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Article · March 2022

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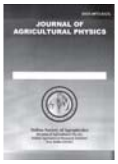
Vol. 21, No. 1, pp. 145-164 (2021)
Journal of Agricultural Physics
ISSN 0973-032X
http://www.agrophysics.in



Special Issue Article

Conservation Agriculture for Soil Health and Carbon Sequestration

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ABSTRACT

Conventional agriculture practices over long-run have generated a number of challenges for sustainability of agriculture, *viz.*, soil degradation, depletion of ground water level, declining soil organic matter, loss of soil biodiversity, subsurface compaction, and greenhouse gas (GHG) emissions. Conservation agriculture (CA) has been seen as an option to maintain the soil health and improve soil organic carbon (SOC) storage, amongst other collateral benefits which may ensure agricultural sustainability. CA modifies soil hydro-physical properties such as an increase in water infiltration, reductions in runoff, evaporation and soil loss, thus it helps in reverting soil degradation and sustaining the soil health. There are reports on improved soil chemical and biological properties on different agro-ecologies under CA throughout the globe. Meta data analysis showed that NT significantly improved mean weight diameter (MWD) and field capacity moisture content by 19-58% and 6-16%, respectively, and resulted in no significant change in bulk density (BD), but infiltration rate increased by 66%. CA improves SOC stocks by addition of more C inputs through greater biomass production and reduction in SOC losses due to surface soil cover and locking SOC in soil aggregates. This causes net sequestration of atmospheric C into the soil, leading to climate change mitigation. Potential impacts of CA on soil health and SOC sequestration through various practices such as minimal soil tilling, residue management, and diversified crop rotation from the field studies have been widely reported in the literature. Although studies on SOC sequestration potential of CA had contradictory reports under diverse soil and climatic conditions, and need to be synthesized for site-specific recommendations. Nevertheless, findings of majority of studies suggest that CA can be a potential alternative to the conventional agricultural practices for managing soil health and improving soil C stock, and thereby sustaining productivity and mitigate climate change.

Key words: Aggregation, bulk density, porosity, soil organic carbon, crop residue, zero tillage

Introduction

Our natural resources are severely affected due to over-exploitation through conventional agriculture practices to produce more food to feed the ever-growing human population. The adverse effects of long-term adoption of conventional agriculture practices lead to various problems such as soil erosion and desertification (Montgomery, 2007); soil organic matter

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depletion; decrease in soil biodiversity; subsurface compaction of soil; greenhouse gas (GHG) emissions into the atmosphere (Yan *et al.*, 2006; Parihar *et al.*, 2018); soil moisture depletion; air and water pollution; declining soil fertility (Alam *et al.*, 2014) and soil health (Bhattacharya *et al.*, 2020) and agricultural sustainability (Memon *et al.*, 2018). In spite of availability of improved crop varieties with greater yield potential, crop yield has not reached its potential level, which might be due to poor crop management (Reynolds and Tuberosa, 2008). Indian agriculture has entered into a new era where the issues of efficient use and management/conservation of natural resources have been given high priority. This can safeguard our agricultural production environment and soil health so that the past achievements of the Green Revolution can be sustained and further enhance the food grain production to meet the increasing current and future needs (FAO, 2017). Natural resource management has become a vital component for sustainable agriculture because of extensive resource degradation. The challenges to lower production costs and increase farm profitability have made agriculture more competitive. Conventional or traditional agriculture is based on intensive tillage operations; *i.e.*, mould board ploughing or disk harrowing, subsoiling or chiselling, “spiked” harrowing, etc. Intensive tillage severely modifies the original soil structure, breaks up natural soil aggregates and incorporates the residues of previous crops into the soil and thus makes the soil surface bare and highly prone to erosion and soil degradation (Doraiswamy *et al.*, 2007). This causes reduced crop yields over time and losses in soil productivity leading to poor soil health, and farm profitability. Widespread degradation of soils and natural resources now pose a challenge for researchers/scientists to come out with an advanced natural resource management practice for sustainable productivity (Jat *et al.*, 2014) and improved soil health (Bhattacharya *et al.*, 2020). Thus, the concept of conservation agriculture (CA) has slowly come out as an alternative to maintain soil health and agricultural sustainability (Jayaraman *et al.*, 2021). Conservation agriculture, according to Food and Agriculture Organisation (FAO), aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. CA is primarily based on four basic principles i.e. reduction in tillage, retention of crop residues, crop diversification and controlled traffic (FAO, 2011). These CA principles are applicable to a wide range of agroecosystems from low-yielding, dry rain-fed to high-yielding irrigated conditions and hill and coastal regions. It contributes to environmental protection as well as improved and sustained agricultural production (FAO, 2017). CA has the potential to sequester soil organic carbon (SOC). Soils can sequester around 20 Pg 10^{15} g C in 25 years, more than 10% of the anthropogenic emissions (FAO, 2015). The 4 per 1000 initiative (4PT) shows that storing carbon (C) in agricultural soils is possible through proper management of soils (Rumpel *et al.*, 2018). CA is also an option to achieve the goal of 4 per 1000 through C sequestration in soils (Corbeels *et al.*, 2019). CA has been identified as an agricultural practice that ensures agricultural sustainability, associated with a potential to mitigate greenhouse gas emissions (Paustian *et al.*, 1997; Schlesinger, 1999) and enhance SOC sequestration (Parihar *et al.*, 2018a; Bhattacharya *et al.*, 2020). Managing agro-ecosystems for sustaining enhanced productivity, farm profitability and food security, along with protecting the environment and improving soil health, enhancing C sequestration and natural resource base are the characteristics of CA (Bhattacharya *et al.*, 2020). In this paper, we discussed how CA affects soil health and carbon sequestration.

