Conservation agriculture for regenerating soil health and climate change mitigation in smallholder systems of South Asia

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Contents

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Abstract

The increase in agriculture production to meet the food demand of growing human population from a limited availability of arable land with low environmental footprints and preserving natural resources (soil, water and air) simultaneously are major challenges in South Asia. The situation is further complicated by the climate change, which will further lower the food production, compounding the challenge of meeting food demand. Conservation Agriculture (CA) is solution to several challenges being faced in farming such as soil health, climate change, water scarcity, agricultural pollution, farm profitability, human health, etc. This exhaustive review examines the published literature from South Asia to assess the impact of CA on soil organic carbon (SOC) and the subsequent impacts on soil health (physical, chemical and biological properties), C sequestration and greenhouse gases emissions in major cropping systems. The results from several studies demonstrated that CA increased SOC and improved soil health parameters, mainly in the surface soil layer. The effects of CA on the changes in soil pH and electrical conductivity are small. The CA showed a remarkable positive impact on the nutrient availability in the soil. The CA system helped in both climate change mitigation and adaptation for sustainable crop production. The present gaps in our knowledge in soil health assessment and research agenda to fill the gaps are also included in this chapter. We hope this review of past accomplishments, current activities, and future opportunities will stimulate additional soil health research throughout the 21st century.

1. Introduction

Around 1.94 billion people live in South Asia and by 2050, that number is expected to grow to 2.40 billion (www.worldometers.info/world-population/southern-asia-population, assessed on 01 September 2022). Meeting the future food demand for the burgeoning population is a great challenge in the face of rapidly depleting natural resources and growing climate crisis (Jat et al., 2020b, 2022; Pooniya et al., 2021). The anthropogenic climate change has already slowed down the agricultural productivity growth by 21% in last 50 years (Ortiz-Bobea et al., 2021). The agrifood systems supporting growing population are responsible for one-third of global anthropogenic greenhouse gases (GHGs) emissions (Crippa et al., 2021) and hence further intensifying the climate crisis. The climate risks in recent past anticipated climate changes have been very frequent; leading to significant yield losses, for example, heat wave 2022 and highly variable monsoon rains in summer 2022 in India. Globally, deterioration in soil health is the key constraint contributing to poor yields in subsistence agriculture, and thus a major contributor to food and nutritional insecurity of billions (Lal, 2009). Among several factors making agriculture unsustainable in South Asia, conventional tillage (CT) based input intensive farming practices are significant ones specially for deterioration of soil health; the foundation for the sustainability of farming. The CT-based management practices have resulted in decrease soil organic matter (SOM) leading to deterioration of soil health, loss of soil biological fertility and biodiversity (Choudhary and Behera, 2020a; Jat et al., 2020a, 2022). Deteriorating soil health, diminishing soil organic carbon (SOC), and declining system productivity are barriers to achieving sustainable production in the conventional rice (*Oryza sativa*)—wheat (*Triticum aestivum*) (RW) cropping system in South Asia (Hati et al., 2020; Jat et al., 2020a; Mondal et al., 2021; Roy et al., 2022; Sapkota et al., 2017). Without long-term corrective measures, the challenge will further compound given the agrifood systems' contribution of greenhouse gases (GHGs) and rapidly deteriorating soil health and drying aquifers. Therefore, agrifood systems require systemic solutions bundling climate-smart, regenerative and profitable innovations without jeopardizing the soil health and the environment for sustainable crop production in smallholder systems of South Asia (Jat et al., 2022). The future increases in food production in South Asia requires new management approaches such as Conservation Agriculture (CA) that are efficient and climate smart to make perceptible contributions to the United Nations' Sustainable Development Goals (SDGs) (Jat et al., 2018; Roy et al., 2022; Sapkota et al., 2017). In the past two decades, concept of CA in South Asia has emerged as a sustainable approach for greater agricultural production and profitability, for improving soil health and for mitigating adverse effects of climate change as a "sustainable intensification" strategy (Bell et al., 2018; Gathala et al., 2017, 2020b; Hobbs et al., 2008; Jat et al., 2020a,b, 2021; Kumar and Nath, 2019; Mondal et al., 2021).

2. Conservation agriculture as regenerative and scalable solution

CA system is characterized by three interlinked core principles: (1) continuous ZT or direct seeding with minimum mechanical soil disturbance; (2) permanent organic mulch (crop residues, cover crops) on the soil; and (3) diversification of crop rotations including legumes, along with other complementary good agricultural production practices to optimize soil health and resilience to climate change (FAO, 2014; Farooq and Siddique, 2015; Kar et al., 2021). CA is currently adopted over 205 million hectares globally (Kassam et al., 2020), have shown promise to address the soil health and climate change mitigation through soil carbon sequestration and GHG emission reduction (Gathala et al., 2020b; Jat et al., 2020b, 2022). The principles of Regenerative Agriculture are the same as listed above for CA, with integrating livestock as an extra one. Like CA, Regenerative Agriculture addresses restoration of soil health including mitigation of climate change and reversal of biodiversity loss. Permanent bed planting with minimum soil disturbance and maintaining permanent soil cover with crop residues as mulch and following crop diversification is another form of CA system. The three CA-principles should be complemented with the best agronomic practices for systems sustainability in any agri-food systems. Recent studies by Gora et al. (2022) and Jat et al. (2020b) demonstrated many benefits of CA in terms of increases in yield, water use efficiency (WUE), net income and a reduction in global warming potential (GWP) when CA principles are implemented either separately or in tandem in diversified cropping systems of South Asia.

CA practices have been extensively and widely adopted in irrigated ecosystems in the Indo-Gangetic Plains (IGPs) of South Asia under the RW system (Parihar et al., 2016; Powlson et al., 2016). The CA concept was first introduced in South Asia during the 1980s by using zero till (ZT) technology in India and Pakistan. The CA system is now spreading rapidly throughout the South Asia. The area under CA in South Asia is currently rather small compared to the rest of the world (Gupta and Sayre, 2007; Hossain et al., 2015; Kassam et al., 2019; Poddar et al., 2017), primarily due to the long-term history of CT and small farm holdings that have traditionally been managed with tillage-based systems. A recent estimate suggested a partial CA-based system (at least one crop has ZT, with or without residue retention) is spread to over 2.5 million ha in South Asia (Jat et al., 2020b). In rice-wheat systems of South Asia, CA practices are generally adopted in wheat (defined as partial CA), while following rice is grown as traditional crop due to issues of high weed infestation and iron deficiency causing low productivity of ZT dry seeded rice. In CA-based RW system, >75% of wheat straw is collected after combine harvesting for use as animal fodder. The remaining wheat stubbles (about 2 Mg ha^{-1}) are retained as mulch. On the other hand, about 75% of rice straw is disposed of through on farm burning to clear the fields for wheat sowing causing intense air pollution in northwestern India. New generation of machinery (Happy Seeder) is now available which can directly sow wheat into heavy loads of rice residue without burning in rice-wheat system (Yadvinder-Singh et al., 2017a). To address the challenges of soil health and environment degradation, declining crop productivity and profitability under CT agriculture, CA is now being promoted in South Asia as sustainable options (Gathala et al., 2017, 2020b; Hobbs et al., 2008; Jat et al., 2020b). The impacts of CA systems on soil health integrating soil physical, chemical and biological attributes together are mainly reported from India and Bangladesh but relatively less studied in other countries of South Asia.

3. Soil health defined and parameters

Soil health is regulated by the interactions of the physical, chemical, and biological properties, which are sensitive to land management practices (Islam and Weil, 2000) and vary in space and time. The health of the soil, plants, animals, humans and ecosystems are interdependent, interconnected and indivisible (Wall et al., 2015). Doran and Zeiss (2000) and Norris et al. (2020) defined soil health as the continued capacity of soil to function as a vital living system, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Soil health is the capacity of soils to provide a sink for carbon to mitigate climate change and a reservoir for storing essential nutrients for sustained ecosystem productivity. The terms soil quality and soil health are often used interchangeably to describe the soil's ability to support crop growth without becoming degraded or otherwise harming the environment.

The soil health indicators could be site-specific for the intensively managed soils of the IGPs of South Asia. Since it is impossible to consider all the soil indicators, it is necessary to make a selection. With regard to the selection of properties for use as indicators, Doran and Parkin (1997) consider a "*minimum data set*" (MDS) related to physical, chemical and biological properties for use in soil health evaluation. However, it is difficult to decide which soil health indicators and soil functions need to be measured, and how to best measure those properties when attempting to assess soil health?

CA systems are known to promote healthy soil over time for sustainable production systems and enhance resource use efficiency (water and nutrient), and conserve natural resources without sacrificing yields (Choudhary and Behera, 2020c; Hobbs, 2007; Indoria et al., 2017a; Kumar and Nath, 2019; Mondal et al., 2021; Reicosky, 2020; Somasundaram et al., 2020) and reduction in soil erosion loss (Turmel et al., 2015). Generally, SOC is considered as a component of the soil chemical health; however, in this chapter, we considered that SOC as an independent soil health indicator, which influences all the three physical, chemical and biological indicators.

The changes in soil health are monitored using a wide range of physical (soil erosion, aggregation and aggregate stability, bulk density, infiltration rate, soil porosity, compaction, hydraulic conductivity, plant available water rooting depth, soil heat capacity and the temperature regime), chemical (pH, electrical conductivity, total N, available nutrients) and biological (microorganisms and their microbial biomass C and N, enzyme activity, respiration, mineralizable N, microbial biomass C and N, earthworm biomass) indicators (Fig. 1). The objective of this review is to analyze the information on the impact of CA systems on different attributes of soil health with emphasis on C sequestration and climate change in South Asia.

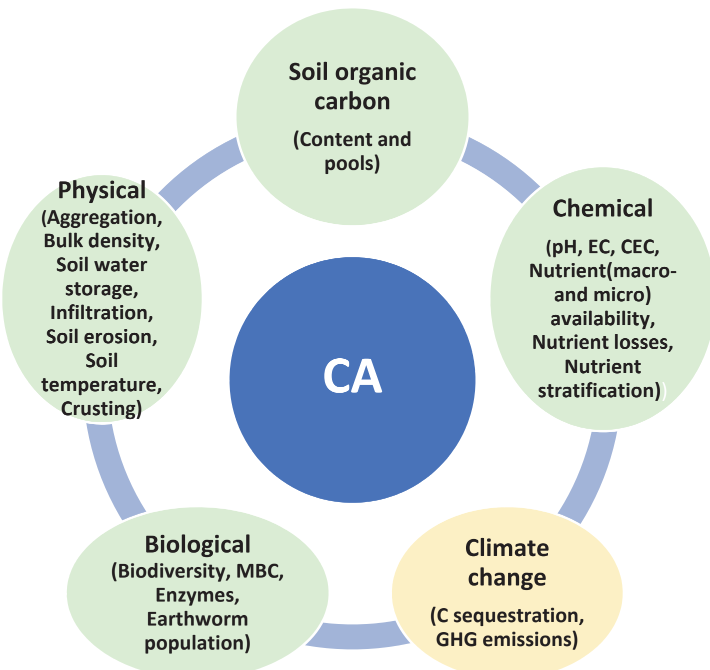

Fig. 1 Soil health indicators and climate change delivered through Conservation Agriculture. CEC, Cation exchange capacity; EC, Electrical conductivity; GHG, Greenhous gases.

4. Conservation agriculture and soil carbon health

Soils in the arid and semi-arid tropics regions of South Asia are generally low in SOC content due to intensive tillage, removal or burning of crop residues and high temperature (~45–50 °C) during the summer season causing fast microbial decay of SOM (Wani et al., 2003; Yadvinder-Singh, 2018). Improving SOC in arable soils is one of the important strategies to achieve sustainable yields and mitigate climate change. SOC is considered as one of the most important attributes of soil health, being inextricably linked to the physical, chemical and biological indicators of soil health, and is an important driver of agricultural sustainability (Bünemann et al., 2018; Jat et al., 2019a; Mondal et al., 2019; Rajan et al., 2010). The knowledge of particulate organic carbon (POC) and active C fractions of SOC is desirable because these fractions respond quicky to management practices compared to SOC content (Aziz et al., 2009). In CT, destruction of C-rich macroaggregates results in oxidation of intra-aggregate SOC leading to low levels of SOC (Dey et al., 2020; Jat et al., 2019b; Parihar et al., 2019). The detrimental effects of CT on soil health could be reduced by adopting CA practices that increase the accumulation of SOC in surface soil due to minimal soil disturbance and retention of crop residues (Bhattacharyya et al., 2015; FAO, 2014). The increase in the SOC content in soil can be achieved by either increasing C input or decreasing C loss through adopting CA practices. This section collates the information on the potential impact of CA on SOC and C sequestration in the context of South Asia.

4.1 Soil organic carbon

A wide range (10–75%) in the accumulation of SOC (both SOC content and stock) in surface soil layer (0–15 cm) with CA adoption have been widely reported in several studies from South Asia, irrespective of soil type and climate (Table 1). Many other researchers from South Asia (Bhattacharyya et al., 2019; Hati et al., 2015a; Sarker et al., 2018; Tiwari et al., 2021) have also reported significant increases in SOC in surface layer of soil under CA compared to CT system. The CT systems lead to considerable loss of SOC during the tillage operations due to its disruptive effect on macro-aggregates and increased soil microbial respiration (Choudhary and Behera, 2020a,b,c; Das et al., 2021). The reasons for wide range of increase in SOC under CA systems over CT are possibly due to the differences in climate (temperature and moisture), soil characteristics (texture and native organic matter content), residue load and quality, duration of the study, sampling depth and the

Table 1 Effect of Conservation Agriculture system on soil organic carbon (SOC, Walkley & Black).

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	SOC content ($g\,kg^{-1}$) CT	CA	Δ (%)	References
Bihar, India	Rice-wheat	Clay loam	12	0–15	22.9	27.5	+20.1	Dey et al. (2021)
				15–30	19.9	28.0	+45.7	
Haryana, India	Rice-wheat	Sandy loam	4	0–15	4.5	7.5	+66.7	Jat et al. (2019b)
				15–30	3.5	3.6	+2.9	
Haryana, India	Rice-wheat	Sandy loam	6	0–15	4.9	8.2	+67.3	Jat et al. (2019b)
				15–30	4.4	4.0	−9.1	
New Delhi, India	Rice-wheat	Sandy clay loam	3	0–15	6.95	7.25	+4.3	Dey et al. (2016)
				15–30	4.04	4.24	+5.0	
Punjab, India	Rice-wheat	Sandy loam	5	0–7.5	5.94	6.86	+15.5	Bera et al. (2017)
Punjab, India	Rice-wheat	Sandy loam	5	0–15	4.80	6.20	+29.1	Dhaliwal et al. (2020)
				15–30	3.27	4.00	+22.3	
Punjab, India	Rice-wheat	Sandy loam	5	0–7.5	14.8	16	+8.11	Sharma et al. (2021)
				7.5–15	12.3	13.9	+13.5	
Haryana, India	Rice-wheat	Sandy loam	4	0–15	4.5	7.7	+71.1	Jat et al. (2018)
				15–30	3.5	3.6	+2.9	
New Delhi, India	Rice-wheat	Sandy loam	5	0–7.5	5.53	6.75	+22.1	Parihar et al. (2019)
				7.5–15	4.77	5.82	+22.0	
				15–30	4.57	5.44	+19.0	

New Delhi, India	Rice-wheat	Sandy loam	4	0–15	5.11	6.05	+18.4	Parihar et al. (2020)
				15–30	4.53	5.52	+21.9	
Uttar Pradesh, India	Rice-maize	Sandy loam	5	0–15	4.30	5.92	+37.7	Singh et al. (2016)
				15–30	2.84	3.76	+32.4	
Alipur, Bangladesh	Mustard-rice	Silt loam	5	0–10	6.56	10.02	+52.7	Alam et al. (2018a)
Uttar Pradesh, India	Rice-based cropping systems	Sandy loam	7	0–20	3.73	5.21	+39.7	Kumar and Nath (2019)
New Delhi, India	Wheat-mungbean	-do-	2	0–15	15.2	16.4	+7.9	Nath et al. (2017)
M.P, India	Soybean–wheat	Vertisol	3	0–15	5.3	5.5	+3.8	Somasundaram et al. (2019)
				15–30	4.3	04.4	+2.3	
New Delhi, India	Maize based	Sandy loam	7	0–15	4.8	6.5	+34.8	Parihar et al. (2016)
				15–30	4.5	5.7	+26.6	
New Delhi, India	-do-	Sandy loam	6	0–5	5.46	7.68	+37.2	Parihar et al. (2018)
				5–15	4.71	6.01	+33.9	
				15–30	4.35	5.52	+26.9	
Tripura, India	Rice-rice	Sandy clay loam	3	0–20	10.6	10.9	+2.8	Yadav et al. (2019)

Continued

Table 1 Effect of Conservation Agriculture system on soil organic carbon (SOC, Walkley & Black).—cont'd

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	SOC content ($g\,kg^{-1}$)			References
					CT	CA	Δ (%)	
Patna, Bihar, India	Rice-wheat/maize	Silty clay	6	0–20	6.38	7.24	+13.5	Nandan et al. (2019)
Haryana, India	Rice/maize-wheat	Loam	4	0–15	6.5	11.1	+70.8	Jat et al. (2019b)
				15–30	3.8	3.8	0.00	
			6	0–15	6.3	11.0	+74.6	
				15–30	5.6	5.2	−7.1	
Karnal, India	Rice/maize-wheat	Typic Natrustalf	6	0–15	4.7	8.4	+78.7	Choudhary et al. (2018c)
M.P., India	Soybean–wheat	Heavy clay	12	0–5	5.9	8.8	+49.2	Kushwa et al. (2016)
				5–15	5.0	6.3	+26.0	
				15–30	4.3	5.0	+16.3	
M.P., India	Soybean–wheat	Clay	6	0–5	7.8	10.4	+33.3	Hati et al. (2015a)
				5–15	5.9	6.3	+6.8	
				5.1	5.0	+2.0		
New Delhi, India	Pearl millet-based	Loamy sand	3	0–15	5.0	5.5	+10.00	Singh et al. (2018)

Peshawar, Pakistan	Maize-wheat	Silty clay loam	2	0–20	9.12	9.60	+5.3	Khan et al. (2019)
Bihar, India	Rice-maize	Clay loam	2	0–15	7.52	7.68	+10.0	Sahoo et al. (2021)
New Delhi, India	Rice-mustard-Mb	Sandy clay loam	8	0–15	5.26	6.39	+21.1	Das et al. (2018)
				15–30	3.02	3.66	+21.2	
Gazipur, Bangladesh	Rice-wheat-Mb	Clay loam	4	0–15	1.2	1.8	+50.0	Alam et al. (2014)
New Delhi, India	Rice-wheat	Clay loam	5	0–5	6.92	9.58	+38.4	Mondal et al. (2020a)
				5–15	4.34	5.86	+33.0	
Haryana, India	Rice-wheat	Loam	10	0–5	6.30	9.90	+57.1	Roy et al. (2022)
				5–15	6.80	7.90	+16.2	
				15–30	6.30	3.70	−41.3	
Soil organic carbon stock (Mg ha^{-1})								
New Delhi, India	Rice-wheat	Sandy clay loam	3	0–5	5.48	6.17	+12.6	Bhattacharyya et al. (2015)
				5–15	11.3	11.6	+2.56	
Bihar India	Soybean-wheat	Clay loam	7	0–5	3.5	6.1	+74.3	Sapkota et al. (2017)
				5–15	7.1	9.0	+26.8	
Bihar, India	Soybean-wheat	Silty clay	7	0–10	16.2	19.4	+19.8	Samal et al. (2017)
				10–20	15.1	15.2	+0.93	

