship between soil water content (VWC) and BD while a significant linear relationship was also reported by Archer and Smith (1972). Higher SOC improved overall soil quality which might have translated to higher wheat grain yield. Oldfield *et al.* (2019, 2020) also observed positive correlations between crop yield and SOC in a global meta-analysis.

Greenhouse gases emission

The Climate Change, Agriculture and Food Security-Mitigation Option Tool (CCAFS-MOT) was used to estimate likely emissions of CH_4 and N_2O emissions and SOC sequestered under different management practices. We grouped farmers into five categories based on fertilizer application and management practices: 1($F_{CA\text{-}High\ Fertilizer}$) - farmers applying 375 kg ha^{-1} urea, 125 kg ha^{-1} DAP and following CA (21 farmers) such as zero tillage, green seeker and nutrient expert based N application, line sowing with happy seeder under residue retention; 2 ($F_{CP\text{-}High\ Fertilizer}$) - same as 1 but under conventional practices for sowing wheat (38 farmers); 3 ($F_{CA\text{-}Medium\ Fertilizer}$) - farmers apply 325 kg ha^{-1} urea and 125 kg ha^{-1} DAP under CA (1 farmer); 4 ($F_{CP\text{-}Medium\ Fertilizer}$) - same as 3 but in conventional (6 farmers) practices; 5 ($F_{CP\text{-}Low\ Fertilizer}$) - farmers those apply 250 kg ha^{-1} urea and 125 kg ha^{-1} DAP under conventional practices (4 farmers) (Table 6).

Results showed that large differences in GHG emissions as well as emission intensity were observed in all the categories. Scenarios with CA resulted in lower GHGs emission ($F_{CA\text{-}High\ Fertilizer}$: 1474 kg CO_2 eq ha^{-1}) as compared to conventional practices ($F_{CP\text{-}High\ Fertilizer}$: 2400 kg CO_2 eq ha^{-1}) (Table 6). The intensity of GHG emissions was higher in $F_{CP\text{-}High\ Fertilizer}$ (0.37 kg CO_2 eq kg^{-1}) over $F_{CA\text{-}High\ Fertilizer}$ (0.10 kg CO_2 eq kg^{-1}). Crop residue burning in conventional practices resulted higher CH_4 (788 kg CO_2 eq ha^{-1}) and N_2O emission (179 kg CO_2 eq ha^{-1}) whereas in CA, no GHG emissions due to burning took place (Table 6). Higher N_2O emissions were estimated in $F_{CA\text{-}High\ Fertilizer}$ (559 kg CO_2 eq ha^{-1}) over $F_{CP\text{-}High\ Fertilizer}$ (518 kg CO_2 eq ha^{-1}) from fertilizer induced field emission. A large amount of C was sequestered in soil under $F_{CA\text{-}High\ Fertilizer}$ (899 kg CO_2 eq ha^{-1}) as compared to $F_{CP\text{-}High\ Fertilizer}$ (172 kg CO_2 eq ha^{-1}) wheat (Table 5). In $F_{CA\text{-}Medium\ Fertilizer}$, lower GHG emissions (1296 kg CO_2 eq ha^{-1}) were observed over $F_{CP\text{-}Medium\ Fertilizer}$ (2062 kg CO_2 eq ha^{-1}). The GHG emission intensity was also lower in the former (0.06 kg CO_2 eq kg^{-1}) than in $F_{CP\text{-}\ Medium\ Fertilizer}$ (0.41 kg CO_2 eq kg^{-1}), although the fertilizer dose was same. Also N_2O emissions were higher in $F_{CA\text{-}Medium\ Fertilizer}$ (501 kg CO_2 eq ha^{-1}) than $F_{CP\text{-}Medium\ Fertilizer}$ (452 kg CO_2 eq ha^{-1}) practices (Table 6). Due to burning crop residues in $F_{CP\text{-}Medium\ Fertilizer}$, 665 and 151 kg CO_2 eq ha^{-1} CH_4 and N_2O were emitted, respectively. Significantly higher quantities of SOC were sequestered under $F_{CA\text{-}\ Medium\ Fertilizer}$ (929 kg CO_2 eq ha^{-1}) than $F_{CP\text{-}\ Medium\ Fertilizer}$ (122 kg CO_2 eq ha^{-1}) wheat. Conventional practices with application of 250 kg urea and 125 kg DAP ha^{-1} ($F_{CP\text{-}Low\ Fertilizer}$) caused additional GHG emissions of 1827 kg CO_2 eq ha^{-1} with an intensity of 0.37 kg CO_2 eq kg^{-1}. Similar quantities of CH_4 and N_2O were emitted due to crop residue burning as in $F_{CP\text{-}\ Medium\ Fertilizer}$

with conventional practices. Field induced emissions of CH_4 and N_2O were 151 and 375 kg CO_2 eq ha^{-1}, respectively under $F_{CP\text{- Low Fertilizer}}$ (Table 5).