Conservation agriculture is practised in around 180.4 m ha area worldwide, most of the areas are in the USA, Brazil, Argentina, Canada and Australia (Kassam *et al.*, 2018). CA became an acceptable practice for the farmers in these countries due to decades of research and extension and concerns of the farmers, scientists and the public on soil erosion. Due to the efforts of the Rice-Wheat Consortium and several institutions of the National Agricultural Research System

(NARS), zero tillage technology was introduced into India and neighbouring countries, and it is gradually being adopted by the farmers, largely in the Indo-Gangetic Plains (IGP). In the world, CA has spread mostly in rainfed agriculture, while, in India, its success is more prominently observed in the irrigated belt of the IGP. Despite all the efforts, the progress of adoption of CA in India is slow and only 1.5 Mha is under CA in the country (Kassam *et al.*, 2018).

Soil Health under Conservation Agriculture

Soil health can be defined as the continued capacity of soil to function as a vital living system, within ecosystem and land use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal and human health (Doran *et al.*, 1996). The main functions of soil include water flow and retention, solute transport and retention, physical stability and support, retention and recycling of nutrients, buffering and filtering of potentially toxic materials, maintenance of biodiversity and habitat. Soil health needs to be maintained and improved by following appropriate management practices to sustain productivity continuously at higher levels in the long run. Different management practices involved in CA are enlisted in Table 1.

CA practices is proved to improve soil health (Araya *et al.*, 2016), soil biological activities (Choudhary *et al.*, 2018a, b), SOC (Chakrabarti *et al.*, 2014; Parihar *et al.*, 2016; Bhattacharya *et al.*, 2020), soil hydraulic properties (Patra *et al.*, 2019; Ghosh *et al.*, 2020), nutrient availability (Jat *et al.*, 2018), root water uptake (Aggarwal *et al.*, 2017; Parihar *et al.*, 2019), ecosystem services (Pathak *et al.*, 2017), productivity (Jat *et al.*, 2019a), conserve soil moisture (Chakrabarti *et al.*, 2014), and reduce the water footprints (Borsato *et al.*, 2018). CA makes necessary modifications in different soil hydro-physical properties, *viz.* increased soil water infiltration (Ghosh *et al.*, 2020), reduction in water runoff and soil loss, and reduction in evaporation loss, thus improves soil health. Balanced application of inorganic fertilizers and organic amendments greatly influences the accumulation of SOC and also influences the soil physical environment (Hati *et al.*, 2007). Crop management practices such as tillage and crop establishment techniques and cropping systems can affect soil health governing properties and ultimately to the soil health. Conservation agricultural practices cause an increase in soil organic matter (SOM), soil structure due to conservation of soil aggregates, reduced oxidation of SOM compared to conventional tillage (Beare *et al.*, 1994; Halvorson *et al.*, 2002). Similarly, crop diversification either in rotations/intercropping of legumes can also affect soil health by affecting C contents, due to the difference in chemical composition of different crop residues that are added to soil (Parihar *et al.*, 2016; Srinivasarao *et al.*, 2013). Further, long-term CA practices (ZT+R) coupled with crop rotation, diversification and irrigation water management had been found to improve soil quality under cereal based cropping system in north-west India (Roy *et al.*, 2022). These

Table 1. Different components and practices of conservation agriculture

No-tillage, minimum and reduced tillage	Drip /trickle/sprinkler irrigation technology
Nutrient cycling	Crop and pasture rotation.
Agro-forestry or farm forestry	No burning of crop residues/ retention of crop residues at soil surface
Trap cropping for insect control	Alley cropping
Biological mode of pathogen control	Bed and furrow planting
Integrated pest management (IPM)	Contour farming and strip cropping
Cover and green manure cropping	Organic and biodynamic farming
Stubble mulching	Continuous crop land use

Source: modified from Pramanik *et al.* (2014)

effects of either tillage or cropping systems on soil physical and chemical properties affect the microbial biomass and their activities and some other important processes such as organic matter decomposition and mediation of plant nutrient availability (Balota *et al.*, 2003; Parihar *et al.*, 2018a). Table 2 showed the effects of different CA practices on soil health. In the following sections, we have discussed how CA practices affect soil health.

Bulk density and soil compaction under conservation agriculture

Tillage has prominent effects on soil bulk density (BD) and porosity. Bulk density is one of the most important soil physical parameters which determines soil compactness and other properties (Bhattacharya *et al.*, 2020). BD greatly depends on inherent soil qualities and management practices. Blanco-Canqui and Lal (2007) and McVay *et al.* (2006) showed that the effect of additional residue kept on the surface (under CA) for reducing BD is very prominent in the 0–3 cm and to a lesser range in the 3–10 cm soil depth. However, Gantzer and Blake (1978) reported that soils under zero tillage (ZT) had a higher BD than conventional tillage (CT). Bautista *et al.* (1996) found that ZT with residue retention significantly reduced BD in a semi-arid ecosystem. Jat *et al.* (2018) reported significantly lower BD at surface and subsurface soil depth under partial CA based rice (puddle transplanted)-wheat (ZT)-mungbean (ZT) system over conventional and full CA based systems in semiarid Northwest India. In contrast, no change in BD was reported after 10 years of