Continued

Table 1 Effect of Conservation Agriculture system on soil organic carbon (SOC, Walkley & Black).—cont'd

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	SOC content (g kg^{-1}) CT	CA	Δ (%)	References
Bihar, India	Soybean-wheat	Clay loam	6	0–15	46.6	55.7	+19.5	Dey et al. (2020)
				15–30	42.2	58.8	+39.3	
Bihar, India	Rice-wheat	Silty clay	10	0–7.5	7.1	10.0	+40.8	Mondal et al. (2021)
				7.5–15	5.1	6,9	+35.3	
				15–30	8.1	10.3	+27.2	
West Bengal, India	Rice-maize/wheat	Silt loam	4	0–5	8.0	9.6	+20.0	Rakesh et al. (2021)
				5–10	7.2	8.1	+12.5	
				10–20	8.1	12.3	+51.9	
Haryana, India	Rice/maize wheat	Clay loam	3	0–10	6.8	10.5	+54.4	Choudhary et al. (2018a)
New Delhi, India	Maize-wheat	Sandy clay loam	2	0–5	5.82	6.87	+18.0	Das et al. (2018)
				5–15	10.7	12.9	+20.8	
				15–30	12.4	14.5	+17.2	
Haryana, India	Rice/maize-wheat	Loam	8	0–15	13.0	16.2	+24.6	Patra et al. (2019)

CT, Conventional till; Mb, mungbean.

cropping system used (Jat et al., 2019a; Kumar et al., 2018; Samal et al., 2017; Yadvinder-Singh and Sidhu, 2014). According to Luo et al. (2017) inherent SOC content, C input amount and climate are the three most dominant variables, which can influence SOC dynamics. The increases in SOC content under CA over CT are linked to slower decomposition rates of C from surface residues and minimum soil disturbance (Choudhary et al., 2018a; Ghimire et al., 2012; Jat et al., 2019b; Yadvinder-Singh et al., 2010). Jat et al. (2022) described that increase in SOC due to increased earthworm activity in CA plots promoted the formation of stable aggregates that protected the SOC against microbial attack. Choudhary and Behera (2020a,b,c) reported the increase of 8–9% in SOC content under CA than CT, respectively, measured after two annual cycles of maize-wheat (MW) system. Choudhary et al. (2020) reported much higher increase (110%) in SOC content under CA over the CT after 4 cycles of RW and MW systems. Dey et al. (2016) reported that CA practices showed prominent effect on the SOC in 0–15 cm layer even after 2 years of RW rotation. Salahin et al. (2021) reported increase in SOC content under strip tillage plus high residue load (6 Mg ha^{-1}) in non-rice crops at the at 0–5 cm depth compared to CT but it remained unaffected at 5–10 cm and 10–15 cm soil depths after 3 years of rice-lentil/wheat-jute cropping system in Bangladesh. The increases in SOC under CA were associated with a better physical protection of macro-aggregates as well as minimal contact between residue and soil which s remain on the soil surface with lesser turnover of C.

From a literature review, Page et al. (2020) concluded that while the effects of CA on SOC worldwide are variable, with both increases and decreases observed. In regions where soil and climatic conditions are favorable for biomass production and where the system does not negatively impact yield, then CA can lead to higher amounts of SOC relative to CT systems, particularly in the surface of the soil layer. Sun et al. (2020) presented a global meta-analysis of ZT-induced changes of SOC and found a significant increase in SOC (in the top few cm) in arid and semi-arid regions, while in cold and cold humid regions, no changes were observed. In this way, most croplands in Australia, China, India, Pakistan and Sub-Sahara Africa are therefore, likely to profit more from CA-based management practices.

In majority of studies from South Asia, SOC content is based on equal depth basis ignoring the role of bulk density (BD) influencing the SOC calculations under CA and CT systems. This might lead to overestimation or underestimation of SOC values depending on the changes in BD (Govaerts et al., 2009a). Palm et al. (2014) concluded that most of the published values of SOC are almost certainly inflated by 20–30% due to the inappropriate soil sampling method used: equal soil depth rather than equal soil mass, particularly in cases where surface BD is higher under CA compared to CT systems. Dey et al. (2020) reported that on equal soil mass basis, the increase in SOC stock of 0–15 cm under ZT system was ~13%, whereas calculations based on equivalent depth basis showed an increase of 20% over CT.

In most of the studies, SOC content under CA is measured at 0–15 cm depth and in a few cases up to 40 cm depth. Hati et al. (2020) observed lower SOC content in CA compared to CT at lower depths. Similarly, Roy et al. (2022) reported significant increases in SOC at 0–5 and 5–15 cm depths under CA system after 10 years of RW-mungbean (*Vigna radiata*, Mb) and MW-Mb compared to CT RW rotation. However, a reverse trend was observed at 15–30 cm depth, where significantly lower SOC content was recorded under CA compared to CT. Rakesh et al. (2021) recorded 18% increase in total soil C under ZT practice over CT at 0–10 cm depth under a long-term rice-maize (*Zea mays*) (RM) cropping system. However, at lower depth (10–20 cm), comparatively higher amount of total OC concentration was found in the soil under CT system in comparison to ZT system. The meta-analyses suggest a mere redistribution of soil C under ZT, with a net gain in shallow depths and a net loss in deeper layers (Luo et al., 2010). Therefore, estimation of SOC stock for upper soil layers (say up to 30 cm) could cause overestimation of SOC accumulation under CA (Mondal et al., 2020a).

There are, however, many reports showing significant increases in SOC at lower soil depths (15–30 cm and below) under CA compared to CT systems (Dey et al., 2021; Jat et al., 2022, 2021; Parihar et al., 2018; Samal et al., 2017). Zahid et al. (2020) from Pakistan observed significant increase in SOC content under CA even at lower depths (15–45). From a long-term (15 years) study conducted in ZT wheat in RW cropping system in semi-arid regions of northwestern India, Singh et al. (2014) reported that effective depth of increase in SOC content depended on soil texture. A significant increase in SOC content was observed in 0–10, 0–15 and 0–25 cm layers in sandy loam, loam and clay loam soils, respectively, indicating build-up of SOC to a deeper depth with increase in fineness of the texture of soil. Mondal et al. (2020a) recorded 32% higher SOC content in CA at 0–15 cm depth, but it was 27% lower in the 15–30 cm layer compared to CT. Many reports (Luo et al., 2010; Piccoli et al., 2016) from other parts of the globe also showed significantly higher SOC content under CT at lower soil depth (15–30 cm). The increase in SOC at lower depths was ascribed to the leaching of dissolved organic carbon through rainfall and irrigation water (Samal et al., 2017; Somasundaram et al., 2020). Other reasons for increase in SOC under CA in lower layers might be due to increase in deep rooting system of crops, and inclusion of deep-rooted legumes in the cropping systems. Inclusion of legumes in the cropping system (green gram and cluster bean) increased SOC. Mondal et al. (2020b) reported that inclusion of legumes such as Mb (*Vigna radiata*) and clusterbeans (*Cyamopsis tetragonoloba*) in the cropping system increased SOC concentration at depths below 15 cm. Choudhary et al. (2018b) and Jat et al. (2019b) reported 50–75% increase in SOC content under CA-based MWMb and RWMb systems over CT RW system at 0–15 cm soil depth after 4–6 years of the study in the IGP of northwestern India. A similar trend was observed in total OC content. The increase in SOC content was more after 6 years of CA than that after 4 years of the study. Study by Pooniya et al. (2021) however showed relatively small increase (18–20%) in SOC under CA-based practices in the top 0–10 cm layers at 7 years after adoption. Saurabh et al. (2021) reported that SOC concentration under CA was increased by 18.5% in the upper layer of soil (0–10 cm) and an increase of 15% in 10–20 cm compared to CT. In CA, increasing cropping intensity with the integration of a legume, e.g., sesbania (*Sesbania aculeata*) as green manure and Mb in double cropping systems will result into greater augmentation of SOC content compared to cropping system with no legume (Alam et al., 2017; Bhattacharyya et al., 2015; Jat et al., 2018; Mondal et al., 2021). Somasundaram et al. (2019) reported that cropping systems had a significant effect on SOC content at 0–15 and 15–30 cm depths; maize–chickpea had significantly higher SOC than soybean–wheat cropping system at both the depths.

Alam et al. (2018a,b) observed significant increases in SOC under CA (strip till + high residue load for non-rice crop and non-puddled for rice) in the surface layer at two locations of the Eastern Gangetic Plains (EGPs) of Bangladesh after 4–5 years of intensive triple rice-based cropping systems. The increase in SOC stock was equivalent to an additional 3.8–4.2 Mg C ha^{-1} in the soils after 5 years under CA (Alam et al., 2018b). Mondal et al. (2021) measured the effect of CA practices on SOC after the 10 cropping cycles of RW system in the EGPs of India. The results revealed that adoption of CA improved the SOC by 46% and 33% in 0–7.5 and 7.5–15-cm soil layers compared to CT, respectively. The impact of CA on total C was visible in the 0–60 cm soil profile.

Alam et al. (2019) observed significant increase in SOC content and C stock in 0–7.5 cm layer in CA-based legume- and cereal-based systems, but remained unchanged at 7.5–15 cm depth. Based on the C balance, it is estimated that annual crop residue inputs of 4 Mg C ha^{-1} under CA in the legume-dominated system, and 1 Mg C ha^{-1} under CA in the cereal-dominated system, would be required to maintain SOC at the antecedent level. It may be concluded from the results of several studies, that CA through crop residue addition coupled with minimum soil disturbance plays a crucial role in increasing SOC content by increasing aggregation and providing the physical protection of C through soil aggregation in a semi-arid region of South Asia.

Based on the analysis of several data from the published literature, Powlson et al. (2016) reported annual increases in SOC stock between 0.16 and 0.49 Mg C ha^{-1} $year^{-1}$ under CA compared to CT. Maintaining a constant level of SOC stock (zero change) requires C input of 3.47 Mg C ha^{-1} $year^{-1}$ in Vertisols under soybean-based system under semi-arid tropics of India (Srinivasarao et al., 2015). A positive relationship has been observed between air temperature and critical C input requirement, indicating the need of a higher or repeated C inputs to maintain SOC in tropical dry ecosystems.

Stratification ratio of >1 suggests greater increase in SOC in the surface layer than in the immediate lower layer and is regarded as an improvement in soil health. Hati et al. (2020) reported stratification of SOC and available nutrient levels in soil under CA due to greater increases in the soil surface compared to lower layer. Jat et al. (2019b) reported SOC stratification ratio of 2.5 in CA system. The stratification ratio is strongly influenced by the soil texture. For example, in the Coochbehar soils (sandy loam textured), downward movement of total C and its fractions may have occurred into the soil profile, resulting in lower stratification than that in the Malda soils of finer soil texture.

According to Lal (2006) crop yields can be increased by 20–70 kg ha^{-1} for wheat, 10–50 kg ha^{-1} for rice, and 30–300 kg ha^{-1} for maize with every 1 Mg ha^{-1} increase in SOC pool in the root zone, depending on climate, soil type, and site-specific management in South Asia. Srinivasarao et al. (2013) reported a highly significant positive correlation between sustainable yield index and SOC stock in a number of dryland crops. These authors estimated that for every 1 Mg ha^{-1} increase in SOC stock in the root zone, there was an increase in grain yield by 145, 170 and 160 kg ha^{-1} for soybean, pearl millet and rice, respectively.

4.2 Soil carbon pools

SOM is not a single uniform material but it differs highly in its chemical and physical properties that influence its capacity to carry out many functions

(Reicosky, 2020). It consists of several pools, namely, active, slow and passive (humus or less labile + non-labile), with differential turnover rate ranging from months to over several hundred to thousand years (Dey et al., 2021). The labile or active pool of SOC consisting mainly of POC and some dissolved organic C, is readily available and consequently rapidly decomposed. The POC fraction plays a crucial role in soil aggregate formation, nutrient supply and responds swiftly to changes in soil management practices because of its rapid turnover time (Dey et al., 2021; Reicosky, 2020). The passive or resistant SOC fraction pool is in close contact with mineral surfaces (silt + clay) and provides limited access to microorganisms, and is related to C sequestration and climate change (Six et al., 2002).

The increase in the labile fraction of the soil C due to C input is a feature of soil health (Tirol-Padre and Ladha, 2004). Dey et al. (2021) demonstrated that CA practices had greater impact on the very labile fraction of SOC with values higher by ~50% over CT in both surface and sub-surface soil layers after 6 years. The lability index of C, a ratio of labile C (very labile + labile + less labile) to non-labile SOC pools, was ~64% higher under CA compared to CT, whereas carbon pool index was higher by ~21%. Many other researchers (Bhattacharyya et al., 2012; Dey et al., 2016; Sharma et al., 2019) reported greater increase in the labile pool of SOC compared to SOC content under CA system. The carbon management index (CMI), which is based on integration of both C pool and C lability, is highly sensitive indicator of the rate of change of SOC in response to changes in cropping system and soil management (Whitbread et al., 1998). Sharma et al. (2019) reported that CMI under ZT + residue treatment in wheat was 28–42% higher than CT (without residue) in RW system. Kumar and Nath (2019) observed notable increase (36%) in the CMI in CA-based rice-chickpea (*Cicer arietinum*)—Mb system compared to the CT R-W system after 7 years of cropping.

Kumar and Nath (2019) reported that partial CA-based RW system enhanced the C content in "silt+ clay" fraction by 45% and 74%, at 0–20 cm and 20–40 cm depth, respectively, over the in 7 years of the study. Similarly, Jat et al. (2019b) and Shekhawat et al. (2016) recorded significant increases in mineral associated C under CA over CT at 0–15 cm depth. The process and the extent of binding of SOC onto silt+ clay fractions vary among the different clay types (Blanco-Canqui and Lal, 2004; Jat et al., 2019b). The clay content and mineralogy also regulate the SOC pools by influencing the sensitivity of soil C to microbial attack (Choudhary et al., 2018a,b; Kumari et al., 2011). Higher C associated with "silt+ clay" sized fraction at 0–15 cm soil depth under CA-based management systems might be due to higher specific surface area of silt and clay serving as sorption sites through cation bridges and ligand exchange (Bandyopadhyay et al., 2010; Choudhury et al., 2014; Somasundaram et al., 2017).

Study by Kumar et al. (2018) revealed that POC and labile fractions of SOC under CA were more than two times greater than in CT plots at 0–15 cm soil depth; the magnitude of increase was relatively lower in 15–30 cm layer. Many researchers from India (Bhattacharyya et al., 2013, 2015; Jat et al., 2018; Kumar and Nath, 2019; Parihar et al., 2016; Somasundaram et al., 2018, 2019; Yadav et al., 2021) have stated higher "labile" and "less labile" SOC pools in CA compared to CT system mainly in the surface layer under different cropping systems. The changes in labile fraction depends largely on the crop residue load, which explains why larger values were recorded in the surface layer and there was also more variation in this fraction with increasing soil depth. Rakesh et al. (2021) observed significant improvement in all the C fractions (hot water extractable C and POC, mineral associated SOC) at 0–10 cm depth under CA than CT treatment.

Results from a 3-year study by Bhattacharyya et al. (2015) revealed that CA-based RWMb resulted in ~24% larger labile C pool (very labile + labile) but not on recalcitrant C pools (less labile + non-labile) in surface soil layer than CT treatment. Das et al. (2020) reported ~51% and 48% higher concentration of very labile and labile C, respectively, under CA compared to CT system at 0–5 cm depth of soil. Kumar and Nath (2019) reported that POC was 72% and 38% higher in partial CA-based RW system (CT rice followed by ZT wheat + R) in both surface (0–20 cm) and subsurface (20–40 cm) soil layers compared to the CT RW system, respectively. These authors demonstrated that integration of legumes in partial CA-based cereal systems (rice-chickpea-Mb) increased the active and passive carbon pools compared to RW system in a sandy loam soil after 7 years in Uttar Pradesh, India. Rice-chickpea-Mb rotation had higher soil POC compared to rice-chickpea and RW systems.

Jat et al. (2019b) reported that the CA-based MW system had about 11% higher POC than RW system; this was attributed due to more biomass added in the former than the latter system in 0–15 cm soil layer after 6 years of experimentation. However, in 15–30 cm soil layer, POC content was similar under CT and CA systems. In the surface 0–15 cm soil layer, Dey et al. (2016) recorded 71% more POC in CA-based RWMb system compared with CT.

4.3 Carbon sequestration in soil

Carbon sequestration refers to increase in C stored in soils by transferring atmospheric CO_2 into the soil through plants, plant residues and other organic solids as a result of change in land use pattern (Powlson et al., 2011). Lal (2004) estimated 0.5–6.7 Tg C year^{-1} as the potential of agricultural intensification for SOC sequestration in India. Recognizing the role of soils as a potential sink for atmospheric CO_2, there is a growing interest in adopting CA to promote C sequestration in soils for offsetting anthropogenic emissions of CO_2 and mitigate GHG emissions and increase soil productivity (Corsi et al., 2012; Ladha et al., 2016; de Sá et al., 2020; Somasundaram et al., 2019).

C sequestration is the increase in amount of SOC in recalcitrant (non-labile or passive pool) pool, which is less vulnerable to loss from decay. Passive SOC pool comprising humus or non-labile form of C, which is related to C sequestration and climate change. Significantly higher values of passive pool of SOC are recorded under CA (Samal et al., 2017). Kassam et al. (2009) identified roots as the main source of C sequestration due to their capacity to partially stock C above- and belowground as a resistant SOC pool. The below-ground C sequestration (>20 cm depth) is a sustainable strategy for long-term carbon storage, because it is less prone to soil disturbance (Lal, 1997). In CA, continuous addition of organic residue as C source over the years often exceed the capability of native soil microbes to decompose, degrade and/or assimilate C to meet their cell nourishment or respiration needs resulting in improvement of C content and stock (Bhattacharyya et al., 2015; Dey et al., 2018; Ghimire et al., 2012; Jat et al., 2019a; Parihar et al., 2019). From a comprehensive review of literature on C pools and sequestration in South Asia, Goswami et al. (2020) reported that CA practices increased allocation of SOC into passive pools of longer residence time which helps to achieve higher C sequestration in soils under rice-based systems. A global analysis of data from 67 long-term experiments indicated that C sequestration rates with ZT could peak in 5–10 years with SOC reaching a new equilibrium in 15–20 years (West and Post, 2002). In CA, long-term C sequestration or stabilization in soils is expected to be through (i) increasing stable proportion of macro- and microaggregates, and physical protection by micro-aggregates, (ii) chemical protection by binding with clay minerals forming organo-mineral complexes and inter-molecular interactions with organic or inorganic substances (Lal and Kimble, 1997), and (iii) molecular recalcitrance promoted stabilization of hydrophobic POC (Zhou et al., 2010).