The main source of variation in GHG emissions between CA and conventional agricultural practices was the management practices. Conventional practices in $F_{CP\text{-High Fertilizer}}$ registered about 63% higher total GHG emissions than $F_{CA\text{-High Fertilizer}}$ which were due to less soil disturbance (zero tillage), residue retention instead of burning, green seeker and Nutrient Expert based N applications to soil in later stages, leading to lower emissions (Kakraliya *et al.* 2018b). Kakraliya *et al.* (2018a) studied different layers of CA based practices, calculating GHG emissions using CCAFS-MOT, and observed higher GHG emissions in conventional practices over CA. In CA based practices, higher N_2O emissions might occur due to denitrification from soil under residue retention conditions developing anaerobic micro pockets in the presence of high soil moisture content at soil surface where microbes use nitrate and nitrite as terminal electron acceptor and produce N_2O (Brady and Weil 2007). Bhatia *et al.* (2010) and Gupta *et al.* (2016) also observed higher N_2O emissions under CA based agricultural practices in North India.

Sapkota *et al.* (2017) pointed out that the source and amount of N fertilizer also influences GHG emissions from soil. Lower GHG emissions were observed upon application of lower doses of N fertilizer to soil. In conventional wheat, about 12% less N_2O emissions were observed than in zero-tilled wheat in Northern India (Bhatia *et al.* 2010). Higher N_2O emissions from zero tilled wheat than conventional were also observed by Sapkota *et al.* (2015) in rice-wheat cropping systems of Northwestern Indo-gangetic plains. Higher C sequestration in CA based practices was due to ZT and residue retention at the soil surface, which upon decomposition added C to the soil. Jat *et al.* (2018a, b) also reported higher SOC sequesterd in CA based practices.

Conclusions

Climate Smart agricultural practices such as CA with zero tillage, residue retention with diversified crop rotation resulted in a decrease in soil pH in wheat compared to conventional agriculture practices. Soil organic C pools significantly increased under CSA practices. Significant interactions between organic C and pH with farming type were observed. CSA enhanced soil quality and higher wheat grain yield was observed compared to conventional practices. Lower GHG emissions were estimated from CSA than from conventional practices. These CSA practices provide an excellent alternative to conventional agriculture practices in Northwest India for adaptation to climate change irrespective of farm type and size. In conclusion, CSA not only improves SOC pools, but also helps to improve other soil properties and the overall quality of the soil. Therefore, it should be popularized among the farmers of North West India for sustainability of the cropping system and future posterity in the context of climate change.

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Declaration

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Data Availability Statement

The authors confirm that the data supporting the findings of the study are available within the article and its supplementary file. Raw data are available from the corresponding author upon request.

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Figure captions

Fig. 1. Sampling locations of the farmers field (22 farmers following CA and 48 farmers following CT) in Karnal district, Haryana