Table 2. Effects of different CA practices on soil health parameters

Soil health parameters	CA practices	Remarks	References
Bulk density and Soil organic carbon	ZT + residue retention	Decrease in BD and ZT increased SOC stock up to 30 cm but residue retention increased it up to 60 cm	Bhattacharya *et al.* (2020) and Modak *et al.* (2020)
Hydraulic conductivity and infiltration rate	PBB+R	Increased HC and infiltration rate in 0-15 and 15-30 cm of soil depth as compared to CT	Ghosh *et al.* (2020); Parihar *et al.* (2016)
Microbial and enzymatic properties	CA-based maize-wheat (MW)	MBC and MBN increased by 208% and 263%, whereas, dehydrogenase and alkaline phosphatase activity increased by 210 and 48%	Choudhary *et al.* (2018a)
Soil compaction and penetration resistance	CA based systems ZT and PB	Decrease in bulk density (4.3–6.9%) and penetration resistance (15.9–30.7% as compared to CT based maize	Parihar *et al.* (2016); Saha *et al.* (2010)
Total soil N (TSN)	Zero tillage with bed planting (ZT-B) and zero tillage with flat planting (ZT-F)	15 % higher TSN concentrations than conventional tillage and bed planting plots (CT-B)	Bhattacharyya *et al.* (2013)
Soil aggregation process	Minimum tillage (MT) and addition of organic matter	Enhanced soil aggregation processes and water stable aggregates and decreased long-term soil erosion on a gentle slope (~2%) in the Indian Himalayas	Ghosh *et al.*, (2016)

ZT = Zero-tillage; PBB + R - Permanent broad bed + residue; CA - Conservation agriculture; Conservation tillage experimentation with cereal based cropping systems in north-west India (Roy *et al.*, 2022). Subsurface drip irrigation with ZT negates the beneficial effect of residue addition as water evaporates through capillary rise and cause shrinkage of top 0-5 cm layer, thereby increasing the BD. Several researchers (Ehlers, 1983; Pikul *et al.*, 1990; Sauer *et al.*, 1990) have reported that on certain soils, switching from conventional tillage to a no-tillage (NT) agriculture caused an increased BD and decreased porosity in NT system. Mielke *et al.* (1986) conducted a study comparing BD between NT systems and mouldboard plough by taking seven soils at two depths (14 combinations), and they reported a greater BD under NT system. There appears to be a tendency for greater bulk densities in NT systems. Study conducted by Das *et al.* (2013) reported that plots under ZT along with bed planting system had about 5% higher BD than CT with bed (1.51 Mg m^{-3}) in the 0–5 cm soil layer. In another study, Horne *et al.* (1992) had shown lower BD at a depth of 3–7 cm in ZT than in CT and there were no significant changes in the deeper layer. The reported BD in published literatures is highly variable and affected by many factors like climate, soil type, adoption duration, cropping systems etc. Therefore, many authors have conducted meta-analyses to draw a general conclusion out of diverse results on the effect of CA on soil BD. Li *et al.* (2019) concluded a significant increase (1.4%) while Blanco-Canqui and Ruis (2018) and Mondal and Chakraborty (2022) noted no change in soil BD under NT than CT. Duration of adoption could be a determining factor to ascertain the CA effect on BD. The higher BD during the initial years of CA could be avoided by longer duration of adoption (Mondal *et al.*, 2019, 2020). However, Logsdon and Karlen (2004) reported that farmers need not worry about increased compaction as BD is not a useful indicator while shifting from CT to NT on deep loess soils of the USA. Fabrizzi *et al.* (2005) also showed higher penetration resistance and BD in NT experiments, but the values were below the thresholds to affect crop growth. In contrast, lower penetration resistance and consequently better root growth in the subsurface soil layer was observed in the rice-wheat cropping system by Mondal *et al.* (2019). Similarly, a lower soil penetration resistance (SPR) was observed under partial CA based cereal systems in semiarid northwest India (Jat *et al.*, 2018). Higher duration of NT has been reported to decrease the soil BD and penetration resistance as compared to CT (Blanco-Canqui and Ruis, 2018). Different crop rotations and residue retentions and crops with different rooting depths used in CA practices can reduce the compaction constraints.

Effects of different conservation agriculture practices on infiltration characteristics and hydrothermal properties

Results from a study conducted in the research farm of the ICAR-Indian Agricultural Research Institute (IARI), New Delhi showed that initial infiltration rate was highest (22.93 cm hr^{-1}) in PBB+R (permanent broad bed+residue retention) and was lowest (7.64 cm hr^{-1}) in CT under maize- wheat cropping system after 10 years (Ghosh *et al.*, 2020) (Table 3). The final/ steady state infiltration rate was maximum (7.49 cm hr^{-1}) in PBB+R and 2.58 h was taken to get final infiltration rate. In all residue applied plots initial infiltration rate and steady state infiltration

Table 3. Characteristics of infiltration of soil under different CA treaments (Ghosh *et al.*, 2020)

Treatments*	Initial infiltration rate (cm hr^{-1})	Steady state infiltration rate (cm hr^{-1})	Cumulative infiltration (cm)
CT	7.64e	2.11e	5.00d
PNB	15.29c	4.78c	20.61b
PNB+R	20.37b	5.12c	22.64b
PBB	17.20c	6.02b	13.79c
PBB+R	22.93a	7.49a	27.17a
ZT	11.46d	3.50d	11.15c