Several studies (Bhattacharyya et al., 2015; Jat et al., 2019a; Kumar and Nath, 2019; Mondal et al., 2020a) from South Asia have demonstrated the beneficial effects of CA practices on soil C stocks and fractions compared to CT practices, which eventually affects the C sequestration in soil. CA may not store more soil C than CT if limited amounts of residues are left (Hati et al., 2020). Results from a 3-year study on RW and RW–Mb cropping systems by Bhattacharyya et al. (2015) demonstrated a gain of ~330 kg C ha^{-1} $year^{-1}$ in total SOC stock in the 0–15 cm soil layer under CA. Jat et al. (2019a, 2022) showed significantly higher C sequestration in CA-based cropping systems over CT RW system. The MW-Mb showed higher rate of C sequestration than RW-Mb possibly due to larger biomass produced by maize than rice.

Singh et al. (2014) reported that oil C stock increased by 19–39% in the surface 0–40 cm soil depth under partial CA compared to CT after 15 years of adoption and the increase depended on the soil texture with higher increase in fine-textured clay loam than coarse-textured soils. These authors calculated C sequestration rates of 0.24, 0.46 and 0.62 Mg ha^{-1} $year^{-1}$ in sandy loam, loam and clay loam soil, respectively, under ZT over CT. Das et al. (2021) and Srinivasarao et al. (2015) opined that adoption of CA in fine texture soils have more potential of soil C sequestration than coarse texture soils.

In mustard-based cropping systems on a clay loam soil semi-arid region of North India, Shekhawat et al. (2016) reported that rate of C sequestered ranged from 0.20 to 0.44 Mg C ha^{-1} $year^{-1}$ under CA practices, while CT caused a loss of 0.41–0.66 Mg C ha^{-1} $year^{-1}$ at 0–15 cm soil depth. Based on the C balance, it is estimated that annual crop residue inputs of 4 Mg C ha^{-1} under CA in the legume-dominated system, and 1 Mg C ha^{-1} under CA in the cereal-dominated system, would be required to maintain SOC at the antecedent level. After 6 years of cropping cycles, Dey et al. (2020) reported that CA in RW system sequestered ~2 Mg ha^{-1} total SOC in the 0–15 cm soil layer, whereas significant losses were registered in CT. The improvement in both labile and non-labile pools of SOC under CA (see previous section on SOC), appears to be a promising option for both greater C sequestrations in tropical soils. Another study by Dey et al. (2021) showed increase in C stocks in deep soil layers (15–60 cm) under ZT accounting for ~68% of sequestered C after 9 years of the study), which is considered more advantageous than that of C stored in ≤15 cm soil layer. Microbial access to C substrate (due to increased root derived C) is inhibited in deeper soil layers due to lack of O_2, resulting in greater SOC storage.

Yadav et al. (2017) reported that under partial CA-based double rice crop rotation, C sequestration rate (428 kg C ha^{-1} $year^{-1}$) at 0–20 cm depth after 3 years of experimentation in North Eastern Hill Region of Tripura (India). A similar increase in C sequestration was reported by Yadav et al. (2019) in ZT with residue retention as mulch over CT in rice-mustard cropping system. From another study in North-West India, Parihar et al. (2020) reported a C sequestration rate of 1.15 Mg ha^{-1} $year^{-1}$ under CA along with site-specific nutrient management in maize-based cropping system. Globally, rates of C sequestration by different types of management practices including ZT range from 0.11 to 3.04 Mg C $ha^{-1}year^{-1}$, with a mean of 0.54 Mg C ha^{-1} $year^{-1}$, and are highly influenced by soil type and climate (West and Post, 2002). The potential of adoption of CA along with improved agronomic practices can lead to sequestration of an additional 6–7 Tg C $year^{-1}$ in India (Srinivasarao et al., 2013). A 20-year meta-analysis of ZT system in IGPs of South Asia suggested that estimated C sequestration potential of ZT in the RW system as 44.1 Tg (Grace et al., 2012). Further, implementation of ZT in maize–wheat and cotton (*Gossypium herbaceum*)—wheat (CW) systems would sequester an additional 6.6 Tg C (Grace et al., 2012). Results based on a 5-year study in Bangladesh by Alam et al. (2020) showed rate of increase in SOC stock ranged from 0.15 to 0.6 Mg C ha^{-1} $year^{-1}$ in a silty clay soil. Using Day-Cent model, Begum et al. (2017) showed C sequestration of 0.67 t CO_2-eq. $ha^{-1}year^{-1}$ under reduced tillage management with higher crop residue retention in a rice-based cropping systems in Bangladesh. According to Lal (1997) the rates of C sequestration through conversion from CT to ZT have been reported to range from 0.12–0.29 Mg C ha^{-1} $year^{-1}$ in Asia to 0.14–0.56 Mg C ha^{-1} $year^{-1}$ in United States. Gupta et al. (2021a) argued that C sequestration duration does not indicate soil C sequestration potential rather it reflects only the time to attain new steady state when C input equals C output with a given management. There is a strong need to address the issue of optimum time frame and soil depth for observing eal changes in C sequestration under CA in South Asia.

5. Conservation agriculture and soil physical health

Soils of South Asia are prone to physical degradation due to their low organic matter content and use of intensive tillage practices (Das et al., 2021; Gathala et al., 2013; Srinivasarao et al., 2019). In the conventional RW systems of South Asia, puddling for the rice and intensive tillage for the wheat field preparation both destroy soil structure and cause subsurface soil compaction, but the former is more destructive as the process destroys soil aggregates, macro pores, causes the formation of subsurface hardpan and retards wheat root penetration by forming a hard pan at shallow depths (Aggarwal et al., 2006; Chauhan et al., 2012; Gathala et al., 2011; Singh, 2015). Thus, the knowledge of impact of CA on soil physical health is inevitable. CA can lead to significant improvements in soil physical properties and associated processes, such as soil structure, bulk density (BD), soil crusting, porosity, water infiltration and storage, hydraulic properties, and soil and water conservation in different cropping systems, soil types and climate scenarios (Jat et al., 2009, 2020a,b; Lal, 2015; Salem et al., 2015; Somasundaram et al., 2019). The magnitude of the effect of CA on different soil physical properties is likely to vary with the duration of the study, cropping system, intrinsic soil properties and climatic conditions of the region. The information available from studies in South Asia on the effect of CA system on different soil physical parameters is discussed below.

5.1 Soil structure

Soil aggregate stability is considered as the main soil physical indicator as it influences soil aeration, root growth, water retention, soil and water erosion, C sequestration and microbial habitat (Lal, 2007; Mondal et al., 2020b, 2021; Sharma et al., 2022; Toor et al., 2021). A strong body of literature has been built up over the past decade, showing considerable improvement in the WSAs (ranging from 11% to 89%) in surface 0–15 cm layer under CA systems, particularly in experimental plots in South Asia (Table 2). The magnitude of increase in WSA depended of the duration of the study and the type of cropping system. The less soil disturbance and regular additions the crop residues under CA systems ranging from 2 to 10 years led to build up of SOC content which is responsible for improvement of soil structure under different soil and agroclimatic conditions. Meena et al. (2015) reported 37% increase in MWD of aggregates after 3 years in ZT+ residue treatment on a sandy loam soil under maize-based cropping systems.

However, soil aggregation was not influenced by different cropping systems (Table 2). As well, a number of other researchers (Choudhary et al., 2020; Gathala et al., 2017; Jat et al., 2019b; Kumar and Nath, 2019; Mohanty et al., 2015; Mondal et al., 2020b; Ronanki and Behera, 2019; Saurabh et al., 2021; Somasundaram et al., 2019) have reported greater increase in WSA in CA compared to CT system, mainly in the upper soil layer. Similar reports of improvement in soil structure under CA are available from other parts of the globe—a change that can be observed within two or three seasons of starting a CA system (Govaerts et al., 2009b; Thierfelder et al., 2015). After 8 years of study under CA-based rice-mustard (*Brassica juncea*)-Mb system, Das et al. (2021) recorded 29.3% and 49.3% higher

Table 2 Effect of Conservation Agriculture (CA) on water stable aggregates (WSA) (>0.25 mm).

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	WSA (%)			References
					CT	CA	Δ (%)	
Uttarakhand, India	Rice-wheat	Sandy loam	2	0–15	59	70	18.6	Jat et al. (2009)
U.P., India	Rice-wheat	Silt loam	6	0–15	84	96	14.3	Kumari et al. (2011)
UP, India	Rice-wheat	Sandy loam	7	0–15	58.4	77.3	32.0	Kumari et al. (2019)
Bihar, India	Rice-wheat	Silt loam	5	0–15	33.9	57.2	68.7	Mondal et al. (2019)
U.P., India	Maize-wheat	Sandy loam	3	0–15	57	73	28.1	Jat et al. (2013)
U.P., India	Rice-maize	Sandy loam	5	0–15	46.8	53.9	15.2	Singh et al. (2016)
Haryana, India	Rice/maize-wheat	Loam	6	0–15	23.5	44.4	88.9	Jat et al. (2019b)
Haryana, India	Rice/Maize-wheat	Loam	4	0–15	21.9	40.3	84.0	Jat et al. (2019b)
Bihar, India	Rice-wheat/maize	Silty clay	6	0–15	43.0	48.9	13.7	Nandan et al. (2019)
Bihar, India	Rice-wheat	Clay loam	7	0–7.5	22.7	32.6	43.6	Mondal et al. (2019)
				7.5–15	22.3	29.2	30.9	
	Maize-wheat		7	0–7.5	22.7	59.6	163	
				7.5–15	22.3	48.1	116	
M.P., India	Soybean-wheat	Clayey	6	0–15	51.4	60.5	17.7	Hati et al. (2015b)
Bihar, India	Rice-wheat	Clay loam	10	0–7.5	58.0	73.4	26.6	Mondal et al. (2021)
				7.5–15	63.5	71.2	12.1	
M.P., India	Soybean-wheat	Clayey	4	0–5	59.5	70.7	18.8	Somasundaram et al. (2018)
				5–15	58.6	64.9	10.8	

CT, Conventional till; M.P., Madhya Pradesh.

MWD of aggregated in CA-based rice-mustard-Mb system compared to CT in 0–5 and 5–15 cm layers, respectively. In some studies, significant increase in WSAs as a result of the predominance of macroaggregates was reported in both surface as well as sub surface soil (Bhattacharyya et al., 2012; Jat et al., 2019b; Kumar and Nath, 2019; Mondal et al., 2020a). Jat et al. (2019b) reported 68% and 86% increase in WSAs and 39% and 47% increase in MWD at 0–15 cm soil depth under CA based systems over CT-RW after 4 and 6 years, respectively. The increases in WSAs and MWD were greater in CA-based MWMb compared to RWMb system at 0–15 cm depth. Intensive tillage in CT system resulted in the breakdown of macroaggregates during tillage operations and facilitating the decomposition of protected SOC.

Results from their study by Mondal et al. (2020a) observed greater impact of CA on soil aggregation when a legume (Mb) was included in RW system due to more biomass input. In CA, crop residue retained on the soil surface has twofold effects on soil aggregation. First, it acts as a barrier between soil aggregates and external forces such as raindrop impact (Blanco-Canqui and Lal, 2009). Second, organic compounds such as polysaccharides and proteins released during residue decomposition along with the synergistic interactions between plant roots and fungal hyphae help bind soil particles into various-sized aggregates (Indoria et al., 2017b; Naveed et al., 2017; Parihar et al., 2016; Somasundaram et al., 2017, 2019). CA practices have been reported to improve soil structure (MWD and WSA) through increasing SOC content, microbial biomass and activity, and earthworm population (Choudhary et al., 2018a,b; Gathala et al., 2020a; Jat et al., 2022, 2019a,b,c; Mondal et al., 2020a; Ronanki and Behera, 2019; Sarker et al., 2018; Saurabh et al., 2021; Sharma et al., 2022). The contribution of soil biota to soil aggregation has also been documented by Lehmann et al. (2017) through a global meta-analysis. Contrary wise intensive tillage practices in CT result in the breakdown of the stable soil macroaggregates to finer aggregates and exposes the protected SOC to microbial decay and kills the earthworm population (Jat et al., 2022, 2013).

5.2 Soil bulk density

Soil BD describes the soil conditions in terms of porosity, root growth, soil compaction and porosity used in soil health studies (Reynolds et al., 2007). Development of a compact soil layer with high BD in subsurface (15–30 cm) layer has been extensively reported due to puddling for rice in the RW system of the IGPs of South Asia (Aggarwal et al., 2006; Gathala et al., 2011; Mondal et al., 2013; Saha et al., 2022; Singh et al., 2014) as well as in other cropping systems (Jat et al., 2013; Parihar et al., 2016; Singh et al., 2016). Several studies from South Asia have reported significant decrease in soil BD under CA system in different cereal-based cropping systems compared to CT, particularly in the surface (0–15 cm) soil layer (Table 3). Similar decreases in soil BD under CA system compared to CT have been reported by many other researchers (Alam et al., 2017, 2018a; Jat et al., 2020a; Khan et al., 2017; Kumar et al., 2018; Mondal et al., 2021; Parihar et al., 2016; Pooniya et al., 2021; Sadiq et al., 2021;; Salahin et al., 2021; Shekhawat et al., 2016). The reduction in BD under CA systems over CT was attributed to lesser soil disturbance and maintaining crop residue mulch, which improved SOC content, aggregation, porosity and faunal activities, and reduced the sub-surface compaction due to lesser passes of machinery (Abdallah et al., 2021; Somasundaram et al., 2019). Choudhary et al. (2018b) and Jat et al. (2022) reported that soil BD was the lower in CA-based MW-Mb compared to RW-Mb system in the surface (0–15 cm) layer possibly due to more biomass input by maize than rice. After 6 years of study in dry-seeded rice-wheat cropping system. Dhaliwal et al. (2020) reported that residue retention in wheat decreased bulk density by 1.9% compared with no residue retention for the 0–15 cm soil layer.

Contradictory reports on the effect of ZT or CA system on soil BD in the surface layer even after 2–8 years of cropping are also available in the literature showing higher (Alam et al., 2016; Choudhary and Behera, 2014; Govaerts et al., 2006; Jat et al., 2018; Khorami et al., 2018; Mondal et al., 2019, 2020b, 2021; Roy et al., 2022; Singh et al., 2014; Yadav et al., 2017) or similar (Hati et al., 2015a) BD in ZT plots. High soil BD in ZT system may be ascribed to little or no input of crop residues. Hati et al. (2015a) reported no significant effect of ZT system on BD at 0–7.5 and 7.5–15.0 cm soil depths in a vertisol after 7 years of under soybean-wheat rotation. Mondal et al. (2020a) observed significant increase in BD in the surface soil layer under CA compared to CT but CA practice reduced the BD in subsurface soil layers (15–30 and 30–45 cm) by 20–25% ascribed mainly to higher water content and increased the total porosity in the deeper layers after 8 years of RW-Mb system. Alam et al. (2014) stated that lower BD under CT in surface layer compared to CA in the initial 2–3 years of the study was possibly due to frequent soil disturbance, which increased soil porosity compared with the ZT, although in the long-term higher SOC and better aggregation due to the regular addition of crop residue under CA systems lead to lower BD (Somasundaram et al., 2019; Verhulst et al., 2010). From Indian Punjab Ram et al. (2010) also reported higher soil BD under continuous ZT than

Table 3 Effect of Conservation Agriculture on soil bulk density (Mg m^{-3}).

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	Bulk density CT	CA	Δ (%)	References
Haryana, India	Rice-wheat	Clay loam	3	0–10	1.47	1.35	−8.16	Choudhary et al. (2018a,b)
Punjab, India	Rice-wheat	Sandy loam	5	0–15	1.56	1.60	+2.56	Dhaliwal et al. (2020)
				15–30	1.77	1.65	−6.78	
U.P., India	Rice-wheat	Sandy loam	2	0–15	1.24	1.38	+11.3	Bazaya et al. (2009)
Bihar, India	Rice-wheat	Typic Calciorthent	7	0–5	1.55	1.46	−5.81	Sapkota et al. (2017)
				5–15	1.58	1.51	−4.43	
				15–30	1.58	1.51	−3.80	
Haryana, India	Rice-wheat	Clay loam	4	0–15	1.67	1.63	−2.5	Jat et al. (2018)
Haryana, India	Maize-wheat	Clay loam	3	0–10	1.38	1.34	−2.90	Choudhary et al. (2018a)
Haryana, India	Maize-wheat	Clay loam	4	0–15	1.67	1.64	−2.5	Jat et al. (2018)
U.P., India	Maize-wheat	Sandy loam	3	0–15	1.50	1.54	+2.7	
New Delhi, India	-do-	Sandy loam	2	0–15	1.61	1.60	−0.62	Choudhary and Behera (2020a,b,c)
				15–30	1.62	1.62	0.00	
U.P., India	Rice-maize	Sandy loam	5	0–15	1.53	1.42	−7.19	Singh et al. (2016)
				15–30	1.59	1.47	−7.55	
Rajshahi, Bagladesh	-do-	Sandy loam	3	0–15	1.29	1.24	−3.88	Rashid et al. (2019)

M.P., India	Soybean–wheat	Vertisol	3	0–7.5	1.35	1.39	+2.96	Somasundaram et al. (2019)
				7.5–15	1.42	1.38	−2.82	
				7.5–15	1.42	1.36	−4.23	
M.P., India	Maize–chickpea	Vertisol	3	0–7.5	1.39	1.35	−2.88	Somasundaram et al. (2019)
				7.5–15	1.45	1.42	−2.07	
Tripura, India	Maize- based system	Sandy clay loam	3	0–10	1.38	1.38	0.00	Yadav et al. (2021)
				10–20	1.41	1.41	0.00	
Tripura, India	Rice-rice	Clay loam	3	0–20	1.32	1.32	0.00	Yadav et al. (2019)
Haryana, India	Rice/maize-wheat	Sandy loam	4	0–15	1.67	1.64	−1.80	Jat et al. (2018)
Haryana, India	Rice/maize-wheat	Loam	6	0–15	1.63	1.55	−4.91	Choudhary et al. (2018c)
Uttrakhand, India	Soyabean–wheat/ lentil/field pea	Sandy clay loam	4	0–7.5	1.34	1.35	NS	Bhattacharyya et al. (2006)
				7.5–15	1.35	1.35	NS	
				15–22.5	1.39	1.38	NS	
Gazipur, Bangladesh	Rice-rice	Silty clay loam	3	0–5	1.31	1.35	NS	Rahman et al. (2017)
New Delhi, India	Rice-maize-Mb	Sandy clay loam	8	0–5	1.53	1.51	NS	Das et al. (2021)
				5–15	1.55	1.52	−19.4	
New Delhi, India	Cotton–wheat/ maize-wheat-Mb	Sandy loam	4	0–5	1.56	1.60	NS	Das et al. (2018)
				5–15	1.59	1.63	NS	
				15–30	1.63	1.58	NS	

U.P., Uttar Pradesh; Mb, Mungbean; NS, Non-significant.