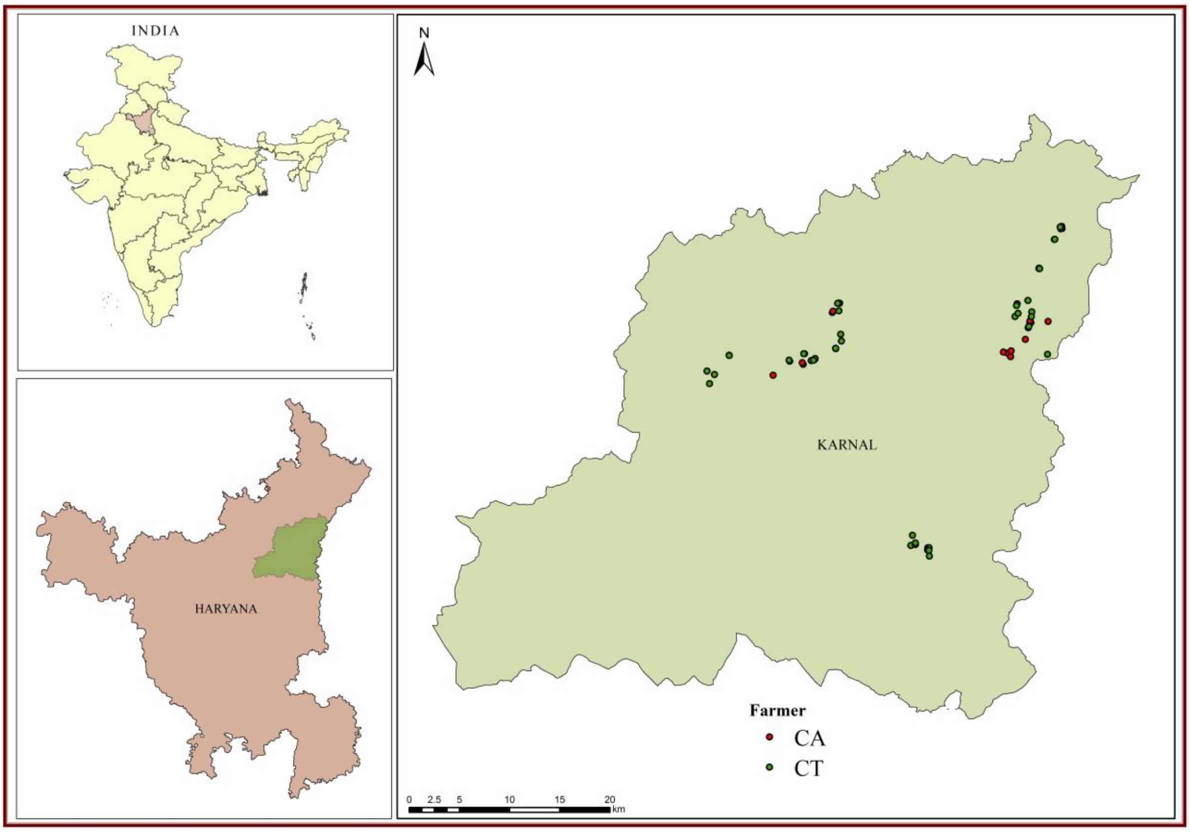
Fig.2. Sugarcane residues used as mulch

Fig. 3. Line sowing of wheat by seed drill

Fig. 4. Principal component plot of soil physicochemical properties under CA based wheat (22 farmers).

Fig. 5. Principal component plot of soil physicochemical properties under CT based wheat (48 farmers).

Fig. 6. Wheat grain yield and soil quality index under CA (average of 22 farmers) and CT practices (average of 48 farmers)



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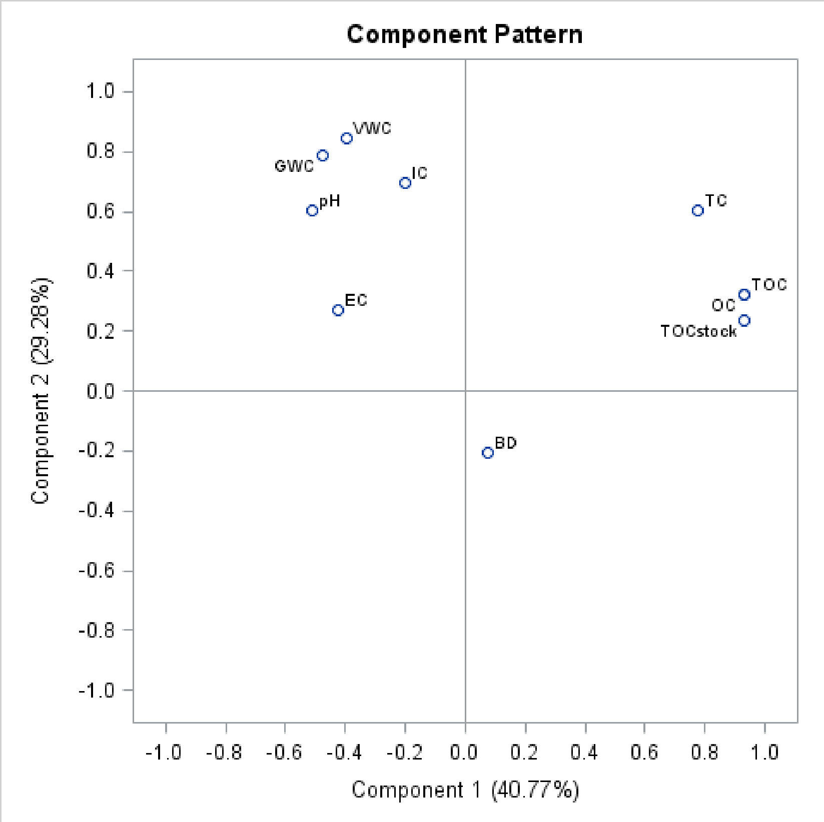