*CT, conventional tillage; PNB, permanent narrow bed; PNB+R, permanent narrow bed +residue; PBB, permanent broad bed, PBB+R, permanent broad bed +residue, ZT, zero tillage. . Means followed by a similar lowercase letter within a column are not significantly different (at P < 0.05) rates were higher than the non-residue applied plots. Better soil structure and pore connectivity enables higher infiltration and eventually better available water for crop production under CA practices (Aggarwal *et al.*, 2017; Thierfelder *et al.*, 2005). CA based cereal systems recorded significantly higher infiltration rate and cumulative infiltration in semiarid environment of northwest India, (Jat *et al.*, 2018). Shaxson and Barber (2003) concluded that in CA, due to higher soil porosity and physical aggregation, there was an increase in water infiltration and decrease in surface runoff, which resulted in greater plant-available moisture in the soil. A meta-analysis performed by Mondal *et al.* (2020) showed that NT significantly improved MWD and field capacity moisture content at surface and sub-surface layers by 19-58% and 6-16% respectively, and resulted in no change in BD in either of the layers, but infiltration rate increased by 66%.

Patra *et al.* (2019) conducted an experiment at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal and reported that no till-based CA enhanced near saturated hydraulic conductivity, k(h) as compared with conventional cultivation practice. Although the interaction effect of treatments with crop seasons were statistically non-significant ($p<0.05$), considerable changes of soil hydraulic properties were observed over crop seasons under CA. Transition from maize to wheat in the crop sequence reduced k(h) values by about 55, 44, 34 and 40% at pressure heads of 0, –1, –2 and –4 cm, respectively. In contrast, transition from rice to wheat in rice-based no till CA increased k(h) values by 129, 164, 124 and 24% in the same pressure head ranges. Irrespective of crop seasons, higher k(h) was observed under CA due to formation of macropores with better continuity, greater size and numbers as compared with CT. Reduced till-based CA showed an intermediate effect with respect to the different soil hydraulic characteristics in both crop seasons. Moreover, higher flow weighted mean pore radius values were observed for a given k(h) for CA treatments suggesting that interaggregate pores are the dominant pathways of infiltration flux in CA. CA also enhanced hydraulically active macropores as compared with intensive tillage based conventional agriculture.

Lal (2008) showed that residue cover enhanced the interception of the rainfall, reduced the soil crusting and soil losses due to runoff, and therefore it helped to increase the soil water infiltration rate. After the decomposition of residue, it helps in improving soil structure through enhanced soil aggregate stability and soil porosity, which also improved the soil water infiltration rate as reported by Jordán *et al.* (2010). Sharratt *et al.* (2006) explained that the presence of mulch may restrict water infiltration by imparting water repellent and hydrophobic properties in the soil surface. McGarry *et al.* (2000) showed that ZT practices improved the hydraulic conductivity (HC) of soils. The probable reason for the increased HC of no tilled soils was improved pore size distribution, pore diameters and pore continuity and an increased in numbers of macropores (Cameira *et al.*, 2003) and greater activity of fungi and build-up of organic matter due to higher crop residue addition on the field (Logsdon and Kasper 1995). Study conducted by Bhattacharyya *et al.* (2006) reported the significant increase in laboratory estimated saturated hydraulic conductivity under zero-tilled plots (1.13 and 1.07 cm hr^{-1} at 0-15 and 15-30 cm soil layers, respectively). The soil under ZT has the lowest porosity compared to conventional management practices. A good soil structure and porosity can be achieved following CA practices (Bhattacharyya *et al.*, 2006). Mondal and Chakraborty (2022) observed a 2.5 and 32.3% reduction in total porosity and macro-porosity, respectively under NT as compared to CT while micro-porosity was increased by 7.3% (Fig. 1). Bag *et al*. (2020) reported that the BD (upto 45 cm), penetration resistance (10-27 cm) reduced under NT + residue plots while total porosity (15-60 cm), MWD (0-15 cm), SOC (0-15 cm) improved in a sandy loam soil under maize-wheat cropping system. Álvarez and Steinbach (2009) indicated the role of no till in Argentina under inadequate soil water conditions. They observed that soil water content was greater (18 mm water) in semi-arid coarse textured soil, while it was less (9 mm water) in humid fine textured soil,

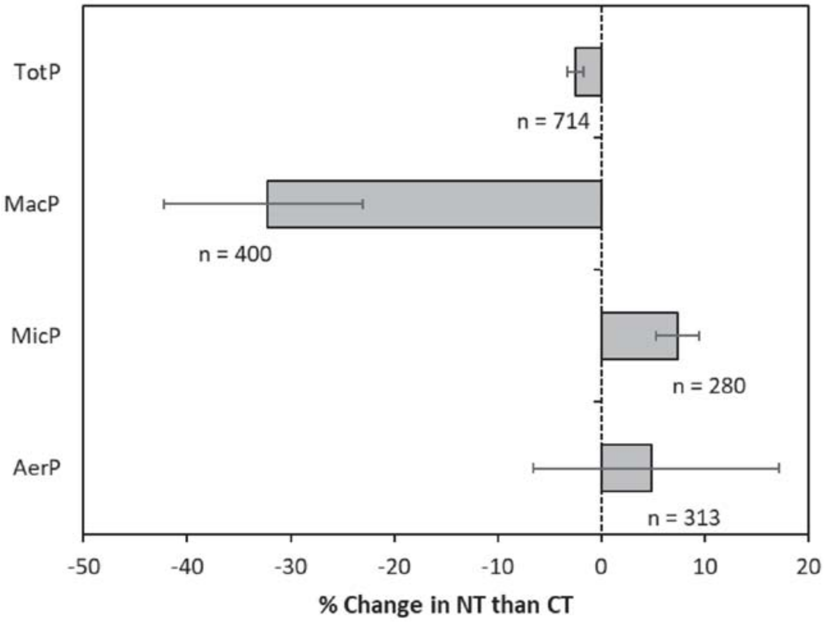

Fig. 1. Impact of tillage on soil porosity under no-tillage (NT) as compared to conventional tillage (CT) in 0-10 cm soil layer. Horizontal bars indicate confidence interval. 'n' means number of paired data points. TotP: Total porosity, MacP: Macroporosity, MicP: Microporosity, AerP: Aeration porosity