CT practice in maize–wheat cropping system in the surface layer of coarse texture soil. Global meta-analyses also reported a contrasting impact of ZT on soil BD and showed a small increase in BD under CA over CT (Li et al., 2019).

5.3 Soil porosity

The long-term (10 years) adoption of CA in RW system improved macro-porosity by 27% and 36% in the 0–7.5 and 15–30-cm soil layers over CT, respectively (Mondal et al., 2021). Similarly, increase in porosity, larger macropores and volume of total pores under CA were reported in many other studies from South Asia (Alam et al., 2018a; Mondal et al., 2019, 2020b; Patra et al., 2019; Pooniya et al., 2021; Roy et al., 2022; Sadiq et al., 2021). Mondal et al. (2020a) reported the effects of CA on soil porosity were observed mainly in the upper soil layer and no change in pore characteristics was observed for deeper soil layers. The increase in porosity and better and stable pore network under long-term adoption of CA-practices is attributed to the improvement in SOC content, aggregate stability and number of bio-pores because of regular in situ addition of crop residues, presence of decayed root channels and the higher population of undisturbed soil macro-fauna, in particular earthworms (Choudhary et al., 2018a,b; Kumar et al., 2018; Mondal et al., 2021; Page et al., 2020). The magnitude of effects of CA on soil porosity differs depending on soil texture, climate, and the time since CA-practices have been implemented (Li et al., 2019). A decline in total- and macro-porosity has also been observed due to adopting short-term CA-based management practices, particularly in cases where BD increased due to CA over CT (Abdallah et al., 2021). The importance of the duration of CA has been recognized in literature reviews focusing on the effect of CA-practices on soil porosity, in which the authors concluded that most consistent results were obtained at or above 15 years after the conversion to CA (Kay and VandenBygaart, 2002; Blanco-Canqui and Ruis, 2018), while short-term (<5 years) adoption of CA-practices showed a little effect on soil porosity (Blanco-Canqui and Ruis, 2018; Mondal et al., 2018).

5.4 Soil penetration resistance

Soil penetration resistance (SPR) affects plant growth by manipulating soil compaction, aeration, and root penetration and growth in soil profile. Since SPR is inversely related to soil water content, normalization of soil water content is necessary for effective comparison of SPR data. However, majority of the studies from South Asia on SPR measurement under CA did not consider soil moisture content, which will significantly influence the SPR values. While CT operations increase subsoil compaction thereby increasing the SPR, adoption of CA may reduce SPR through improvement in SOC and soil structure, and lower traffic passes in the absence of tillage. Results from a 7-year study by Gathala et al. (2011) showed that SPR was significantly reduced under ZT (with little residue) up to the 25-cm depth, except at the 10-cm depth in CT-RW system. At 15 and 20 cm depths, SPR was up to 25% and 33% lower in ZT treatment than CT, respectively. ZT maintained SPR below the critical value of SPR in the root zone compared with CT practice. Many other studies from South Asia (Alam et al., 2016; Jat et al., 2013; Mondal et al., 2020a; Parihar et al., 2016; Roy et al., 2022; Saha et al., 2010; Salahin et al., 2021; Saurabh et al., 2021; Singh et al., 2016) showed significant decrease in SPR in CA system compared to CT mainly in 0–15 cm root–zone depth after 3–6 years of adoption in RW, MW, RM and lentil (*Lens culinaris*)/wheat-jute (*Corchorus capsularis*) cropping systems. Contrarywise, few researchers reported either no effect or increased SPR in CA practices compared to CT in the surface layer despite improvement in soil aggregation and SOC content under CA (Mondal et al., 2020a; Somasundaram et al., 2019).

Mondal et al. (2021, 2020a) reported significant decrease in SPR under CA system compared to CT at lower (10–50 cm) soil depths with maximum decrease at 15–45 cm depths, while reverse trend was noted in surface 0–10 cm layer after 10 cropping cycles. The lower SPR in subsurface layer under CA system was partly due to higher soil water content compared to CT. Study by Singh et al. (2016) showed no significant effect of CA (ZT and crop residue) practices on SPR at 0–5 cm depth in RM system. However, at the 5–10 cm depth, ZT+ residue retention decreased the SPR by 23–31% compared with CT in RM system. Saurabh et al. (2021) reported that SPR values in CA treatment were lower by 41% and 27% in 0–10 and 10–20 cm soil profile, respectively, than CT at the end of 4th annual cropping cycle of RW system.

5.5 Soil infiltration rate

Infiltration rate (IR) is an important soil physical parameter as it influences leaching, runoff and soil water storage. Many researchers from South Asia (Table 4; Das et al., 2018; Gathala et al., 2017; Choudhury et al., 2014; Jat et al., 2019a,b,c, 2022; Sadiq et al., 2021) have reported higher IR

Table 4 Effect of Conservation Agriculture on infiltration rate ($mm\,h^{-1}$).

Location	Cropping system	Soil type	Duration (years)	Infiltration rate CT	Infiltration rate CA	Δ (%)	References
Punjab, India	Rice-wheat	Sandy loam	5	6.3	7.7	+22.2	Dhaliwal et al. (2020)
U.P., India	-do-	Sandy loam	2	11.4	9.58	−16.0	Bazaya et al. (2009)
U.P., India	-do-	Sandy loam	7	1.8	3.3	+83.3	Gathala et al. (2011)
New Delhi, India	Maize-wheat	Sandy loam	2	12.1	13.0	+7.33	Choudhary and Behera (2020a,b,c)
U.P., India	Maize-wheat	Sandy loam	3	13.0	14.0	+7.69	Jat et al. (2013)
Tripura, India	Maize-based systems	Sandy loam	3	1.83	2.23	+21.9	Yadav et al. (2021)
Haryana, India	Rice-wheat	Haplic Solonetz (Silt loam)	4	0.90	3.10	+244	Jat et al. (2018)
Haryana, India	Maize-wheat			0.90	2.90	+222	
Patna, Bihar, India	Rice-wheat	Silty clay	5	25.4	35.9	+41.3	Mondal et al. (2019)
Uttar Pradesh, India	Rice-maize	Sandy loam	5	4.7	6.9	+46.8	Singh et al. (2016)
Uttar Pradesh, India	Rice-maize	Sandy loam	2	6.2	9.4	+51.6	Kumar et al. (2018)
Haryana, India	Rice-wheat-Mb	Loam	10	4.4	8.3	+88.6	Roy et al. (2022)

U.P., Uttar Pradesh; Mb, Mungbean.

(initial as well as steady state) under CA system compared to CT. The increases in IR in CA compared to CT plots were attributed to the increase in the microporosity and continuity of water conducting pores, lower number of disconnected pores and improvement in SOC and soil aggregation (Dwivedi et al., 2012; Jat et al., 2013; Singh et al., 2016; Patra et al., 2019). A global meta-analysis showed an increase in the soil IR with the increase in the duration of CA practice (Mondal et al., 2018). The time trend analysis by Gathala et al. (2011) showed a decline in IR under CT, and an increase under ZT over 7 years of RW system. Jat et al. (2018) and Kumar and Nath (2019) recorded about 100% and 244% increase in IR in CA systems over CT after 2 and 5 cropping cycles, respectively. Jat et al. (2022) reported that IR in CA system was significantly higher than CT but differences between CA-based RW and MW systems were not significant. However, Roy et al. (2022) reported recorded significantly higher IR under CA based MW-Mb compared to CA-based RWS. The magnitude of increase in IR in CA over CT depends on the duration of the study (Mondal et al., 2018), cropping system (Roy et al., 2022), initial water transmission characteristics of the soil profile, the antecedent water content, aggregation and the presence of macropore channels.

The reports of lower IR (Franzluebbers and Stuedemann, 2008; Gangwar et al., 2006; Liu et al., 2015; Mondal et al., 2019; Sharma et al., 2005) or no effect (Alam et al., 2016; Choudhary and Behera, 2014) with the adoption of ZT or CA compared to CT are also available in the literature. This is possible within a few years of adoption of CA due to initial compaction and lack of sufficient biological activity for development of a stable soil structure. Zero tillage without residue retention leads to crust formation, with low aggregation and reduced infiltration (Govaerts et al., 2007). Results from a long-term study in Haryana, India showed that among three soil types (sandy loam, loam and clay loam), significant increase of 28% in IR was observed in clay loam soil (Singh et al., 2014). The observed increase in IR under CA advocates the need for improved irrigation and N management techniques to minimize the loss of water and N through percolation during irrigation or heavy rainfall events. The increase in IR under CA can help to minimize the risk of waterlogging in years with heavy rainfall events during crop growing season (see Section 9.2).

5.6 Soil hydraulic conductivity

Saturated hydraulic conductivity (Ks) determines water transmission characteristics of soil. Singh et al. (2014) reported that Ks for different layers of the three soil types differing in texture were largely higher under ZT wheat than that of CT, however, differences were significant to a depth of 10 cm. Mondal and Chakraborty (2022) reported that Ks in ZT plots was more than CT in RW system because CT caused destruction of soil aggregates and reduced non-capillary pores whereas ZT had more macropores continuity. Results from many other studies (Table 5; Kumar et al., 2018; Mondal et al., 2021) also showed significant improvement in Ks under CA compared to CT system in both surface (0–15 cm) and subsurface (15–40 cm) soil layers. Das et al. (2021) reported 83% and 165% increase in Ks in 0–5 and 5–15 cm layers under over CT, respectively, after 8 years of rice-mustard-Mb system on a sandy clay loam. Similar increases in Ks on 0–15 and 15–30 cm layers under CA after 3 years of maize-based and 7 years of soybean-wheat cropping systems were reported by Meena et al. (2015) and Hati et al. (2015a), respectively. The improvement in Ks in CA was probably due to increase in the SOC content which improves the soil macro-aggregates and macro-porosity, and vertical interconnection of macro-porosity and better root growth and continuous channels formed by decaying roots serve as routes linking the soil surface to deeper layers that facilitates easy movement of water in the soil (Choudhary and Behera, 2014; Choudhary et al., 2020; Sadiq et al., 2021).

There are however, conflicting reports on the changes in Ks under CA system. For example, Sharma et al. (2005) observed lower values of Ks under ZT than that of CT in a silty clay loam soil under RW system of Tarai region of Northern India. On the other hand, Choudhary and Behera (2014) reported similar values of Ks under ZT (with no residue) and CT systems after 2 years of MW system, which was probably due to no residue mulch was used in ZT plots and the short duration of the study. Sadiq et al. (2021) also reported that soil Ks was not significantly affected by tillage and straw mulch in the first 2 years, but ZT plots recorded significantly higher values of Ks in the 0–10 cm and 10–20 cm soil layers after 3 years.

5.7 Soil thermal regime

Soil temperature is a vital physical property that governs soil processes, and also regulates the heat energy exchange between the atmosphere and soil. Soil thermal regime depends on solar radiation received at the soil surface and soil thermal properties (volumetric heat capacity, thermal conductivity, and thermal diffusivity) (Gathala et al., 2011). CA practices moderate the variation in soil temperature due to presence of crop residue at the soil

Table 5 Effect of Conservation Agriculture on hydraulic conductivity (mm h^{-1}).

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	Hydraulic conductivity (mm h^{-1}) CT	CA	Δ (%)	References
Karnal, India	Rice-wheat	Loamy	8	0–15	3.18	10.5	+230	Patra et al. (2019)
Karnal, India	Maize-wheat			0–15	3.18	7.45	+134	
New Delhi, India	Maize-wheat	Sandy loam	2	0–15	10.9	13.6	+24.8	Choudhary and Behera (2020a,b,c)
				15–30	9.34	11.1	+18.4	
Uttarakhand, India	Maize-wheat	Sandy clay loam	4	0–7.5	14.3	16.3	+14.24	Bhattacharyya et al. (2006)
				7.5–15	13.3	15.5	+18.1	
				15–22.5	12.5	13.8	+7.47	
Madhya Pradesh, India	Soyabean-wheat	Clayey	7	0–7.5	7.70	26.4	+243	Hati et al. (2015a)
				7.5–15	5.61	14.2	+153	

CT, Conventional till.

surface which regulates the penetration of the sunlight and retaining the heat, and thereby buffering the soil temperature, such that minimum temperature is relatively higher and maximum temperature is lower congenial for plant growth compared to CT (Bazaya et al., 2009; Kumar et al., 2018; Mondal et al., 2020a, 2021; Rani et al., 2017; Sadiq et al., 2021; Somasundaram et al., 2018).

The moderation of soil temperature in CA system was mainly attributed to increased Ks, reduced thermal conductivity, negative heat flux to the atmosphere and greater availability of soil water content compared with the CT practices (Sadiq et al., 2021; Kumar et al., 2018). Singh et al. (2016) reported that in winter months (December to February), minimum soil temperature in maize was 1.0–3.0 °C higher in residue retention plots but the maximum temperature was lower by 2.1–7.1 °C compared to the no residue plots in RM system of north-west India. The residue mulch buffered the soil temperature by 0.8–4.8 °C in the months of March–April in maize. The decrease in soil temperatures under residue mulch in CA system, especially at grain filling stage of wheat, reduced the canopy temperature and helped to reduce adverse impact of terminal heat on the crop productivity was earlier reported by Gathala et al. (2017) and Gupta et al. (2010).

5.8 Soil water conservation and water productivity

Groundwater reserves are becoming rapidly depleted in many vital agricultural regions across the South Asia (Humphreys et al., 2010; Yadvinder-Singh et al., 2014). Furthermore, climate change will intensify the demands on water use in agriculture. CA is a promising approach in the arid and semi-arid climates, where rainfall is far lower than the mean evaporation. CA practices increase soil moisture content and WUE due to its ability to reduce the unproductive evaporation loss from the top layer, capillary rise of water and surface runoff (Jat et al., 2019a,b; Mohammad et al., 2018; Parihar et al., 2019; Patra et al., 2019). Even the small amounts of water saved in CA system from the mulch effect (Jat et al., 2019c; Mondal et al., 2019), and increase in IR and water holding capacity (WHC), and deep rooting system access provides resilience in both wet and dry periods (Stewart and Peterson, 2015) and contribute toward food security and ecosystem services. The role CA in improving storage of water in the soil profile and thereby increasing water use efficiency is depicted in Fig. 2.

From a study in NW India on RW system, Kumar et al. (2018) reported 9% and 44–54% increase in soil water content in the 0–15 cm layer under

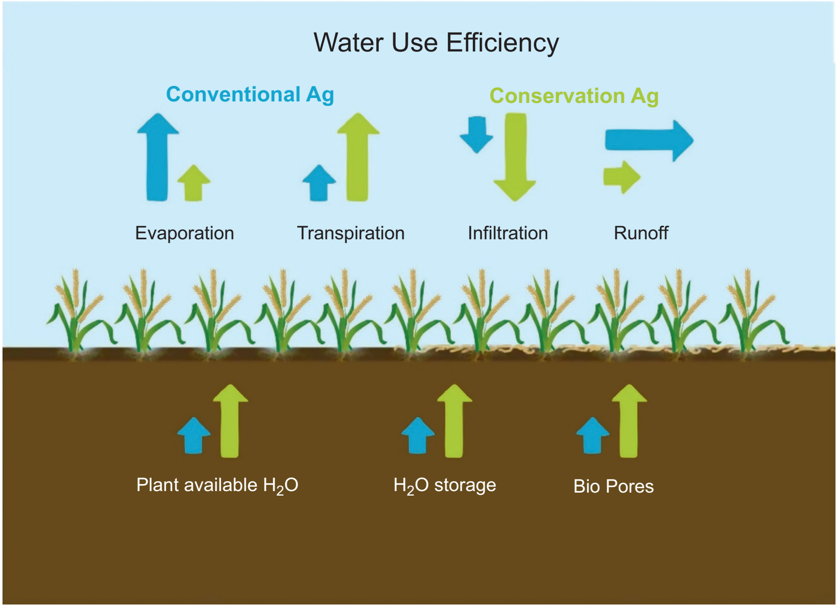

Fig. 2 Possible mechanisms for improved soil–plant–water relations in CA systems (blue arrows) vs conventional agriculture (yellow arrows). The relative magnitude of the process or function is indicated by the length of the arrows. http://www.cabi.org/cabreviews.

CA compared to CT after 5 and 8 years of the study, respectively. CA encourages higher root mass density as well as deeper rooting due to improvement in soil structure, resulting in utilizing water directly from deeper soil layers. Kumar et al. (2018) demonstrated that root length, root length density and root mass were 59%, 57% and 16% higher in CA treatment compared to CT, respectively, in a RW system in eastern (Bihar) India. The favorable effects of CA system on enhancing soil water content and on soil have also been reported in many other studies from South Asia (Alam et al., 2016; Bhattacharyya et al., 2006; Gathala et al., 2017; Jat et al., 2018; Kumar et al., 2018; Mondal et al., 2019; Pradhan et al., 2018; Roy et al., 2022; Sadiq et al., 2021; Salahin et al., 2021; Saurabh et al., 2021; Sidhu et al., 2007; Somasundaram et al., 2019; Yadav et al., 2018). These authors described the increase in soil water content and water retention at field capacity, particularly in surface soil layer under crop residue mulching in CA systems due to reduction in evaporation loss. Zahid et al. (2020) reported increase in soil water content under conservation tillage by 7%, 15%, and 18% than CT at 0–15 cm, 15–30 cm, and 30–45 cm depths, respectively, in RW system of Punjab, Pakistan.

Mondal et al. (2019) observed 16–32% reduction in soil water depletion in CA plots from 0 to 60 cm profile compared to CT system, which substantiates the role of micro-pores in retaining water for a longer period of time. The water retained in soil at matric potential between 100 and 330 cm was 1.5 times higher in CA than the CT system. Under subtropical conditions of India, Kumar et al. (2018) reported 31% increase in WHC after 7 years of the adoption of CA practices over CT in RW system. From a long-term study in Haryana (India), Singh et al. (2014) reported that ZT practice was more effective in increasing WHC in clay loam as compared to loam and sandy loam soils. Alam et al. (2017) also reported that CA increased WHC of a clay loam soil by 27% over CT in 0–15 cm layer after 3 years of RW system in subtropical humid climate of Bangladesh. The benefits from CA in soil water content and WHC could depend upon the improvement in soil structure and stability, increase in SOC content, extent of residue mulch cover, cropping system and regional climate (Alam et al., 2016). From a review of published literature, Abdallah et al. (2021), however, concluded that effect of CA-practices on soil WHC is relatively small and governed by soil type and SOC levels under different agro-ecological conditions.