Fig. 4. Principal component plot of soil physicochemical properties under CA based wheat (22 farmers).

where EC: electrical conductivity, OC: oxidizable organic carbon concentration, TOC: total organic carbon concentration, TOC stock: total organic carbon stock, BD: bulk density, IC: inorganic carbon, TC: total carbon concentration, GWC: gravimetric water content, VWC: volumetric water content

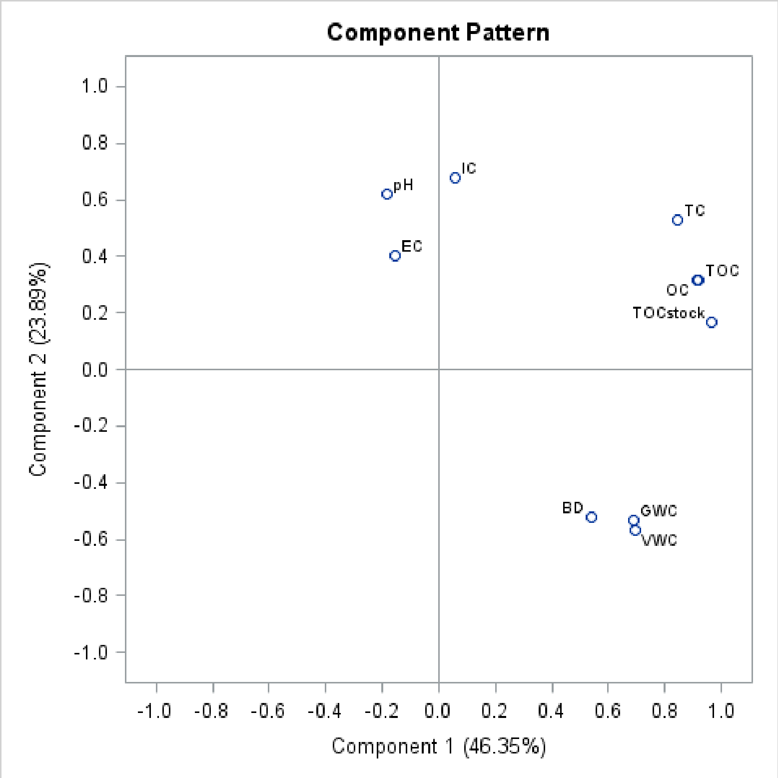

Fig. 5. Principal component plot of soil physicochemical properties under CT based wheat (48 farmers).

where EC: electrical conductivity, OC: oxidizable organic carbon concentration, TOC: total organic carbon concentration, TOC stock: total organic carbon stock, BD: bulk density, IC: inorganic carbon, TC: total carbon concentration, GWC: gravimetric water content, VWC: volumetric water content