compared with plow and reduced tillage. McVay *et al.* (2006) observed higher soil water content (SWC) in the surface soil (0–10 cm) under NT. Jat *et al.* (2018) also observed 7-9% higher volumetric water content at 0-15 cm soil depth under CA based cereal systems over conventional practice. Various tillage operations undertaken in CT disturb the soil surface and create more air pockets in the soil, thus after every tillage operation, soils are exposed to heat and solar radiation which leads to increase the rate of evaporation, loss of soil moisture, and ultimately soil dryness (Licht and Al-Kaisi, 2005). Aggarwal *et al.* (2009) stated that permanent bed can moderate soil temperature more effectively than CT.

Influence of CA on soil aggregation

Aggregate stability and size information is a useful property to predict or evaluate the effect of different agricultural techniques like tillage practices, the addition of organic matter or to acquire knowledge about the susceptibility of soil to wind and water erosion (Nimmo and Perkins, 2002). Fuentes *et al.* (2012) showed that ZT in combination with crop diversification and crop residues retention resulted in a higher proportion of stable macro-aggregates (40%) and higher mean weight diameter (MWD). Paul *et al.* (2013) reported that CT is negatively related to soil aggregate stability when compared to reduced tillage, as indicated by lower values of MWD upon wet sieving. This suggests increased susceptibility to slaking and soil erosion. Bhattacharyya *et al.* (2013) also reported that after 4 years, ZT with raised bed plots had a greater proportion of large macroaggregates (2–8 mm) than CT with a flat and CT with raised bed plots. Jat *et al.* (2019a) observed around 50% higher water stable aggregates as well as improved aggregate indices such as MWD, GMD, aggregate ratio and aggregate stability at surface soil under CA based cereal systems over conventional practice. Oicha *et al.* (2010) showed that the aggregate stability of permanent bed (PB) (0.94) was higher than CT (0.83), but the difference was not significant. Several previous studies had shown better soil aggregation under CA plots than CT (Bhattacharya *et al.*, 2020; Prakash *et al.*, 2004). Dagar *et al.* (2020) reported increases in water-stable aggregates and mean weight diameter by 18 and 2%, respectively over CT at 0-5 cm soil depth in a sandy loam soil. Ratio of macro- to micro-aggregates increased under NT with crop residue mulching. Bhattacharya *et al.* (2020) observed that greater glomalin content of soil was associated with more stable aggregates and higher MWD.

Soil biological health as influenced by CA

Soil organisms such as soil macro and micro flora and fauna play an important role in maintaining soil biodiversity besides serving many ecosystem functions. Soil enzymes play a vital role in catalyzing the reactions essential for organic matter decomposition and nutrient cycling. They are involved in energy transfer, environmental quality and crop productivity (Ekenler and Tabatabai, 2004). Management practices such as tillage, crop rotation/ intercropping and residue management influences different biological activities like microbial populations, soil enzymes, microbial biomass C (MBC) and N (MBN) (Ekenler and Tabatabai, 2004; Choudhary *et al.*, 2018a,b,c; Jat *et al.*, 2019b; 2020; 2021a). In the IGP of India, improved MBC (208%), MBN (263%), dehydrogenase (DHA) (210%) and alkaline phosphatase activity (APA) (48%) were found in CA-based maize-wheat (MW) system as compared to conventional RW system (Choudhary *et al.*, 2018a). However, CA- based RW system also improved the MBC and MBN by ~40% and DHA and APA by ~15% (Jat *et al.*, 2019a) as compared to conventional RW system. Soil enzyme activities and microbial biomasses at different stages of crop growth responded differently in different management practices (Jat *et al.*, 2020). Microbial population viz., bacteria, fungi and actinomycetes improved in CA-based MW system than conventional RW system (Choudhary *et al.*, 2018a,b). Soil biological properties like MBC, APA, fungal and microarthropod population are found as key soil quality indicators under CA based cereal systems (Choudhary *et al.*, 2018a,b). Under different management systems, high SQI (1.45) was recorded in CA-based MW system as compare to CA-based RW system (0.58) and conventional RW system (0.29) (Choudhary *et al.*, 2018b). Residue load and quality influence micro-arthropod population as in the study of Choudhary *et al.* (2018b) it was found higher under RW than MW system. In the next generation sequencing studies it was found that bacterial diversity was higher with CT system than CA based management in cereal (rice/maize based) systems (Choudhary *et al.*, 2018d,e, 2020). *Proteobacteria*, *Acidobacteria*, *Actinobacteria*, and *Bacteroidetes* were the dominating phyla of soil irrespective of management system. But the relative abundance of phyla varies with cropping systems and management systems. The relative abundance of copiotrophs *(Proteobacteria)* was 29% higher in rice-based CA system and 16% higher in maize-based CA system compared to CT practice (Choudhary *et al.*, 2020). The relative abundance of Acidobacteria and Actinobacteria (oligotrophs) was respectively 29% and 91% higher in CT than CA based rice and 27% and 110% higher than maize-based systems. Fungal diversity was found to increase with CA- based management practices, in order of Ascomycota>Basidiomycota> Glomeromycota (Choudhary *et al.*, 2018c). Recently Jat *et al.* (2021b) studied the enzymes activities in rhizosphere and bulk soil (away from roots) after 8 years of Climate Smart Agriculture (CSA) practices and reported higher or similar enzymes activity in bulk soil where residues were retained for longer period and rhizosphere. Recently Datta *et al.* (2021) also observed higher enzymes activity under CSA practices in cereals-based systems of Northwest India.