The increase in soil water storage due to mulching in CA helps to increase water productivity (WP) by lowering irrigation requirement (Balwinder-Singh et al., 2011; Chakraborty et al., 2008). Results from a study in North-West India (Balwinder-Singh et al., 2011) showed that ZT + rice residue mulch in wheat in RW system can save ~30% of irrigation water due to reduction of soil evaporation by ~42–48 mm compared to ZT wheat. In a ZT dry seeded RW system, Gupta et al. (2021b) reported a soil evaporation loss of 600–700 mm. They further reported that mulching of ZT wheat with rice straw decreased total system soil evaporation by around 45 mm with no irrigation saving. The long-term experiment with RW–mung bean and rice–lentil–boro rice rotations on silty clay loam soil at Rajshahi, Bangladesh demonstrated that CA practices saved 11–33% of irrigation water compared to CT (Alam et al., 2019). Another study by Alam et al. (2016) demonstrated that ZT+ residue mulch under wheat-sesbania green manure (cover crop)-rice system conserved 49 mm of soil moisture by reducing water loss with the cultivation of cover crop compared to CT. In CW rotation, total water applied (including the rainwater) was about 14% lower under PB + R system compared to CT (Das et al., 2014). Kakraliya et al. (2018) demonstrated that CA practices saved 24% less irrigation water and increased system WP by 31% over CT system Higher WP of CA wheat under CA than in CT system was mainly due to elimination of pre-sowing irrigation thereby requiring less water coupled with higher grain yield.

The CA-based RW and MW cropping systems required 30% and 71% less irrigation water as compared to CT RW system, respectively (Kumar et al., 2018). Similarly, Choudhary et al. (2018a) demonstrated that CA-based MW system recorded about 38% higher system productivity and increased system WP by 41% and 270% with CA-based RW-Mb and MW-Mb systems compared to CT RW system, respectively, in the North-West IGP of India. In a CW system, Choudhary et al. (2016) reported that mean system WP was 131% higher with CA (PB + R) compared with CT in cotton-wheat-MB cropping system. Das et al. (2021) reported that CA based under CA-based rice-mustard-MB system provided 28% and 35% higher WP in rice and mustard under CA compared with the CT system, respectively. The savings in irrigation water increases in WP under CA system have also been reported by many other researchers from South Asia compared to CT system (Devkota et al., 2019; Gathala et al., 2020a; Jat et al., 2013, 2019c, 2021; Parihar et al., 2016; Singh et al., 2016). A recent meta-analysis showed average increase of 12.6% in WP owing to CA-practices in South Asia (Jat et al., 2020b).

6. Conservation agriculture and soil chemical health

Soil requires best chemical environment like pH, electrical conductivity (EC), total and available plant nutrients, etc. for optimum plant growth. While, most of the researchers consider SOC as an integral part of soil chemical indicators, we argue that since the SOC is linked to all the three indicators (physical, chemical and biological) of soil health, it has been discussed separately. Conventional practices based on removal or burning of post-harvest residues can adversely impact soil chemical properties. The impact of CA on different parameters of soil chemical properties is discussed below.

6.1 Soil pH and electrical conductivity

Many studies from South Asia (Alam et al., 2018a; Bera et al., 2017; Chaudhary et al., 2017; Choudhary et al., 2018a,b,c, 2020; Das et al., 2021; Gathala et al., 2017; Jat et al., 2018, 2019a,b, 2022; Nandan et al., 2019; Rashid et al., 2019; Roy et al., 2022; Singh et al., 2018) showed non-significant changes in soil pH in surface layer under CA practices over a 3–10 years in surface 0–15 cm layer under CA-based RW and MW systems. The initial values of soil pH in these studies were in the normal range. Similarly, small changes in and electrical conductivity (EC) were reported in these studies, except Choudhary et al. (2018a,b, 2020) who reported significant decrease in EC under CA compared to CT. Somasundaram et al. (2021) also observed no significant influence of tillage and cropping systems on soil pH in a rainfed Vertisol of Central India even after 18th cropping cycle. These authors explained that non-significant variation in pH might also be due to buffering capacity of soil which offered resistance against change in pH in a clayey soil (>55% clay content) containing smectite clay minerals. Similarly, Mondal and Chakraborty (2022) reported a decrease in soil pH with the conversion to CA practice, but EC was not influenced significantly by CA in both 0–15 and 15–30 cm soil layers. Choudhary and Behera (2020a,b,c) and Ronanki and Behera (2019) surmised that both pH and EC parameters are slow to respond to CA management practices and hence, changes may not appear in short span of time (<5 years).

Sadiq et al. (2021) reported significant decrease in soil pH under CA over CT. Results from a study conducted in Eastern region (Bihar), India on an acid soil showed significant decrease in soil pH from 6.3 under CA to 5.8 under CT in rice-based cropping system (Sinha et al., 2019). Few other studies (Ghimire et al., 2017; Rahman et al., 2008; Zahid et al., 2020) from Bangladesh and Pakistan also showed significantly lower soil pH and EC under CA than CT at 0–15 cm soil depth. The changes in soil pH and EC under CA system might depend upon climatic conditions, soil type, and fertilizer management factors. The reduction in soil pH with CA-based practices was linked to the production of organic acids during decomposition and mineralization of crop residues at the soil surface and nitrification of surface-applied N fertilizer (Jat et al., 2018; Singh et al., 2005, 2016).

6.2 Soil total N

Adopting CA practices will help to reduce the risk of soil N depletion and ultimately conserving more total N in soil supplied by the crop residues in comparison to CT. Significantly more (7–63%) total N was observed under CA in surface layers (0–15 cm) in comparison to CT after 3–12 cropping cycles in many studies from India (Choudhary et al., 2018c, 2020; Das et al., 2021; Jat et al., 2018; Kushwa et al., 2016; Patra et al., 2019; Rashid et al., 2019; Sinha et al., 2019; Zahid et al., 2020), which might be due to microbial immobilization of N from the soil and increased residue retention with slow decomposition rate compared to CT. Several other researchers from South Asia (Alam et al., 2014, 2018a, 2020; Dey et al., 2016; Haque et al., 2016; Islam et al., 2016; Sadiq et al., 2021; Salahin et al., 2021) have also reported higher total N content in soil in the different rice-based cropping systems. Alam et al. (2020) stated that adoption of partial

CA (non-puddled transplanted rice and strip tillage along with high residue load) increased total N content in soil by 62% relative to CT at 0–10 cm depth in Jute-mustard-rice triple cropping system. Inclusion of a legume or green manure crop in RW system had greater effect on the increase of total N in soil under CA compared to when no legume crop was included in the RW system. The wide variations in the changes in total N stocks in soils under CA systems in the different studies can be attributed to the differences in the quantity and quality of residue input and the duration of the study (Alam et al., 2016; Ghimire et al., 2017; Yadav et al., 2017). In addition, the differences in total N in soil under CA systems can be attributed to the differences in inherent soil characteristics and slower decomposition of surface residue. and lower N loss processes, which facilitated conservation of N in organic and inorganic forms (Islam, 2016; Kader et al., 2017). From a global meta-analysis with 2268 pairs of data Mondal and Chakraborty (2022) reported 21% and 16% increases in total N concentration and N stock, respectively, under ZT compared to CT in the surface soil layer (0–10 cm) only. An incremental increase in soil N was evident with an increase in the duration of ZT adoption.

6.3 Available nutrients in soil

6.3.1 Available macro- and secondary nutrients

Usually, in the first few years of CA implementation, lower N availability in soils is expected due to greater N immobilization by soil microbes due to high C/N ratio of cereal residues, however, net immobilization period may be transient (Yadvinder-Singh et al., 2015). The effect of CA on available N in soil will also depend on the time and method of fertilizer application (Yadvinder-Singh et al., 2015). A higher immobilization of N under CA may require 20–30 kg ha^{-1} more N fertilizer in the early stages of the CA implementation until the new equilibrium of N cycling is attained; fertilizer N requirement decreasing over time owing to increased availability of soil N on the remineralization of the immobilized soil organic N (Jat et al., 2018; Yadvinder-Singh et al., 2014, 2021). However, the temporary immobilization of N under CA may minimize the losses of mineral N by leaching and denitrification as suggested by Follett and Schimel (1989). From Bangladesh, Alam et al. (2020) stated that basal N fertilizer dose recommended for CT practices may be sufficient to accelerate the N mineralization from the low N crop residues when they were used as surface mulch in CA system.

Several studies from South Asia (Table 6; Das et al., 2020; Hati et al., 2015a; Indoria et al., 2017b; Jat et al., 2018, 2022; Kushwah et al., 2016; Mondal and Chakraborty, 2022; Mohammad et al., 2018; Yadav et al., 2019) have

Table 6 Effect of Conservation Agriculture (CA) vis-a vis conventional till (CT) system on available macronutrients (N, P and K) contents in soil.

Location	Cropping system	Duration (years)	Soil depth (cm)	Available macronutrients (kg ha^{-1}) CT N	CT P	CT K	CA N	CA P	CA K	References
Punjab, India	Rice-wheat	3	0–7.5	43.0	4.31	–	47.2	7.96	–	Bera et al. (2018)
Bihar, India	Rice-wheat	3	0–10	155	11.2	144	178	14.8	174	Saurabh et al. (2021)
New Delhi, India	Maize-wheat	2	0–15	147	10.1	230	151	12.1	238	Choudhary and Behera (2020a,b,c)
Bihar, India	Rice-maize	–	0–15	151	24.0	202	167	30.5	230	Kumari et al. (2019)
Bihar, India	Rice-wheat/maize	6	0–15	186	28.4	236	197	29.0	264	Nandan et al. (2019)
Haryana, India	Pearl millet-wheat		0–15	140	52.8	301	157	60.2	242	Kaushik et al. (2018)
New Delhi, India	Pearl millet-mustard	2	0–15	134	15.0	175	149	17.1	197	Choudhary et al. (2019)
Haryana, India	Rice-wheat	9	0–15	119	16.1	137	157	24.2	218	Choudhary et al. (2020)
Punjab, Pakistan	Rice-wheat	3	0–15	–	4.5	127	–	7.4[a]	208[a]	Zahid et al. (2020)
			15–30	–	4.1	110	–	6.2[a]	185[a]	
New Delhi, India	Maize-wheat Maize-mustard-cowpea	4	0–15	169	17.3	173	194[a]	22.2[a]	199[a]	Parihar et al. (2020)
			15–30	144	14.3	146	171[a]	18.0[a]	168[a]	
			5–10	8.8	8.6	78.5	12.1[a]	11.5[a]	81.9	
			10–15	6.6	7.4	74.3	6.9[a]	9.4[a]	71.4	

Tripura, India	Rice-wheat-Mb	3	0–10	439	9.3	345	479[a]	11.9	379	Yadav et al. (2021)
			10–20	417	9.4	325	453	10.5	355	
Haryana, India	Rice-wheat-Mb	4	0–15	117	15.7	183	156[a]	21.6[a]	236[a]	Jat et al. (2018)
	Maize-wheat-Mb	4		0–15	–	–	197[a]	19.6[a]	318[a]	
Haryana, India	Rice-wheat	4	0–5	155	16.2	222	216[a]	22.9[a]	312[a]	Jat et al. (2019c)
			5–10	0.28	4.1	110	0.33[a]	6.2[a]	185[a]	
			10–15	0.22	3.9	105	0.29[a]	4.5	144[a]	
Haryana, India	Rice-wheat-Mb	10	0–5	127	14.5	113	123[a]	35.1	381[a]	Roy et al. (2022)
			5–15	123	13.5	181b	139″	31.3[a]	331[a]	
			15–30	101	5.03	140	118	6.06	190[a]	
Haryana, India	Rice-wheat	10	0–15	137	27	173	134	33[a]	209[a]	Jat et al. (2022)
N. Delhi, India	Rice-maize-Mb	8	0–5	–	44.2	271	–	84.7[a]	388[a]	Das et al. (2021)
			5–15	–	31.5	202	–	47.0[a]	300[a]	
Bihar, India	Rice-wheat-Mb	4	0–10	155	11.7	144	178[a]	14.8[a]	174[a]	Saurabh et al. (2021)
			10–20	138	9.4	128	150[a]	11.4[a]	146[a]	

[a]Values under CA in a row differ significantly at $P \leq 0.05$ from CT according to Duncan Multiple Range Test for separation of means. Mb, mungbean.

demonstrated significant increases in N, phosphorus (P) and potassium (K) availability in the surface soil layers (0–20 cm) after 3–10 years of experimentation under CA over CT practice in different cereal-based cropping systems. However, results from a short-term (2-year) study on MW system showed no significant effect of ZT with no residue on that available N, P and K status in soil (Choudhary and Behera, 2014). Similarly, Sadiq et al. (2021) observed similar values of available N and K under CA and CT systems; while significant increase in available P was noted in CA system. The addition of crop residues in CA system improved the availability of plant nutrients in soils after decomposition and mineralization (Datta et al., 2019). Choudhary et al. (2020) reported 38%, 70%, and 59% increases in the available N, P and K in CA compared to the CT, respectively, after 9 annual cropping cycles of rice-based systems. Saurabh et al. (2021) however, reported nutrient depletion under CA in the deep sampled soil layer (30 cm).

Rashid et al. (2019) showed that SOC, and available P and S contents increased significantly under residue retention in the RM-Mb system over CT in a sandy loam in the EGPs of Bangladesh after 3 years of the study. There are few studies reporting the improvement in available S under CA. While, Jat et al. (2018) recorded lower values of available S in CA compared to CT-based RW system, Salahin et al. (2021) observed significant increase in available S in CA compared CT-based rice-based cropping system. In contrast to increased availability of N, P and K in CA system, Jat et al. (2018, 2019c) noticed the reverse trend in case of available S with higher content under CT practices than that under CA. Similarly, study conducted by Mohammad et al. (2018) in Pakistan showed higher contents of total N, P, K contents and mineralizable N were higher in minimum tillage than that under CT at 0–30 cm soil depths. The increase in soil available P concentration was by 22–38% for ZT compared to CT, particularly in the upper 0–10 cm depth after three cropping cycles (Salahin et al., 2021).

Jat et al. (2018) revealed that CA system enhances the content of available N, P and K contents in surface soil along with saving of 30% and 50% of N and K fertilizers in wheat after 4 cycles of RW-Mb and MW-Mb systems, respectively. Alam et al. (2020) described that the differences in N availability in soils in CA systems, can be attributed to differences in soil N levels, residue biomass load, N content in residues, decomposition rates of organic N, temperature and soil water content. Inclusion of legume crop in the cereal-based crop rotation can significantly improve soil N availability due to biological fixation of atmospheric N_2 and addition of low C:N ratio residue, which decomposed easily and thereby decrease N fertilizer requirement and enhanced N use efficiency (Jat et al., 2021).

Roy et al. (2022) demonstrated significant increase available N, P and K contents under long-term adoption of CA, notwithstanding higher fertilizer application in CT-RW system. The available N was 23% and 37% higher under CA based RW-Mb and MW-Mb systems at 0–5 cm depth, respectively. Results from another study by Das et al. (2021) revealed that the available N, P, K and S; and exchangeable Ca and Mg were significantly higher in minimum tillage as compared to CT. Salahin et al. (2021) reported that compared to CT, partial CA system with high residue retention (6 Mg^{-1}) significantly increased total N, and extractable P, K, S and Zn contents in the upper 0–10 cm soil layer after 3 cycles of the rice-lentil/wheat-jute cropping system in Rajbari district of Bangladesh. By contrast with other elements, exchangeable K also increased also in 10–15 cm soil layer. Sharma et al. (2021) reported that total P, available P and P fractions (NaOH-organic P, $NaHCO_3$-inorganic P and HCl-P) were significantly higher under ZT wheat + rice residue than CT wheat in RW system.

Gupta et al. (2007) also reported notable increase in the soil available P content under CA practices (ZT coupled with crop residue retention) over CT in the surface 0–15 cm layer after 3 years of the study. The greater extractable P levels in CA system, was ascribed to the increase in organic P fraction and release rate of P from the soil. Above authors concluded that there is a possibility of a lower P starter fertilizer requirement under CA in the long-term due to improvement in available P levels in the surface layer. Pradhan et al. (2011) argued that higher Olsen P contents in CA treatment were due to the formation of stable complexes of P-fixing/immobilizing ions like Ca^{2+}, Fe^{3+} and Al^{3+} with soil organic matter. Mycorrhizae, which are obligate symbionts, play an important role in P absorption and translocation to the roots of associated plants under CA. The increases in extractable P in soil under CA system may primarily be due to the; (i) Reduced mixing of P fertilizers with soils, leading to lower P fixation (Duiker and Beegle, 2006), (ii) Reduction in fixation of fertilizer P by soil due to formation of stable complexes of P-fixing ions like Ca^{2+}, Fe^{3+} and Al^{3+} with soil organic metabolites released during decomposition of crop residues, or production of organic anions which competes with phosphate anions for the same adsorption sites (Ohno and Erich, 1997; Pradhan et al., 2011; Sarkar et al., 2020).

Somasundaram et al. (2021) reported that increases in available N, P, K, and micronutrient cations concentrations were positively related with SOC content in CA system. The increases in the concentrations of available N, P and K in surface soil layer under CA compared to CT are associated with regular additions of large amounts of residues, which upon decomposition and mineralization release plant nutrients in soil (Yadvinder-Singh et al., 2014, 2021). In general, as a result of improvement in soil fertility over time under CA, and fewer fertilizer amendments are most likely will be required to achieve optimal yields (Tomar and Rai, 2017; Yadvinder-Singh et al., 2021). Alam et al. (2020) reported that CA practices (strip tillage in upland crops and non-puddled transplanting of rice seedlings, together with high residue load) increased total N by 62% relative to CT with low residue load at 0–10 cm soil depth in the intensive rice-based triple cropping systems of the EGPs of Bangladesh. The long-term retention of high residue mass together with minimum soil disturbance increased N uptake and N use efficiency by the crops in the triple RW-Mb cropping system after 4–5 years at both the sites (Alam et al., 2020). The increased N availability in soil under CA will possibly reduce fertilizer N application rates compared to CT system (Das et al., 2014). Thus, the N fertilizer requirement of different over time is likely to decline in the CA systems. Study by Alam et al. (2020) showed that on a short-term basis (up to the 7th crop in a RW-Mb rotation), no significant effect of CA system was observed on the N fertilizer requirements for realizing maximum yield of rice or wheat.

Available K concentrations in soil are considerably influenced by CA system, as more than 80% K remains in the residue, which is released quickly in the soil (Yadvinder-Singh et al., 2014). Yadvinder-Singh et al. (2017b) reported that CA practices conserve and enhance the availability of nutrients such as K in the top layer, where crop roots proliferate and utilize it ultimately reducing the fertilizer K requirements. Many researchers have recorded increase in nutrient uptake under CA, especially where it provided higher crop yields compared to CT system. For example, Jat et al. (2020a) recorded increase of 15%, 48% and 17% in N, P and K uptake, respectively, with CA-based systems than CT after 7 annual cropping cycles. The increased uptake of plant nutrients under CA has not been considered in majority of the studies when accounting for changes in nutrient availability in soil.

6.3.2 Available micronutrients

Similar to macronutrients, DTPA-extractable micronutrient cations (Zn, Fe, Cu, and Mn) are generally present in higher concentrations in surface 0–15 cm layer under irrigated CA systems as compared to CT (Jat et al., 2018, 2022; Kumar and Nath, 2019; Rashid et al., 2019; Salahin et al., 2021; Zahid et al., 2020). Roy et al. (2022) reported significantly higher concentration of DTPA-Zn under CA-based RW-Mb and MW-Mb systems compared to CT-RW system at both 0–5 cm and 5–15 cm soil depths

Table 7 Effect of Conservation Agriculture (CA) on vailable micronutrients (DTPA-extractable Zn, Mn, Fe and Cu) at 0–5 and 5–15 cm soil depths after 10 annual cropping cycles (mg kg^{-1}) (Roy et al., 2022).