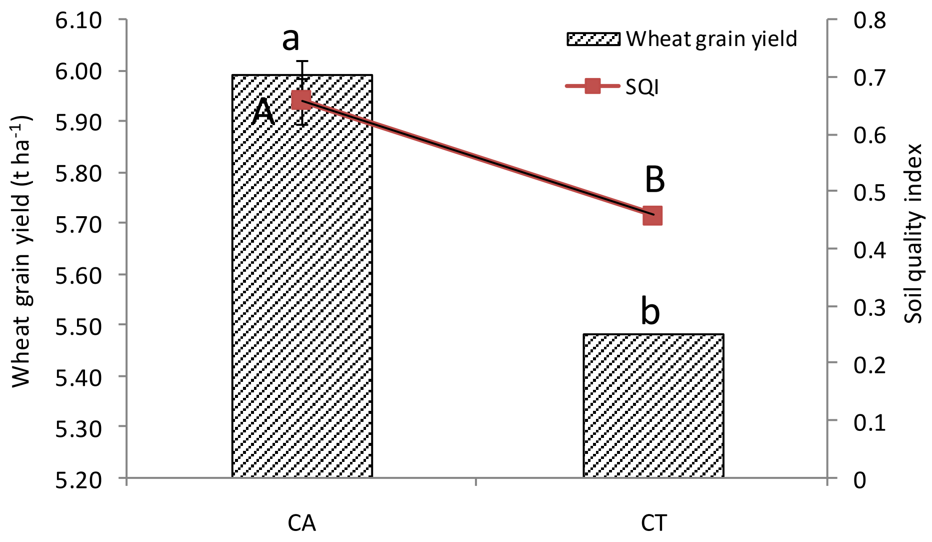

Fig. 6. Wheat grain yield and soil quality index under CA (average of 22 farmers) and CT practices (average of 48 farmers)
where different upper and lower case letter showed statistically significant for SQI (t=3.02, p<0.05) and crop yield (t=8.38, p<0.001) through independent sample T test.

Table 1. Total number of farmers, villages, and crops grown selected from Karnal district, Haryana, India

Name of Villages	No. of farmers	Crops grown	
		Kharif	*Rabi*
Gheer	5	Rice	Wheat
Badarpur	6	Jowar	Sugarcane
Chandsamand	5	Sugarcane	Garlic
Chorpura	7	Dhaincha	Mustard
Kartarpur	8		Chickpea
Dabkoli	2		Berseem
Rindal	1		Linseed
Taraori	5		Vegetables
Nadana	10		
Sambhli	5		
Sagga	5		
Kutail	11		

Table 2. Descriptive statistics of soil parameters of soils collected from 70 farmers from different crops at 0-20 cm soil depth from Karnal district, Haryana, India. Note: EC = electrical conductivity; WB-C =Walkley and Black oxidisable organic carbon; TOC = total organic carbon; BD = bulk density; IC = inorganic carbon; TC = total carbon; N = number of observations = 173; SE is the standard error

Farming type		WB-C (%)	EC (1:2)	pH (1:2)	TOC (%)	TOC stock (Mg ha^{-1})	BD (Mg m^{-3})	GWC (g g^{-1})	VWC (g cm^{-3})		IC (%)	TC (%)
Conservation	Mean	0.92	0.50*	7.76	1.18	32.03	1.36	0.27	0.35		0.22	1.40
	N	22	22	22	22	22	22	22	22		22	22
	SE	0.04	0.11	0.07	0.05	1.29	0.02	0.02	0.11		0.02	0.05
Conventional	Mean	0.73	0.49*	7.99	0.94	25.26	1.34	0.21	0.28		0.22	1.16
	N	48	48	48	48	48	48	48	48		48	48
	SE	0.03	0.10	0.05	0.04	1.23	0.02	0.02	0.02		0.02	0.05
Overall	Mean	0.79	0.50*	7.92	1.01	27.38	1.34	0.23	0.30		0.22	1.24
	N	70	70	70	70	70	70	70	70		70	70
	SE	0.03	0.08	0.04	0.03	1.01	0.01	0.01	0.02		0.01	0.04

*Median value for EC as it was not distributed normally

Table 3. Analysis of variance showing interactions between farming type and soil properties. Note: WB-C =Walkley and Black oxidisable organic carbon; EC = electrical conductivity; TOC = total organic carbon; BD = bulk density; GWC = gravimetric water content; VWC = volumetric water content; df = degrees of freedom.

			Sum of Squares	df	Mean Square	F	Sig.
OC (%) * Farming type	Between Groups	(Combined)	0.548	1	0.548	12.850	0.001
	Within Groups		2.898	68	0.043		
	Total		3.446	69			
EC (1:2) * Farming type	Between Groups	(Combined)	0.000	1	0.000	0.001	0.978
	Within Groups		29.565	68	0.435		
	Total		29.565	69			
pH (1:2) * Farming type	Between Groups	(Combined)	0.762	1	0.762	6.921	0.011
	Within Groups		7.486	68	0.110		
	Total		8.248	69			
TOC (%) * Farming type	Between Groups	(Combined)	0.897	1	0.897	12.850	0.001
	Within Groups		4.748	68	0.070		
	Total		5.645	69			
BD (Mg/m3) * Farming type	Between Groups	(Combined)	0.006	1	0.006	0.486	0.488
	Within Groups		0.780	68	0.011		
	Total		0.785	69			
TOC stock (Mg/ha) * Farming type	Between Groups		692.13	1	692.133	11.206	0.001
	Within Groups		4200.10	68	61.766		
	Total		4892.23	69			
GWC (g water per g soil) * Farming type	Between Groups		0.051	1	0.051	4.182	0.045
	Within Groups		0.836	68	0.012		
	Total		0.888	69			
VWC (cm^3 water per cm^3 soil) * Farming type	Between Groups		0.085	1	0.085	4.281	0.042
	Within Groups		1.353	68	0.020		
	Total		1.438	69			