A study by Kumar and Babalad (2018) showed that all the conservation tillage practices recorded significantly greater SMB-C than CT without crop residues. The improvement in SMB-C was mainly due to frequency of organic carbon contribution from plant biomass which is the main aspect governing the amount of SMB (soil microbial biomass) in soil. Doran (1980) found that NT management brought about a considerably greater soil dehydrogenase activity than CT. Mukumbareza *et al.* (2016) reported higher acid and alkaline phosphatase activities for soil under CA because of more microbial activity and SOM improvement.

Table 4. Nutrient content in conservation tillage (NT) compared to conventional tillage (CT)

Soil depth (cm)	Carbon (%)		Nitrogen (%)		Phosphorus (%)	
	NT	T	NT	T	NT	T
0-5	2.5	1.0	0.3	0.1	100	20
10-15	1.3	1.0	0.2	0.1	10	40

Source: Conservation Technology Information, CTIC Partners, 2000, no 1, p. 7, University of Purdue, Indiana, USA)

Availability of macro (N, P, and K) and micronutrients under CA

Soil nutrient supplies and recycling are increased because of enhanced biochemical decomposition of organic crop residues (Table 4). Incorporation of nitrogen-fixing legume crops in rotation meets much of nitrogen requirement of primary food crops, while other plant essential nutrients often must be supplemented by additional chemical and/or organic fertilizer inputs. Soil fertility is built up with time under CA, and lesser fertilizer amendments are required to achieve optimal yields.

Jat *et al.* (2018) observed increased availability of plant nutrients under CA due to more amount of residue rich in nutrient retained on the soil surface and lesser disturbance associated with CA. There was removal of crop residue and subsequently incorporation of stubbles was done CT. Greater amount of available N in soil under CA was reported by Bhattacharya *et al.* (2020, 2013). Jat *et al.* (2018) reported that available P was 25% and 38% higher under CA than CT, which might be due to higher residue retention and mineralization of organic C. Du Preez *et al.* (2001) observed higher values of available P after 11 years of CA whereas, Ben-Moussa *et al.* (2010) reported no difference in available P after 4 years of CA in Tunisia. Murillo *et al.* (2004) and Malecka *et al.* (2012) reported that the available K content of soil was significantly higher in CA treatments in the 0-15 cm and 15-30 cm soil depths than the CT plots, which can be because of additions of K through crop residues. Recently Jayaraman *et al.* (2021) studied the short-term effect of CA on macro and micronutrient content in a Vertisol of Central India and reported higher N, P, K and micronutrient cations concentration at surface soil (0-5 cm depth) under CA over conventional practice. Jat *et al.* (2018) through nutrient omission study showed that continuous CA for four years can save about 30% N and 50% K fertilizers in Northwest Indian situation.

Carbon Sequestration under Conservation Agriculture

The most important soil health indicator is SOC, especially the concentration of SOC at the surface. SOC plays a great role in holding nutrients, reducing soil erosion, and improving water infiltration. The distribution of SOC in the profile is affected by tillage practices and initial SOC content. Carbon sequestration is the long-term storage of C in oceans, soils, vegetation and geologic formations. SOC sequestration is affected by various factors such as land use and natural vegetation, soil texture, climatic conditions, topographic position and the initial SOC stock (Post and Kwon, 2000; Minasny *et al.*, 2017; Mondal *et al.*, 2020). Vegetation types, irrigation, crop rotation, integrated managements of pest and nutrients and livestock affect C sequestration rate in soil (Patle *et al.*, 2013). At field scale, a positive SOC balance is achieved by enhancing the organic matter supply to the soil and minimizing the C losses by mineralization, leaching and erosion or reducing the SOC decomposition rate. The very important agriculture management practices which can improve the SOC content in soils are CA and agroforestry (Corbeels *et al.*, 2019). Substitution of rice with maize causes higher SOC and increase the stability of humic acid C under the CA (Balla *et al.*, 2022). CA practices can improve SOC stocks by supplying more carbon to soil through greater biomass production and reduction in SOC losses due to surface cover (Corbeels *et al.*, 2019). This causes net sequestration of atmospheric C into the soil, leading to the climate change mitigation (Griscom *et al.*, 2017).