	0–5 cm depth				5–15 cm depth			
	Zn	Mn	Fe	Cu	Zn	Mn	Fe	Cu
CT-RW	4.07b	14.1a	27.5a	2.21a	5.30b	10.6a	26.8a	4.09a
CA-RW+ Mb	7.25a	14.1a	8.09b	1.38a	7.83a	11.7a	19.8b	1.94a
CA-MW+ Mb	5.05ab	15.0a	10.1b	1.41a	8.40a	9.43a	17.7c	2.93

CT, Conventional till; RW, Rice-wheat; Mb, Mungbean; MW, Maize-wheat. Means followed by the same letter(s) within each column do not differ statistically ($P \leq 0.05$) using Duncan's Multiple Range Test.

after 10 years of cropping (Table 7). However, no significant effect of CA was observed on DTPA-Mn and Cu contents in both 0–5 cm and 5–15 cm soil layers. On contrary, DTPA-Fe content was significantly higher under CT-RW compared to CA systems in both the soil layers (Table 7). Jat et al. (2018) described that in CT-based RW system, anaerobic conditions in rice resulted in the transformation of less available Fe^{3+} to easily available Fe^{2+}, thereby increasing DTPA-extractable Fe content in CT over CA-systems. Das et al. (2021) observed significant increases in available Zn, Fe and boron (B) in both 0–5 and 5–15 cm layers under CA compared to CT after 8 years of rice-mustard-Mb cropping system.

A study from Bangladesh demonstrated significant increase in Zn concentration under CA-based RW system (non-puddled rice followed by strip tillage + high residue retention in wheat) over CT-RW system (Salahin et al., 2021). In contrast to the reports of increases in micronutrient availability in CA system from South Asia, Govaerts et al. (2007) from Mexico recorded a non-significant effect of different tillage practices on DTPA extractable Fe, Mn, and Cu concentrations. The increases in available micronutrient cations in soil under CA are linked to increase in SOC content and recycling of the micronutrients through crop residues. Limited information is available on the changes in micronutrient status under CA in rainfed conditions of South Asia (Hati et al., 2015a; Kushwa et al., 2016; Srinivasarao et al., 2014).

7. Conservation agriculture and soil biological health

Soil microorganisms are biological machines, which play a major role in the biogeochemical cycles of C, nutrients in the biosphere, decomposition of SOM, soil aggregation (Naylor et al., 2020) and their functioning is essential to soil health (Brady and Weil, 2016). The soil biological attributes, which could be used as possible sensitive indicators for characterization of soil health include: microbial diversity (species diversity and richness), populations of organisms, microbial biomass C (MBC), MBN, respiration rate, mycorrhizal associations, enzyme activities, fatty acid profiles, microbial quotient and mineralization quotient, etc. which changes rapidly in response to management practices (Jat et al., 2021; Saharawat et al., 2010; Saikia et al., 2019; Somasundaram et al., 2020). Conventional practices cause loss of the diversity, microbial population and activity of soil fauna thereby adversely affecting soil health and resilience of agroecosystems (Choudhary et al., 2018a,b; Singh et al., 2018). Lehman et al. (2015) highlighted the role of soil biology in soil health and illustrated how biological properties and processes contribute to sustainability of agriculture and ecosystem services.

7.1 Soil biodiversity

The richness in soil biodiversity is a key indicator of soil health, which has been considered recently in South Asia (Singh, 2015). The variability in the population of microorganisms, which broadly include microflora (bacteria, fungi, actinomycetes), microfauna (nematode, protozoa), mesofauna (acarid, enchytraea), and macro-fauna (termites, earthworms, arthropods), which all together are called soil biodiversity (Choudhary et al., 2018a,b; Kumar and Nath, 2019; Pisante et al., 2015). Microbiological diversities are measured by community profiling by fatty acids, DNA fingerprinting, high-throughput sequencing, etc. (Jat et al., 2021). Soil biodiversity plays an important role in crop production, nutrient cycling and GHG emissions (FAO and ITPS, 2015; Trivedi et al., 2017).

Relatively limited information is available on soil biodiversity under CA systems from South Asia. It has been largely demonstrated that CA practices induce major shifts in the number and composition of soil fauna and flora, including both pests and beneficial organisms (Choudhary et al., 2020; Jaipal et al., 2002; Spedding et al., 2004). In CA, residue mulch promotes biological diversity and the population of beneficial insects due to increase in C pools, improvement in soil aeration, soil moisture and temperature regimes than in CT system where residues are removed (Akter and Gathala, 2014; Choudhary et al., 2020, 2018a,b; Jaipal et al., 2002; Samal et al., 2017). The quality and quantity of C substrate in the form of residue and tillage practices play important roles in the shaping microbial properties of the soil (Choudhary et al., 2018a; Ghimire et al., 2014). On the other hand, CT exposes soil to adverse climatic condition and enhances the organic matter decomposition thereby adversely affects soil biodiversity. In CA, increase in arbuscular mycorrhizal fungi hyphae and secretion of glycoprotein and glomalin content helps in soil particle binding, which improves the stability of aggregate of the soil availability of nutrients, particularly P in soil (McGonigle and Miller, 1996). Saikia et al. (2019) and Sharma et al. (2022) reported significant increase in easily extractable glomalin and total glomalin-related soil protein concentration under ZT + R in wheat, compared with the CT wheat in RW system.

Choudhary et al. (2018c) analyzed biological diversity in CA plots in the surface 0–15 cm soil layer. The rice-based system was dominated by phylum Proteobacteria, while maize-based system was dominated by Acidobacteria. Acidobacteria and Bacteroidetes of Bacteroidia were exceptionally higher in CA-based MW-Mb system compared to RW-Mb system. Shannon diversity index was increased by 47% in maize-based CA practices compared to rice-based CA systems. Ascomycota was more abundant in maize-based CA systems as compared to rice-based CA systems. The results from the above study showed lower bacterial diversity under CA-based systems compared to CT.

Sequencing of soil DNA by Choudhary et al. (2020) revealed that a total of 40 bacterial phyla were observed in CT system and Proteobacteria was dominant in both CT and CA-based cropping systems followed by Acidobacteria and Actinobacteria after 9 years of the study. The relative abundance of Proteobacteria was 29% higher in rice-based CA system and 16% higher in maize-based CA system compared to CT RW system. The relative abundance of Acidobacteria and Actinobacteria was respectively 29% and 91% higher in CT than CA based rice and 27% and 110% higher than maize-based system, respectively. This study demonstrated that Shannon diversity index was higher in CT compared to CA systems; maize-based CA system recorded higher diversity indices than rice-based CA system.

Choudhary et al. (2018a,b) measured significantly higher population of bacteria, fungi and actinomycetes in CA system compared to corresponding CT systems. The population of bacteria compared to fungi and actinomycetes was higher in CA systems compared to CT after three cropping cycles of RW (Table 8). However, relative increase in fungal population compared to bacteria population was higher under CA systems compared to CT systems. The greater increase in population of fungi in soil is preferred under

Table 8 Effect of Conservation Agriculture (CA) on soil microbial population after 3-cropping cycles (Choudhary et al., 2018b).

Treatment	Bacteria (CFU × 10^4 g^{-1} soil)	Fungi (CFU × 10^2 g^{-1} soil)	Actinomycetes (CFU × 10^4 g^{-1} soil)
CT-RW	74.7d	45.3d	35.5c
CA-RW	85.9b	63.7b	50.8b
CA-RWMb	94.3a	73.1ab	68.0a
CT-MW	81.4c	53.8c	44.9c
CA-MW	87.4b	66.5b	54.2b
CA-MWMb	95.5a	76.2a	70.3a

Where CT, Conventional till; CFU, Colony forming unit. Means followed by the same letter(s) within each column do not differ statistically ($P \leq 0.05$) using Tukey's HSD test.

CA because they typically assimilate about 44% of readily decomposable C into biomass, while bacteria typically assimilate only about 32% (Myrold, 1998). Similarly, Jat et al. (2019a) showed noticeable increases in the population of fungal, bacterial and actinomycetes in the surface 0–15 cm soil layer under CA-based RW-Mb and MW-Mb systems than CT-RW system. In CA, residue retention induced higher population counts of total bacteria, fluorescent pseudomonas, and actinomycetes compared to residue removal under ZT and CT (Jat et al., 2019a,c). A 4-year study by Ghosh et al. (2010) revealed that CA-based rice-based system improved SOC by 71%, biological activity by 47% and increased yield by 49% over CT.

From the same study, Choudhary et al. (2018a,b) recorded the higher micro-arthropod population in CA-based RW and MW systems compared to CT-RW system (Table 9). Most abundant micro-arthropod group belonged to Collembola followed by Acari and Protura, irrespective of treatments. The CA system protects the growth and population of micro-arthropod from soil desiccation during summer due to presence of surface mulch. CA-based MW system recorded the highest microbial population, (bacteria, fungi and actinomycetes).

Furthermore, higher fungal diversity indices such as species richness, evenness and Shannon-Wiener diversity index under CA-based MW-Mb and RW-Mb systems compared to CT after 5 years of the study (Table 9). The biological soil health index was 100% and 290% higher in CA-based-RW and MW systems compared to respective CT systems (Table 9). Soil fungal communities of phylum *Ascomycota* was 55–74%

Table 9 Micro-arthropod diversity (number per 2 kg soil) and soil biological health index (SBHI) under Conservation Agriculture (CA) system after 3 years. (Choudhary et al., 2018a).

Treatment	Collembola	Acari	Total[a] population	Evenness	Richness	SBHI
CT-RW	12.3	1.0	17.0	0.393	4	0.29c
CA-RW	10.0	2.3	18.7	0.541	3	0.58b
CT-MW	2.3	1.0	4.0	0.881	2	0.36c
CA-MW	4.3	1.0	6.0	0.617	3	1.40a

[a]Total includes populations of Collembola, Acari, Protura, Diplura, Araneae and Hymenoptera.
Where CT, Conventional till; RW, Rice-wheat; MW, Maize-wheat.

higher in CA-based RW-Mb and MW-Mb systems compared to CT-RW system. Fungi of *Wallemiomycetes* class were exclusively present in CA-based systems, *Epicoccum* was the most abundant genus followed by *Cercophora*. The diversity analysis showed presence of significantly higher number of species in CA-based MW-Mb (95) and RW-Mb (85) compared to 54 species in CT-RW system. CA based MW-Mb treatment showed more fungal diversity and species richness compared to CT-RW and CA-based RW systems, which indicated more stability of the ecosystem.

7.2 Pest dynamics

Information relating to the effect of CA on insect pests and their natural enemies is very scarce in South Asia. Saroj et al. (2021) evaluated the changes in pest dynamics under CA-based RW and MW systems in northwest India. These authors reported that CA practices increased diverse aerial and epigeic arthropod communities which apparently increased biological control of pests through predation by natural enemies, that subsequently resulted in no increase of pests over the CT-based cereal systems. Furthermore, CA-based RW system had the highest insect diversity than CT system. In RW system, populations of stem borers, leafhoppers and grain sucking insects was decreased but the increase in population of leaf folders were noted in CA system compared to CT system. Similarly, in MW system, reduction in populations of silk borers, defoliators, beetles and shoot fly were recorded under CA. The parasitoids and predator density under CA-based RW system was about 20-fold higher at tillering stage as compared to CT system. It was concluded from this study that CA systems conserve and foster beneficial biodiversity that potentially helps mitigating the populations of several detrimental arthropods by making production systems more amenable to biocontrol. CA system with crop diversification by integration of legumes in cereal-based systems will reduce pest infestation by disruption of the pests' life cycle and improved biodiversity (Kassam and Friedrich, 2009). Jasrotia et al. (2021) reported that foliar aphid and termite populations in wheat were lowest in the ZT-protected system, and highest in the CT-unprotected system. Pink stem borer damage was significantly higher in the ZT-unprotected system, whereas the root aphid number was maximum in the RT-unprotected system. Chakraborty et al. (2021) concluded that the presence of crop residues in the soil surface in CA provide the residue- and soil-borne microorganisms including plant pathogens with a favorable habitat.

7.3 Soil microbial biomass carbon and nitrogen

Soil microbial biomass respond much more quickly to the changes in soil management practices as compared to total SOM (Sarkar et al., 2020). The microbial biomass C (MBC) and N (MBN) are relatively low in CT-RW system in the IGPs of South Asia due to intensive tillage practices and removal or burning of crop residues, and low levels of SOC (Das et al., 2014, 2021; Pandey et al., 2014). Several studies from South Asia have demonstrated significant increases ranging from −14.0% to 298% in MBC in CA system compared to CT system in surface soil layer under different cropping systems (Table 10). Similarly, several other studies from South Asia (Choudhary and Behera, 2014; Das et al., 2021; Gathala et al., 2017; Kushwaha et al., 2000; Modak et al., 2019; Saurabh et al., 2021; Yadav et al., 2017, 2019) reported significant increases in MBC under CA compared to CT system in the top 0–15 cm layer. The increases in MBN under CA system ranged from 33.3% to 199% compared to CT, which depended on the duration of the study and soil depth sampled (Bhattacharyya et al., 2018; Choudhary et al., 2018a,b; Jat et al., 2019a,c, 2020a). The increases in the MBC and MBN in CA over CT system were lower at 15–30 cm than at 0–15 cm depth. The lower MBC and MBN in the subsurface than the surface soil layer was ascribed to limited availability of organic C and O_2 in deeper soil layers (Sharma et al., 2005; Mukhopadhyay et al., 2016; Samal et al., 2017).

Recently, from a long-term (10 years) study, Roy et al. (2022) reported that CA-based RW-Mb and MW-Mb systems recorded 181–191% higher MBC at 0–5 cm and 69–85% at 5–15 cm depth over CT-RW. At 15–30 cm soil depth, 177% and 289% higher MBC was recorded in CA based

Table 10 Effect of Conservation Agriculture (CA) on soil microbial biomass carbon (MBC).

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	MBC ($\mu g\, g^{-1}$ soil) CT	CA	Δ (%)	References
Haryana, India	Rice-wheat	Clay loam soil	3	0–10	646	1182	+83.0	Choudhary et al. (2018a)
Haryana, India	Rice-wheat-Mb	Clay loam soil	4	0–15	501	1113	+122	Jat et al. (2019c)
Punjab, India	Rice-wheat	Sandy loam	5	0–7.5	83.6	333	+298	Dhaliwal et al. (2020)
Haryana, India	Maize-wheat	Clay loam soil	3	0–10	895	1990	+122	Choudhary et al. (2018a)
New Delhi, India	Maize-wheat	Sandy loam	4	0–30	357	440	+23.3	Parihar et al. (2020)
M.P., India	Soybean–wheat	Vertisol	3	0–15	336	385	+14.7	Somasundaram et al. (2019)
				15–30	234	275	+17.8	
New Delhi, India	Maize-wheat/chickpea/ mustard	Sandy loam	7	0–30	290	431	+49.0	Parihar et al. (2016)
Tripura, India	Rice-rice	Clay loam	3	0–20	210	295	+40.4	Yadav et al. (2019)
Haryana, India	Rice/maize-wheat	Typic Natrustalf	7	0–15	133	210	+57.5	Jat et al. (2020a)
				15–30	82.6	189	+128.6	
Haryana, India	Rice/maize-wheat	Typic Natrustalf	4	0–15	441	387	−12.2	Jat et al. (2019a)
				15–30	681	416	−38.9	

Continued

Table 10 Effect of Conservation Agriculture (CA) on soil microbial biomass carbon (MBC).—cont'd

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	MBC ($\mu g\, g^{-1}$ soil)			References
					CT	CA	Δ (%)	
Haryana, India	Rice/maize-wheat	Typic Natrustalf	5	0–15	170	266	+56.4	Choudhary et al. (2018b)
New Delhi, India	Pearl millet-wheat	Loamy sand	3	0–15	63.6	90.8	+42.8	Singh et al. (2018)
Bihar, India	Rice-wheat-Mb	Clay loam	4	0–10	67.8	106.3	+56.8	Saurabh et al. (2021)
				10–20	50.8	67.3	+26.6	
Bihar, India	Rice-wheat-Mb	Typic Natrustalf	10	0–5	137	398	+191	Roy et al. (2022)
				5–15	147	272	+85	

Where CT, Conventional till; Mb, Mungbean.

MW-Mb system over CA-based RW-Mb and CT-RW systems, respectively. From the same experiment after 4 years, Choudhary et al. (2018a) reported that CA-based MW system registered 208% and 263% increase in MBC and MBN, respectively, as compared to CT-RW system after three cropping cycles. These authors showed 48% and 73% higher MBC and MBN, respectively, under CA-based MW than that of CA-based RW system due to relatively greater amounts of crop residue recycling by maize than rice as well as varied soil edaphic conditions in the two systems.

The increases in MBC and MBN under CA compared to CT system were possibly due to the higher SOC content compared to CT, better aeration and regular additions of crop residues as C substrate for better activity of soil microbes (Bera et al., 2018; Choudhary et al., 2018a,b; Ronanki and Behera, 2019; Roy et al., 2022). In CA, ZT and crop residue mulch led to gradual decomposition of crop residues which slowly released labile SOM, thus served as food for soil microbes. The other possible reasons for increase in MBC under CA are alteration of plant–soil micro-climate, increased water and nutrient availability, and regulation of soil temperature by surface residue mulch (Gathala et al., 2017). The release of root exudates containing labile carbon provided food for the microbes at 15–30 cm depth thereby causing higher MBC content in CA-based systems at this depth despite containing lower SOC content.

From a study conducted in Bangladesh, Alam et al. (2016) reported 58–69% higher values of MBC under CA (ZT + crop residues) compared to CT in rice-based cropping system. Biswakarma et al. (2021) documented that CA-based maize rotation recorded increase in soil MBC and DHA by up to 80% and more than 100% compared to CT practices, respectively. Choudhary et al. (2018a,b) observed that CA-based RW and MW systems had the lower MBC/MBN ratio compared to CT systems suggesting the dominance of bacteria in the microbial population.

7.4 Soil enzymes

Soil enzymes catalyze the numerous reactions necessary for the life processes of microorganisms in soils, decomposition of organic residues and cycling of nutrients (Srinivasarao et al., 2014). Enzyme activities in soil such as DHA, FDA and hydrolases (e.g., urease, protease, phosphatase and β-glucosidase) and amylase, arylsulphatase, cellulase and chitinase, are important indicators of soil health (Bera et al., 2018; Das and Varma, 2011; Sharma et al., 2021). The enzyme activities are frequently more sensitive to land management and environmental stress than physical and chemical indicators (Choudhary et al., 2018a,b; Lehman et al., 2015).