Table 4. Pearsons bivariate correlation among the soil properties, crop yield and SQI irrespective of cultivation method

	EC	pH	WB-C	TOC	TOCs	BD	IC	TC	GWC	VWC	Yield	SQI
EC	1											
pH	-0.01											
WB-C	-0.07	-0.20										
TOC	-0.07	-0.20	1.00**									
TOCs	-0.13	-0.22	0.97**	0.97**								
BD	-0.28*	-0.21	0.20	0.20	0.43							
IC	0.27*	0.45**	0.05	0.05	0.02	-0.14						
TC	0.02	-0.02	**0.93****	**0.93****	**0.89****	**0.13**	0.40**					
GWC	-0.07	-0.21	**0.34****	**0.34****	**0.41****	**0.39****	0.02	0.32**				
VWC	-0.11	-0.24*	**0.36****	**0.36****	**0.43****	**0.43****	0.03	0.33**	0.98**			
Yield	0.11	-0.18	**0.35****	**0.34****	**0.36****	0.18	-0.07	0.29*	0.24*	0.25*		
SQI	-0.16	-0.23	**0.72****	**0.73****	**0.79****	**0.52****	0.10	**0.70****	**0.63****	**0.64****	**0.29***	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Where EC: electrical conductivity, WB-C: Walkley and Black carbon, TOC: total organic carbon, TOCs: rotal organic carbon stock, BD: bulk density, IC: inorganic carbon, TC: total carbon, GWC: gravimetric water content, VWC: volumetric water content, Yield: wheat grain yield, SQI: soil quality index

Table 5. Different management scenarios with fertilizer application rate, greenhouse gas (GHG) emission and intensity, soil organic carbon (SOC) sequestered during the wheat crop season as calculated using the CCAFS-MOT in Climate Smart Villages (CSVs) of Karnal, Haryana, India. Note:

Management Scenario	Practice	Fertilizer application	No. of farmers	GHG emission (kg CO_2 eq ha^{-1})	GHG emissions intensity (kg CO_2 eq kg^{-1})	CH_4 emission (kg CO_2 eq ha^{-1})		N_2O emission (kg CO_2 eq ha^{-1})		SOC sequestered (kg CO_2 eq ha^{-1})
						Crop residue burning	Fertilizer induced field emission	Crop residue burning	Fertilizer induced field emission	
$F_{CA\text{-}High\ Fertilizer}$	Conservation agriculture (CA) based	375 kg urea; 125 kg DAP	21	1474	0.10	nil	nil	nil	559	899
$F_{CP\text{-}High\ Fertilizer}$	Conventional practices (CP)	375 kg urea; 125 kg DAP	38	2400	0.37	788	nil	179	518	172
$F_{CA\text{-}Medium\ Fertilizer}$	Conservation agriculture (CA) based	325kg urea; 125 kg DAP	1	1296	0.06	nil	nil	nil	501	929
$F_{CP\text{-}Medium\ Fertilizer}$	Conventional practices (CP)	325 kg urea; 125 kg DAP	6	2062	0.41	665	nil	151	452	122
$F_{CP\text{-}Low\ Fertilizer}$	Conventional practices (CP)	250 kg urea; 125 kg DAP	4	1827	0.37	665	nil	151	375	122

DAP = diammonium phosphate.

where

$F_{CA\text{-}High\ Fertilizer}$: Farmers following conservation agriculture (CA) practices with high fertilizer applications
$F_{CP\text{-}High\ Fertilizer}$: Farmers following conventional agriculture (CP) practices with high fertilizer applications
$F_{CA\text{-}Medium\ Fertilizer}$: Farmers following CA practices with medium fertilizer applications
$F_{CP\text{-}Medium\ Fertilizer}$: Farmers following conventional agriculture (CP) practices with medium fertilizer applications
$F_{CP\text{-}Low\ Fertilizer}$: Farmers following conventional agriculture (CP) practices with low fertilizer applications