Shifting of CT to minimum tillage or NT practices causes reduction in C emissions (Lal, 2004). CA practices can sequester 0.90 Mg C ha^{-1} yr^{-1} on crop land in African continent (Gonzalez-Sanchez *et al.*, 2019). Lal (2005) calculated that increasing SOC by 1.0 Mg ha^{-1} yr^{-1} can increase food grain production by 32 million Mg yr^{-1} in developing countries. Heenan *et al.* (2004) in Australia showed that changes in SOC at the surface ranged from a loss of 8.2 t ha^{-1} for continuous tilled cereals and residues burnt to a gain of 3.8 t ha^{-1} where stubble was retained and soil was not tilled. Results of 35 studies conducted in different parts of Canada revealed that reduced tillage can sequester 320-150 kg C ha^{-1} (Vanden Bygaart *et al.*, 2003). Jat *et al.* (2019a, b) reported significant improvement in SOC stock and different pools under CA based maize-wheat-mungbean system over conventional tillage-based system in northwest India. Tillage practice can also influence the distribution of SOC in the profile with higher soil organic matter (SOM) in surface layers with ZT than with CT, but a higher content of SOC in the deeper layers where residue is incorporated through tillage (Jantalia *et al.*, 2007; Thomas *et al.*, 2007; Dolan *et al.*, 2006). The higher SOC content in the 0-15 cm soil depth of CA practices might be due to crop residue retention on soil surface; higher plant biomass production leaving more amounts of root residues in the system, and a slow SOM decomposition rate due to minimum soil disturbance. West and Post (2002) concluded from a global database of 67 long-term experiments that SOC levels under ZT were significantly different from SOC levels under conventional and reduced tillage, while SOC levels under conventional and reduced tillage were not significantly different from each other. On the contrary, Álvarez (2005) found no differences in SOC between reduced (chisel, disc, and sweep tillage) and zero tillage, whereas CT (mould board plough, disc plow) was associated with less SOC in his compilation of data from 161 sites with contrasting tillage systems (at least whole tillage depth sampled). Duration of NT adoption could be an important factor for determining the amount C sequestration. Mondal *et al.* (2020) reported an increasing trend of soil C enrichment particularly in the surface soil layer with increase in duration of NT (Table 5). However, the C enrichment was mostly limited up to 10 cm soil depth. Similarly, loamy textured

Table 5. Effect of duration of experimentation and soil texture in soil organic carbon content in no-tillage over the conventional tillage. Mean values are given with number of paired data points in parentheses. * and ** indicates significant difference at p<0.05 and p<0.01, respectively (Mondal *et al.*, 2020)

Soil layer (cm)	Duration of experimentation (years)					Soil texture		
	>6	6-10	11-15	16-20	>20	Sandy	Loamy	Clayey
0-5	21.4 (70)**	26.9 (108)**	39.1 (78)**	47.3 (104)**	52.8 (100)**	-	37.7 (328)**	32.7 (79)**
5-10	2.1 (56)	3.7 (84)**	5.5 (49)*	7.7 (71)**	8.1 (79)**	-	5.2 (239)**	7.5 (58)**
10-20	-0.6 (60)	-1.4 (91)	-1.7 (76)	-3.2 (81)	-3.5 (89)*	-	-2.4 (282)**	1.2 (60)
20-30	1.0 (41)	-0.8 (63)	-3.0 (47)	-2.4 (58)	-14.8 (30)**	-	-3.4 (205)**	-0.3 (18)
30-60	-5.6 (29)	-11.8 (56)**	-4.1 (52)	-3.3 (67)	3.9 (36)	-	-7.4 (196)**	4.5 (27)
>60	-8.2 (10)	3.9 (11)	10.2 (16)*	1.3 (25)	7.5 (15)	-	9.1 (44)	1.6 (26)

Table 6. Effect of different conservation agriculture practices on soil organic carbon sequestration and soil erosion

Management practices	Erosion (Mg ha^{-1} yr^{-1})	Soil Organic C (Mg/$ha^{-1}yr^{-1}$)
Conventional tillage (CT)	16.5	–0.023
CT with increased fertilizer	15.0	–0.006
Ridge tillage (RT)	6.6	0.001
RT with increased fertilizer	5.9	0.027
RT with fertilizer and residues	3.5	0.086

Source: Doraiswamy *et al.* (2007)

soils had a greater improvement in C status than clay soils under NT. Climatic factors like rainfall determines the effect of no-tillage and the effect is more pronounced in drier areas (Chenu *et al.*, 2019).

When crop residue is removed from the field, there is a decrease in SOC stock (Ruis and Blanco Canqui, 2017; Sykes *et al.*, 2018). On the contrary, when crop residue is retained on the soil surface, there is an increase in SOC stock (Wang *et al.*, 2015). Although Datta *et al.* (2019) found higher carbon mineralization from maize residues placed at soil surface than incorporated to soil in a laboratory study. Ridge tillage along with application of crop residues and fertilizers can improve SOC through reduction in soil erosion (Table 6) (Doraiswamy *et al.*, 2007). Chakrabarti *et al.* (2014) reported after six years of CA practices, SOC increase to 0.71 to 0.74% in NT wheat with or without residue retention compared 0.58% in CT. Across the globe, there are many experimental reports available mentioning that SOC is concentrated at surface 0-5 cm soil layer under CA which was due to zero tillage and surface retention of crop residues and not in the whole soil profile (Dolan *et al.*, 2006; Luo *et al.*, 2010; Piccoli *et al.*, 2016). Veloso *et al.* (2019) proved that most of the carbon accumulated at 0-5 cm soil depth under CA using 30 years old long-term experiment on an Acrisol in southern Brazil. While a consensus seemed to exist on the potential of NT for C sequestration and climate change mitigation, recent studies seem to indicate that the abandonment of tillage may yield limited benefits for C sequestration (Baker *et al.*, 2007; Geisseler and Horwath, 2009; Luo *et al.*, 2010; Mchunu *et al.*, 2011; Dimassi *et al.*, 2014; Powlson *et al.*, 2014). Mchunu *et al.* (2011) showed for instance that the abandonment of tillage only enhances soil C stocks in the first 2 cm of the soil while no difference was observed from soil surface to 1.0 m, confirming the theory of Baker (Baker *et al.*, 2007) of C redistribution instead of sequestration.