Results from several studies have demonstrated significant increases in the DHA ranged from 27.2% to 502% depending on the duration of the study, soil depth and cropping system (Table 11). Similarly, increase in FDA ranged from 15% to 72.2% under CA-based cropping systems over CT in surface soil layer (0–15 cm) under rice- and maize-based cropping systems after 3–7 annual cropping cycles (Table 12). Jat et al. (2020a) reported 210% increase in DHA under CA-based MW and 444% increase under CA-based RW system compared to CT system. From a long-term (10 years) study, Roy et al. (2022) recorded significant increase of 94% and 328% in DHA in CA-based RW-Mb and MW-Mb cropping systems compared to CT-RW system, respectively, only at 0–5 cm depth. In surface soil layer, higher DHA under CA-based systems might be attributed to higher accumulation of SOM. Higher soil moisture availability to microorganisms due to surface residue mulch possibly attributed to higher DHA under CA.

Glycosidases are involved in C cycling by catalyzing decomposition and releasing energy from polysaccharides (Tabatabai, 1994). Many researchers from South Asia (Choudhary et al., 2018b; Jat et al., 2020a; Parihar et al., 2020, 2019; Saikia et al., 2019; Sharma et al., 2021; Singh et al., 2018) have recorded significant increases in β glucosidase in CA over CT system in surface layer after 3–7 years of RW and MW cropping systems. Samal et al. (2017) also reported higher soil enzymatic activities (FDA, DHA, β-glucosidase and APA) after 7 years of CA-based in soybean-wheat cropping systems at 0–15 cm soil depth compared to CT. Similarly, results from a 6-year study on wheat-based cropping systems by Behera et al. (2021) showed higher FDA, DHA and β-glucosidase activity under CA-based MW and pigeonpea–wheat rotations than CW system. Based on the results from a long-term (10 years) study, Roy et al. (2022) demonstrated that β-glucosidase activity was 38.2% higher under CA-based MW-Mb system compared to CA based RW-Mb system at 0–5 cm soil depth. The β-glucosidase activity was not influenced by CA systems at 5–15 and 15–30 cm soil depths. At 0–5 cm soil depth, higher β-glucosidase activity under CA-based system was due to higher SOM content resulting from residue retention and ZT. The higher activities of DHA and APA in surface soil layer of CA system were associated with higher SOM content and MBC resulting from regular additions of crop residue and ZT thereby also creating a positive "rhizosphere effect" on enzymes secretion in soil.

Table 11 Effect of Conservation Agriculture on soil dehydrogenase activity (DHA).

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	DHA (µg TPF g^{-1} h^{-1}) CT	CA	Δ (%)	References
Haryana, India	Rice-wheat	Clay loam soil	3	0–10	7.5	45.1	+502	Choudhary et al. (2018a)
Punjab, India	Rice-wheat	Sandy loam	5	0–7.5	4.42	10.3	+133	Bera et al. (2017)
Haryana, India	Rice-wheat-Mb	Clay loam	10	0–5	115	223	+94.0	Roy et al. (2022)
				5–15	112	66.6	NS	
New Delhi, India	Maize-wheat	Sandy clay loam	5	0–5	14.2	21.7	+52.8	Bhattacharyya et al. (2018)
				5–15	13.3	14.6	+9.77	
Haryana, India	Maize-wheat	Clay loam soil	3	0–10	9.12	23.0	+152.2	Choudhary et al. (2018a)
New Delhi, India	Maize-wheat	Sandy loam	4	0–30	28.7	35.7	+24.4	Parihar et al. (2020)
New Delhi, India	Maize-wheat/chickpea/mustard	Sandy loam	7	0–30	23.2	33.3	+43.5	Parihar et al. (2016)

Continued

Table 11 Effect of Conservation Agriculture on soil dehydrogenase activity (DHA).—cont'd

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	DHA (μg TPF g^{-1} h^{-1}) CT	CA	Δ (%)	References
Tripura, India	Rice-rice	Clay loam	3	0–20	5.2	8.3	+59.6	Yadav et al. (2019)
Haryana, India	Rice-wheat	Typic Natrustalf	7	0–15	69.5	83.5	+20.1	Jat et al. (2020a)
Haryana, India	Rice-wheat	Typic Natrustalf	5	0–15	37.3	62.9	+68.8	Choudhary et al. (2018b)
New Delhi, India	Pearl millet-wheat/ chickpea	Loamy sand	3	0–15	7.72	19.80	+156.5	Singh et al. (2018)
Bihar, India	Rice-wheat-mungbean/ cowpea	Silty clay	7	0–15	29.5	166.6	+465	Samal et al. (2017)
Bihar, India	Rice-wheat-mungbean		4	0–10	12.0	18.4	+53.3	Saurabh et al. (2021)
				10–20	9.2	11.7	+27.2	

Table 12 Effect of Conservation Agriculture on Fluorescein diacetate hydrolytic activity (FDA).

Location	Cropping system	Soil type	Duration (years)	Soil depth (cm)	FDA (µg fluorescein g^{-1} h^{-1})			References
					CT	CA	Δ(%)	
Punjab, India	-do-	Sandy loam	5	0–7.5	0.421	0.628	+49.2	Bera et al. (2017)
Punjab, India	-do-	-do-	5	0–7.5	0.957	1.142	+19.3	Saikia et al. (2020)
New Delhi, India	Maize-wheat	Sandy clay loam	5	0–5	181.7	272.1	+49.8	Bhattacharyya et al. (2018)
				5–15	125.2	215.6	+72.2	
New Delhi, India	-do-	Sandy loam	4	0–30	0.488	0.594	+21.7	Parihar et al. (2020)
New Delhi, India	Maize-wheat/chickpea/mustard	Sandy loam	7	0–30	0.370	0.521	+40.8	Parihar et al. (2016)
New Delhi, India	Pearl millet-wheat/chickpea/mustard	Loamy sand	3	0–15	13.3	27.9	+110	Singh et al. (2018)
Bihar, India	Rice-wheat-mungbean/cowpea	Silty clay	7	0–15	43.0	49.5	+15	Samal et al. (2017)
Bihar, India	Rice-wheat-mungbean		3	0–10	37.4	55.7	+48.9	Saurabh et al. (2021)
				10–20	35.3	48.0	+36.0	

Many researchers (Bera et al., 2017; Choudhary et al., 2018a,b; Datta et al., 2021; Jat et al., 2019a,b, 2020a; Saikia et al., 2019) reported increases in alkaline phosphatase activity (APA) by 13.2–73.3% in the surface layer under CA than in CT system after 3–5 years of the study, and the activity was more under CA-based MW-Mb system compared to RW-Mb cropping system in northwestern India. Crop rotations, particularly inclusion of legume have facilitated higher microbial activity leading to release of both APA and acid phosphatase activity (AcPA)in soil. In CA-based pearl millet-wheat/chickpea/mustard cropping systems, Singh et al. (2018) recorded 50.7% increase in APA after 3 years of study over CT system. However, Parihar et al. (2016) observed no significant increase in APA in CA system after 7 years of maize-based cropping systems. Roy et al. (2022) reported that APA in CA-based MW-Mb system was significantly higher compared to CA-based RW-Mb system at 0–5 cm soil depth. The differences in APA between CA-based RW-Mb and MW-Mb systems were, however, non-significant in 5–15 cm soil layer but was significantly higher under CT-RW system compared to CA systems. Choudhury et al. (2014) observed that after 5 years of CA adoption enzyme activity (DHA and AcPA) increased significantly over CT cowpea-wheat and RW systems in the EGP of India. Roy et al. (2022) reported that AcPA was not influenced by CA-based MW and RW systems at 0–5 cm soil depth even measured after 10 years of the study. In CA based MW-Mb AcPA was significantly increased under MW-Mb compared CA based RW-Mb and CT-RW systems at 5–15 cm soil depth. The higher AcPA under CA was also reported by Jat et al. (2019a). In general, both APA and AcPA in CA system decreased with soil depth.

Results from a study by Sharma et al. (2021) showed higher values of the enzyme activities (urease and arylsulphatase) and MBC under CA compared to CT in sorghum-castor system. Roy et al. (2022) also observed increases in the APA and acid phosphates activities, responsible for hydrolysis of esters in soils, in CA systems compared to CT at both 0–5 and 5–15 cm depths in a RW system after 10 cropping cycles. Other studies have also reported 32–40% increase in APA under CA compared to CT in RW systems (Bera et al., 2017; Saikia et al., 2019; Singh et al., 2018).

The improvements in soil enzymatic activities under CA practices are credited to the improvements in physical and chemical properties of soil. Datta et al. (2021) reported higher activities of DHA, acid phosphatase, FDA, cellulase, urease and arylsulphatase under maize-based compared with the rice-based systems. Sharma et al. (2022) reported ~54%, 56%, and 45%

increases DHA, cellulase, and β-glucosidase activities in soil under ZT + R in wheat in RW system, respectively, compared with the CT.

7.5 Earthworms

Earthworms as soil macro-fauna, are considered as key soil health indicator, because they improve water movement, soil structure, C and N recycling by their biomass releasing the significant amount of N through discharge (Whalen et al., 2000). These are very sensitive to changes in soil management practices as their populations increase significantly after only a few years of CA (Thierfelder and Wall, 2010; Verhulst et al., 2010). The earthworm population density and biomass were significantly higher in the 0–15 and 15–30 cm layers under CA-based RW-Mb and MW-Mb systems over CA-based RW-Mb system (Jat et al., 2022). The increases in earthworm population density in CA-based MW-Mb were 53% and 89% higher and earthworm biomass were 256% and 122% higher than in RW-Mb system in 0–15 cm and 15–30 cm layers, respectively (Jat et al., 2022). No earthworm population was detected in CT-RW system. The anaerobic conditions in conventional rice culture resulted in low earthworm density compared to CA system (Dhar and Chaudhuri (2020). The higher earthworms' density and biomass of CA maize-based over CA rice-based system were attributed to the higher amount of crop residue input with lower C/N ratio in maize compared to rice residue. Effect of CA on soil fauna including earthworms depends on tillage, and residue quantity and quality (Jat et al., 2022; Singh et al., 2020). The reduction in earthworm abundance and diversity in the CT has been reported by many researchers from India (Choudhary et al., 2018a; Jat et al., 2022; Singh et al., 2020; Suthar, 2009) and worldwide (Briones and Schmidt, 2017; Lubbers et al., 2015; Treder et al., 2020). The CT reduces the earthworms' abundance by killing and injuring them, exposing them to predators by bringing them closer to the soil surface, decreasing their food source through the acceleration of SOM decomposition, and creating unfavorable soil physical conditions (e.g., temperature, moisture, and soil structure) (Briones and Schmidt, 2017).

8. Development of soil health index for conservation agriculture

Soil health index (SHI) is a measurable soil parameter that affects the capacity of a soil to perform a specific function in a defined agro-ecosystem (Karlen et al., 2006). It is an integration of physical, chemical and biological properties of the soil, which can provide a better picture of the improvement in soil health in CA system than an individual parameter. Assessment of SHI is based on the integration of soil health indicators using the inductive additive approach and involves four steps; (i) Identification of key indicators, (ii) Selection of minimum data set (MDS) of indicators that represent the soil function, (iii) Scoring the MDS indicators based on their performance, and (iv) Summation and average of the score of the indicators into an index. Choosing indicators is a daunting task since it is difficult to determine which indicators and threshold values of indicators would be the best representation of a particular soil type and cropping system. One should select soil health indicators that interact synergistically which can help in measuring the soil health and stability under different crop cultivation practices.

The scientific literature shows that researchers have been using a variety of indicators for assessing soil health. For example, Bünemann et al. (2018) reviewed 65 studies and found that frequency of detection in soils was 15–30% for four biological indicators, 15–90% for 13 chemical indicators with the highest detection for P, pH, and SOC, and 15–60% for 10 physical indicators with the highest detection for texture, BD, and water storage. Similarly, Haney et al. (2018) constructed SHI using the indicators that measure plant-available N (NO_3-N, NH_4-N), water-extractable OC, and water-extractable organic N.

Principal component analysis (PCA) is generally used to identify MDS for quantifying effect of CA practices on soil health and develop a SHI index (Andrews et al., 2002). The PCA allows, which variables better explain the observed differences in soil health parameters due to CA and CT in different cropping systems. Most of the studies on MDS and development of SHI in CA systems are restricted to India among the South Asian countries. Researchers identified different set of MDS for developing SHI suggesting the lack of unanimity in their choice of the indicators for developing SHI in CA-based cropping systems (Table 13). Furthermore, MDS for developing SHI appeared to be influenced by cropping system, soil depth and inherent soil properties. For example, Saikia et al. (2020) identified three most influential variables as MBC, microbial metabolic quotient (qCO_2) and mineralization quotient (qM), which responded significantly to changes in tillage and residue management practices in the RW (RW) system.

Using 12 variables in the PCA, Choudhary et al. (2018a) identified soil MBC, APA, bulk density and micro-arthropod population as the key indicators (MDS), which contributed 78% of the total variance toward SHI. CA-based MW-Mb had the highest SHI of 1.45 followed by CA-based

Table 13 Minimum data set (MDS) of soil health parameters for developing soil health index in Conservation Agriculture system in different studies from South Asia.

Location	Cropping system	Duration (years)	Minimum data set	References
New Delhi, India	Rice-mustard-mungbean	8	Ks, pH, TN, Av. K (0–5 cm)	Das et al. (2021)
			Ks, pH, Av. K (5–15 cm)	
West Bengal, India	Jute-based triple cropping system,	5	BD, Av. K, Urease, DHA, MBC	Kumar et al. (2021)
Bihar, India	Rice-wheat/maize	6	TOC, Av. P and K	Nandan et al. (2019)
Haryana, India	Rice/maize-wheat-mungbean	10	SOC stock, BD, pH, Av. Fe and N (0–5 cm); MBC, SOC stock, Av. Zn and Fe, β-glucosidase (5–15 cm)	Roy et al. (2022)
New Delhi, India	Maize-wheat-mungbean	4	MWD, SOC, Av. K	Parihar et al. (2020)
Punjab, India	Rice-wheat	6	β-Glucosidase, cellulase, phenol oxidase	Saikia et al. (2019)
West Bengal, India	Jute-rice-wheat/ lentil/ mustard	3	pH, BD, SOC, Av. N and, EC, MWD	Saha et al. (2022)
Punjab, India	Rice-wheat	6	SOC, MBC	Sharma et al. (2019)
New Delhi, India	Rice-wheat	6	Microbial Quotient, MBC, DHA, SOC, WHC, WSAs, Av. N and Fe	Bhaduri and Purakayastha (2014)
New Delhi, India	Rice-wheat	8	Av. Fe, WSA, MBC	Bhaduri et al. (2014)
Haryana, India,	Rice/maize-wheat-mungbean	3	MBC, APA, micro-arthropod population, SOC and BD	Choudhary et al. (2018a,b)
Bihar, India	Rice/maize-wheat-mungbean	3	MBC, DHA and FDA	Saurabh et al. (2021)

Continued

Table 13 Minimum data set (MDS) of soil health parameters for developing soil health index in Conservation Agriculture system in different studies from South Asia.—cont'd

Location	Cropping system	Duration (years)	Minimum data set	References
Haryana, India,	Rice/maize-wheat-mungbean	4	MBC, fungal population and SOC at 0–10 cm soil depth	Jat et al. (2019a)
Madhya Pradesh, India	Rice-wheat	3	BD, SPR, WSAs, SOC	Mohanty et al. (2007)
Punjab, India	Rice-wheat-sesbania green manure	6	FC, TG, non-labile C, WSAs and PWP	Sharma et al. (2022)

BD, Bulk density; Ks, Saturated hydraulic conductivity; Av., Available; TN, Total soil N; SPR, Soil penetration resistance; WSAs, Water stable aggregates; MWD, Mean weight diameter of aggregates; SOC, soil organic carbon; APA, Alkaline phosphatase activity; PWP, Permanent wilting point; DHA, Dehydrogenase activity; FC, Field capacity soil moisture content; MBC, Microbial biomass carbon; FDA, Fluorescein diacetate hydrolytic activity; TOC, Total organic carbon.

RW-Mb system (1.34), and the CT- RW and MW systems had the lowest SHI of 0.29 and 0.36, respectively, indicating the deterioration of soil health under CT system. CA-based MW-Mb and RW-Mb systems recorded the higher SHI compared to CT-RW system. Yields of maize/rice-based systems were positively correlated with SHI. Similarly, significant relationships between SHI and system equivalent yield were obtained by other researchers (Das et al., 2021; Saurabh et al., 2021) in cereal-based systems. From another study, Choudhary et al. (2018a,d) reported that MDS consisted of fungal population, soil pH and micro-arthropod population from the 12 soil health parameters evaluated. The regression of SHI and system yield showed significant positive relation. The PCA using 14 soil health variables, Jat et al. (2019a) identified MBC, fungal population and SOC as the key indicators and can be used for measuring SHI under CA-based RW/MW-Mb cropping systems.

Saikia et al. (2019) identified three soil enzymes (β-glucosidase, phenol oxidase and cellulase activity) as the most influential MDS which can be considered as potential indicators of soil health to distinguish the most sustainable CA-based practices (e.g., ZT and residues retention) from CT in RW system in north-western region of India. Das et al. (2021) identified four MDS (Ks, pH, total N, and available P) in 0–5 cm soil layer from the 15 variables analyzed after 8 years of CA-based rice-mustard-Mb cropping system. The MDS for 5–15 cm layer identified by these authors were Ks, pH and available K. Similarly, Mondal et al. (2021) identified four key soil indicators (MBC, available N, DTPA-Zn, and DTPA-Cu) that contributed the most toward SHI, while contribution of MWD of soil aggregates was the least.

Among the 25 soil health parameters analyzed, Jat et al. (2022) reported that about 60% of the variance (loadings) were provided by the7 parameters in PC1 (IR, MWD, OC stock, earthworm density and available N, P, and K contents) that can be used as key indicators for assessing SHI. Similarly, Saurabh et al. (2021) identified 10 key indicators of soil health, which included three physical (WSAs, available water capacity and SPR), four chemical (SOC, and available N, P and K) and three biological (MBC, FDA and DHA) parameters for developing SHI. The soil chemical and soil physical health indicators accounted for 84% and 81% of the SHI variability, respectively. On the basis of correlation coefficients, these authors concluded that the improvement in soil biological health relates to improvement in soil chemical and physical health, and ultimately soil health. From a 5-year study conducted in West Bengal, India, Kumar et al. (2021) identified five soil parameters, namely; bulk density, available K, urease activity, DHA, and soil MBC as the MDS for the calculation of the SHI in jute-based cropping systems. In another study, Roy et al. (2022) measured 19 soil health parameters and identified 4 MDS (SOC stock, BD, and available Fe and N) for the 0–5 cm soil layer under CA-based rice/MW-Mb systems. The MDS varied according to the soil depth (Table 13). For 5–15 cm soil layer, MDS identified were SOC stock, available Fe and Zn, MBC and β-glucosidase. The SHI was 36–40% higher in RW-Mb and MW-Mb cropping systems compared to CT-RW system.

In conclusion, there is a strong need to identify most common MDS, which can be used for developing SHI depending on cropping system and soil type. Also, use of uniform soil depth is most important to compare values across different cropping systems. Long-term (>10 years) studies are essential to realize maximal benefits from CA on SHI and crop yields.