Crop residues enhance the biological activity and causes low nutrient release into the soil and moderate the soil hydrothermal regimes. Combination of crop residue and minimum tillage can sequester more carbon in the 0-5 cm of soil depth (Ghimire *et al.*, 2008).

Gill (2014) reported that precision land levelling could reduce almost 0.15 Mg of CO_2eq yr^{-1} ha^{-1} GHGs emission in Indian condition due to less pumping time of irrigation water and decreased crop growth period. Crop rotation along with reduced and no tillage can sequester more carbon than mono-cropping system (Sainju *et al.*, 2006; Mandal *et al.*, 2007;). Meyer-Aurich *et al.* (2006) reported that carbon storage of soils was higher when alfalfa was introduced in corn–corn rotation. Proper management of agroforestry system can improve SOC stocks in soil (Montagnini and Nair, 2004). Montagnini and Nair (2004) reported the potential carbon sequestration rate of 1.5 to 3.5 Mg C ha^{-1} yr^{-1} in smallholder agroforestry system of tropics. Improved water management improves SOC sequestration by enhancing net primary productivity (NPP) and more biomass addition to soil (Sykes *et al.*, 2018). The possible effect of no-tillage in increasing SOC is more prominent when cover crop is included in the system (Chenu *et al.*, 2019). Field studies conducted by Autret *et* *al*. (2016) and meta-analyses by Poeplau and Don (2015) have revealed the potential of cover crops to enhance SOC content.

Conservation Agriculture for Climate Smart Agriculture

Conservation farming is now recognised globally as the most important integrated farming system with the potential to reduce the impacts of agriculture, improve and protect the natural resource base, address carbon emissions and climate change issues and improve social and economic outcomes for farming communities all over the world. The global concern about soil degradation is helping to support policies towards conservation farming at the international level. The link between C sequestration in soil, global warming and the role of CA is now recognised by agricultural policy makers world-wide. Conservation agriculture can assist in the adaptation to climate change by improving the resilience of agricultural cropping systems and hence by making them less vulnerable to extreme climatic situations. Improved soil structure and high-water infiltration rate can reduce the chances of flooding and erosion after high intensity rainfall. Increased SOM improves soil water holding capacity and helps to sustain crops in drought periods (Bhattacharya *et al.*, 2020; Kumar *et al.*, 2020). Yield variations under CA in extreme years are less pronounced than conventional agriculture. CA mitigates climate change by emitting lesser amount of GHGs like carbon dioxide, nitrous oxide (through reduction in fossil fuel consumption and elimination of crop residue burning) and sequestrating SOC over a long period (Parihar *et al.*, 2016). In paddy cultivation, no-till systems and adequate water management minimize the release of GHGs, like methane and nitrous oxides

Challenges of Conservation Agriculture

The main constraints to the adoption of CA practices are:

- Knowledge on how to do it (technology know how) and firm on traditional mind set of farmers
- Inadequate policies such as commodity–based subsidies including machinery and direct farm payments for carbon credits and ecosystem services.
- Unavailability of appropriate equipment and machinery, and suitable herbicides to effectively control weeds under CA.
- Knowledge on carryover of pest and pathogens from previous crop to new crops
- Competitive use of crop residue.

In addition, there are few researchable issues which we need to consider

- How good is the C capturing capacity of CA? In CA, crop residues are generally retained at soil surface. The amount of crop residue carbon to be converted to SOC is a very critical issue here. In general, >95% goes out of the system, only ~5% left out as SOC even with best of the best management system. Improving C little of such conversion has a tremendous effect onto C economy of CA system. Indications are there when legumes are included such conversion of CR-C to SOC also increases significantly.
- How can we confer stability or recalcitrance character to SOC and allocate to passive pool? What are the edaphic and ecological factors favour such allocation?
- There is no fertilization and irrigation schedule for different crops under CA. Fertilization and irrigation protocol needs to be formulated for CA practices.
- Till now most of the experiments that reported the effects of CA on different parameters are short- or medium-term experiments. Ecosystem properties (slow-to-change attributes) take long time to mature/stabilize. Recently, Cusser *et al*. (2020) showed minimum 15 years are required to have a consistent trend in yield and soil water availability under no till agriculture.

Conclusions

To avoid the adverse effects of conventional farming practices, CA can play a significant role in enhancing soil health and SOC sequestration and ensuring agricultural sustainability. Conservation agriculture also an option to achieve the goal of 4 per 1000 through carbon sequestration. Conservation agricultural practices improve soil health by increasing soil organic matter (SOM), improvement in soil structure due to formation and protection of soil aggregates, reducing oxidation of SOM and modifying the soil hydrothermal regimes when compared to conventional tillage. Application of crop residues, following suitable crop rotation and no tillage or minimum tillage can help to conserve soil moisture, reduce soil erosion and increase SOC sequestration. Rate and amount of SOC to be sequestered vary with locations, soil types, soil depths, land use and landcovers and climatic conditions.CA can help in climate change adaptation by improving the resilience of agricultural systems and hence by making them less susceptible to extreme climatic conditions. Various issues such as knowledge gap, inadequate policies, carryover of disease and pest and competitive use of crop residues should be addressed at various platforms for rapid spreading of CA in different agro-climatic zones covering dominant soil types and cropping systems.

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Received: March 23, 2021; Accepted: June 10, 2021