9. Impact of conservation agriculture on climate change and adaptation

CA system not only mitigate climate change by reducing GHG emissions and contributing to C sequestration in soils, but also adapt agricultural ecosystems to their effects, by increasing crop resilience facing climatic variations (Pisante et al., 2015). CA reduces water erosion and evaporation losses allowing the crops to have more water available in dry periods. The major sources of GHGs from agriculture include the emission of N_2O from the production and use of synthetic fertilizer, emissions from crop residue burning, CH_4 emission from rice cultivation under flooded conditions, and CO_2 emissions associated with fossil fuel use for powering machinery and irrigation pumps (Searchinger et al., 2018). In major South Asian countries agriculture will face a grim catch-22 situation in the coming decades, where there is an urgent need to increase crop yields to feed a growing population even as increased agricultural production depletes already declining water tables and deteriorating soil health. Making matters worse are the progressing effects of climate change on crop production (Aryal et al., 2021; Banerjee et al., 2020). For instance, the productivity of rice will decline by 10% with every 1 °C increase in temperature (https://warmheartworldwide.org). It is projected that almost half of the IGP of Soth Asia, the major food basket in region, may become unsuitable for wheat production by 2050 as a result of heat stress (Ortiz et al., 2008). It has been projected that average temperatures in South Asia will increase by 0.88–3.16 °C by 2050 and 1.56–5.44 °C by 2080, which will be dependent on the progress of future policies (Vinke et al., 2017). The recent trends of climate change which include increase in extreme weather events such as floods and droughts, and variations in minimum and maximum temperatures are adversely affecting agricultural productivity and food security in South Asia (Aryal et al., 2020, 2021; Hati et al., 2020; Jat et al., 2020b; Sharma et al., 2021; Tesfaye et al., 2017). CA is an environment-friendly production strategy involving recycling of crop residues, less water and energy uses, and lower GHGs emissions contributing to mitigation and adaptation/resilience to climate change for food security compared to CT practices with similar or higher yields (Chakraborty et al., 2017; Hobbs and Govaerts, 2010; Jat et al., 2020b; Nandan et al., 2019; Paustian et al., 2016).

9.1 Climate change mitigation

The climate change mitigation deals with the reduction of atmospheric GHG concentration by tackling its emission sources. Soil is the largest terrestrial reservoir of organic C and is central for climate change mitigation and carbon-climate responses (Georgiou et al., 2022). The intensive tillage practices fragment the soil macroaggregates, accelerate soil C loss and enhance GHG emission, whereas in CA systems, avoiding tillage operations helps in C sequestration in soil, reducing gaseous emissions, reducing global carbon footprints, and sustaining environmental health (Bandyopadhyay, 2020; Hati et al., 2020). Climate change mitigation through CA is based on the three main factors sink effect (net increase in SOC or C sequestration), reduction of GHG (CO, N_2O and CH_4) emissions from the soil including the emissions from reducing or eliminating the burning of crop residues, and reduction of CO_2 emission due to the minimal use of agricultural machinery and other inputs). Improved soil health and nutrient availability in CA systems will also lower fertilizer requirements, which mean less potential for N_2O emissions and energy saving from the manufacture of fertilizers. CA systems also mitigate climate change by enhancing soil moisture conservation thereby savings in irrigation water thereby helping in saving electricity (energy) costs and reduction in GHG emission for energy production consumed in irrigation.

In South Asia, conventional wetland rice culture is considered to be the main source of atmospheric GHGs (particularly CH_4) due to its large area and excessive use of agricultural inputs (Aryal et al., 2015; Sapkota et al., 2014) with a GWP of 13–26 Mg CO_2eq ha^{-1} year^{-1}. CT systems based on extensive tillage and removal or burning of crop residues lead to SOC depletions over time with implications for increased the GHG emissions from soils leading to extreme climate events (Hatfield et al., 2018; Tilman et al., 2011; Tomar et al., 2019). Large scale crop residue burning in northwestern India releases enormous quantity of GHGs and pollutants to the atmosphere (Hobbs and Govaerts, 2010). In India, with ~516 million tons (Mt) of residue production, ~116 Mt. (mainly of rice and wheat) were burnt during the year 2017–18 (Venkatramanan et al., 2021). The burning of these crop residues has been emitting~176 Tg of CO_2, ~10 Tg of carbon monoxide (CO), ~314 Gg of methane (CH4), ~8 Gg of nitrous oxide (N_2O), ~151 Gg of ammonia (NH_3), ~814 Gg of non-methane volatile organic compounds along with the release of more than half a Gg of black carbon and more than 1 Gg of particulate matter contributing directly to environmental pollution (Porichha et al., 2021; Venkatramanan et al., 2021). Gupta and Seth (2007) claimed that avoiding the crop residues burning can minimize CO_2 emissions by 8.7 Mg ha^{-1}.

A 20-year meta-analysis of an ZT system in IGP showed that GHGs emitted in ZT wheat were 3% less than those under CT wheat in RW systems; and C sequestration potential was estimated to be 44.1 Tg C under ZT (Grace et al., 2012). Grace et al. (2003) reported that ZT (first principle of CA) in wheat can eliminate the CO_2 emission by 156 kg ha^{-1} annually and can effectively reduce GHG emissions by half in the IGPs of South Asia

(Erenstein and Laxmi, 2008). Further, implementation of ZT in MW and CW system would sequester an additional 6.6 Tg C. (Grace et al., 2012). Sapkota et al. (2021) demonstrated that total GHGs emissions from agricultural sector in Bangladesh for the year 2014–15 were 76.8 Mt. of CO_2 equivalents (CO_2e). Of this, mitigation potential of 70–75% can be achieved through cost-saving options including CA. The large-scale adoption of CA might not only increase SOC in the soil, but also: (i) help to mitigate emissions of GHGs that contribute to global warming and (ii) reduce C loss, improve soil productivity and reduce environmental damage and degradation from the existing unsustainable CT systems (Hati et al., 2020). Without wide-scale adoption of CA, rising temperatures in the warm wheat-producing environments could reduce production and threaten food security in South Asia (Tesfaye, 2021). Potential of CA technologies to mitigate GHG emissions of the rice-based cropping systems could be significant in South Asia especially they increase SOC stocks (Alam et al., 2019). Pratibha et al. (2015) reported that ZT had significantly lower (20–22%) GWP (kg CO_2 eq. ha^{-1}) compared to CT pigeonpea-castor cropping system under rainfed conditions of South India. The lower GWP in ZT was due to savings on fossil fuel from reduced number of passes and also emissions associated with energy consumed in manufacture, transport, repair and use of machines. The role C sequestration in the mitigation of GHGs emissions under CA has been questioned by some researchers (Chan et al., 2011; Epule et al., 2011), suggesting for the need of continuing research on the environmental sustainability of RW systems in South Asia. The life cycle assessment study conducted by Alam et al. (2019) in rice-rice-mustard system in the EGP of Bangladesh showed that CA practices in rice (non-puddled transplanting and residue retention) decreased the GHG emissions (CO_2eq) by 31% in comparison with the conventional practice. In wheat, strip planting with high residue return (6 Mg ha^{-1}) reduced GHG emissions by 28% relative to CT. On a system basis, CA-based practices reduced the net GHGs by 16% in comparison with conventional practice. These authors emphasized that where the CA practices increase SOC content, accounting for soil C sequestration in life cycle analysis will improve accuracy for determining the net GHG values. In CA systems, ZT in rice cultivation could minimize CH_4 emissions by avoiding puddling by adopting direct seeded rice system and by encouraging soil aeration (Alam et al., 2018b; Hobbs and Govaerts, 2010). A meta-analysis by Jat et al. (2020b) using 9686 paired site-year comparisons from South Asia suggested that ZT with residue retention had a mean yield advantage of 5.8%, mean increase in WUE by

12.6%, increase in net economic return of 25.9% and a reduction of 12–33% in GWP. Furthermore, water used for irrigation will be reduced by 14,100 million m^3, GWP (CO_2e) will be reduced by 2.9 Mt. (Jat et al., 2020b). The analysis of data showed that CH_4 emissions were reduced by 75% and GWP were reduced by 34% in CA-based RW cropping systems. Review of the recent development of CA for rice-based smallholder farms in the Eastern Gangetic Plain (EGP) in Bangladesh demonstrated improvement in soil health in long-term experiments together with reduced GHG emissions (Bell et al., 2018; Kumar and Nath, 2019). Ladha et al. (2016) demonstrated that CA practices in rice could reduce total the GWP by 23% annually over CT system. CA and crop diversification achieved 35% saving in total water input, and a 43% lower GWP intensity.

Field measurements of GHG emissions from fields under RW system by Tirol-Padre et al. (2016) showed that switching CT puddled transplanted rice to ZT-direct seeded rice in CA reduced CH_4 emissions by 56% without significant increases in N_2O emissions. Reduction of GWP in the range of 44–47% without any significant yield loss under ZT-based CA practices compared to CT system. Tirol-Padre et al. (2016) recorded 7–8% lower GWP of wheat in CA-based systems than that of CT due less use of fuel, electricity for irrigation water. In maize, emission of N_2O from soil was much higher than that in rice but no emission of CH_4 was observed from maize plots. Bhatia et al. (2010) also recorded higher emission of N_2O in ZT than CT plots, because the soils under ZT were usually moister with SOC more concentrated at soil surface favoring greater N_2O production. Parihar et al. (2018) reported CA-based practices in maize-based cropping systems had lower N_2O emissions than CT due to increased oxygen diffusion rate which decreased the denitrification and, thus, the production of N_2O. The GWP of with CA practices might be further reduced when precision irrigation and nutrient management practices are followed. Reduction in GHG emissions under CA system is also reported by many other researchers (Bhattacharyya et al., 2012; Gupta et al., 2016a; Sapkota et al., 2015, 2017) in the IGP region of India. Kumar et al. (2018) reported that average seasonal GWP of wheat in CA-based RW and MW systems was 7–8% lower than that of CT wheat. The N_2O emissions did not differ under CA and CT systems at the same fertilizer rate. On an annual system basis total GWP was 30% and 42% lower in CA-based RW-Mb and MW-Mb systems compared to CT-RW, respectively. The CH_4 emissions was 56% lower in rice under CA-based RW system due to adoption direct seeded rice than from puddled transplanted in CT in RW system. From a 5-year study in

NW India, Sapkota et al. (2017) measured large CH_4 emissions from conventional puddled transplanted rice field, while no detectable level of CH_4 emission was observed under ZT-based direct seeded rice in RW system in northwest India. The life-cycle analysis of wheat production by using Cool Farm Tool showed that GWP intensity was 10 times higher in CT-based RW system (~400 kg CO_2-eq Mg^{-1} wheat yield) than in ZT-based production.

From reviews of published literature, Das et al. (2021) and Rani et al. (2019) concluded that substantial decrease in fossil fuel usage under CA system reduces the release of GHG into atmosphere. For instance, by adopting of ZT for land preparation and crop establishment in wheat in RW system of the IGP, farmers could save about 36 L diesel ha^{-1} (Erenstein and Laxmi, 2008), equivalent to a reduction in 93 kg CO_2 emission ha^{-1} $year^{-1}$. A similar saving in fuel could be expected for establishment of ZT direct seeded rice in the CA system. On 3-year mean basis, Kakraliya et al. (2018) estimated 40% lower GWP in climate smart agriculture practices (CA + precision nutrient and water management) compared to CT system (GWP of 7653 kg CO_2 eq ha^{-1} $year^{-1}$). The meta-analysis of published data from South Asia, Jat et al. (2020b) showed that mean CH_4 emissions were reduced by 75% and GWP was reduced by 34% in CA-based cropping systems.

Karki and Gyawaly (2021) reviewed the work on CA practices on mitigation of climate change in Nepal and other parts of South Asia. These authors concluded that CA systems increased and sustained the crop productivity, mitigate GHG emissions from agriculture by enhancing soil C sequestration, improving soil nutrient status and WUE, and reducing fuel consumption. According to Ortiz-Monasterio et al. (2010) about 90% of the total GHG mitigation in CA arises from sink enhancement (soil C sequestration) and about 10% from emission reduction. Thus, CA approaches have potential to mitigate GWP of intensive rice-based cropping systems of South Asia. However, reports are also available in the literature highlighting the limited potential of ZT based CA on climate change mitigation (Corbeels et al., 2020; Powlson et al., 2014), particularly when role of CA in sequestration is ignored.

9.2 Adaptation to climate change

CA has potential to contribute toward adaptation for extreme weather events such as drought and high rainfall events that occur as a consequence of climate change due to higher infiltration rates resulting in high soil moisture storage and minimum flooding than the CT systems in both irrigated and rainfed crops (Williams et al., 2018). Surface mulch cover under CA buffers temperatures at the soil surface which otherwise are capable of harming plant tissue at the soil/atmosphere interface, thus minimizing a potential cause of limitation of yields. Better soil moisture conditions in rooting zones during growing seasons under CA help to reduce the harmful effect of drought on crop growth. Due to the recent climate change, higher temperature toward the maturity stage of winter crops (mainly wheat) shortens the duration of grain filling and slows photosynthesis and grain-filling rates in the IGP of South Asia (Gupta et al., 2016b; Lobell et al., 2012), all leading to smaller grain size and lower yield, commonly known as "terminal heat effect." CA adoption also provides increased adaptation and developing resilience toward the impacts of climate change. Arshad et al. (2017) suggested that CA practices will help escape the period of critically high heat during flowering in wheat, which can advance sowing dates while conserving soil moisture in South Asia. Crop residue retention in ZT wheat regulates terminal temperature up to 2°C in wheat (Balwinder-Singh et al., 2011; Gupta et al., 2016b). Adoption of CA practices will help to advance the planting time in cereal-based cropping systems in the IGP of South Asia (Erenstein et al., 2012; Sapkota et al., 2015), thus escaping from terminal heat effect in wheat. Residue management in CA systems increased leaf water potential and lowered leaf canopy temperature by 0.6–1.5 °C at grain filling stage mitigating terminal heat stress in wheat compared to CT (Gupta et al., 2010; Jat et al., 2019c). At the same time, the mulch minimizes soil evaporation and conserves soil moisture, which also contributes to beat heat stress (Gupta et al., 2021b; Yadvinder-Singh and Sidhu, 2014). It thus seems that under climate changing scenarios emerging under South Asian conditions, crops like wheat following CA will outperform the crops grown under CT. The impact of climate change is especially more severe in the rainfed regions of South Asia. Rainfed agriculture in India currently accounts for about two-thirds of the total cropped area and nearly half of the total value of agricultural output and nearly half of all food grains are grown under rainfed conditions (Roul et al., 2015; Singh et al., 2021).

Sapkota et al. (2015) reviewed the effects of CA from the perspective of adaptation to heat and water stresses, and reduction GHG emissions in South Asia. Their analyses showed that CA-based production systems moderated the effect of high temperature (reduced canopy temperature by 1–4°C) and increased irrigation WP by 66–100% compared to CT systems thus well adapting to water and heat stress situations of IGP. Results from a long-term trial in RW system in IGP showed that retention of rice residue in ZT system lowered the canopy temperature in wheat by 1–4 °C than atmospheric temperature between 138 and 153 days after seeding probably due to soil moisture conservation with residue mulching which provided cooling effect on canopy as a result of enhanced evapotranspiration (Jat et al., 2009). Analysis of data collected from 500 farmers in 2021–22 (year with high temperatures) showed that average wheat yield was 10% higher in CA plots compared to in CT fields suggesting positive effects of CA in climate adaptation (Rajbir Singh, ICAR-ATTARI, Ludhiana, Punjab, India, personal communication).

There are examples of significant decreases in yields of CT maize and wheat due to water logging as a result of low rate of infiltration, and due to terminal heat effects observed in wheat compared to CA-based systems in North-West India (Aryal et al., 2018; Gathala et al., 2020b) (Fig. 3). Aryal et al. (2016) reported that added that CA-based wheat production system produces better yield than CT-based wheat production system in North-West India, especially under untimely excess rainfall conditions which indicates that the CA has potential to cope with rainfall variability and can help in climate risk adaptation in north-western India. CA-based wheat produced higher (twofold) average yield increase in bad than in normal years over CT wheat. Above research information support the role of CA as an effective tool to mitigate the climate change by reducing GHG and adapt to climate change conditions while maintaining crop productivity.

Fig. 3 CA in Maize Systems: Adapting climate risks (200+ mm in 3 days in end of June 2017) in Haryana, India (right) (M.L. Jat, CIMMYT India, personal communication) and CA in wheat systems: Adaptation to terminal heat stress (left) in comparison to conventional agriculture (right) (Aryal et al., 2018).

10. Epilog and future research opportunities

10.1 Epilog

Conventional agriculture practices in South Asia are responsible for soil health and environmental degradation, and slowly triggering decline in factor productivity. The CA is a knowledge intensive management system approach that delivers soil health and environmental benefits and can provide needed yield increases, production stability and food security. Maximum benefits are obtained when the three core principles of CA are applied simultaneously and in conjunction with adapted best agronomic management practices. The assessment of soil health is necessary to evaluate the soil degradation status and changing trends following CA management interventions. CA provides an alternate to crop residue burning, which is causing serious environment pollution, particularly in the IGPs of South Asia. Several studies from South Asia demonstrated the importance of a CA-based cropping systems in improving soil health (physical, chemical and biological parameters), and increasing in SOC and C sequestration. Most of the studies evaluated SOC changes based on the equal soil depth rather than equal soil mass.

In majority of the studies, implementation of CA practices has led to improvements in soil physical indicators. The temperature fluctuations are generally smaller in CA than in CT system, which promote biological activity, crop growth and root development. Crop residue mulch in CA is responsible for conserving soil moisture by reducing evaporation loss and runoff due to increase in IR, thereby provided saving in irrigation water and improved WP. Similarly, CA improved soil chemical properties (mainly nutrient cycling, and macro- and micronutrient availability) after 3–4 years old adoption, which need to be taken into consideration while developing efficient fertilizer management packages for different cropping systems. CA systems may initially result in N immobilization; however, it may ultimately stimulate a gradual release of N in the long run (after 4 years). Results from many studies showed that CA had significant positive impact on biological parameters (such as soil biodiversity, microbial biomass, enzyme activities and earthworm population). The magnitude of changes in soil health parameters depended on soil types, cropping system and agro-ecologies. The effects of CA systems on soil health parameters are generally restricted to surface soil layers. Limited studies from South Asia, suggest that CA can induce major shifts in pest pressure in CA systems.

Majority the studies conducted for a period ranging from 3 to 10 years showed positive effects of CA on soil health parameters. However, there could be a publication bias, whereby the results of field studies with significant effects of CA on soil health are more likely to get published than studies involving sites where there are no significant or negative effects, which may lead to an overestimation of the positive effects of CA in the published literature (Reicosky, 2020). Unfortunately, there are not many long-term studies in South Asia to assess the effects of CA on soil health on cropping system basis. The assessment of soil health requires quantification of MDS or critical soil health attributes, however, there is no unanimity in the MDS for developing soil health index in CA vis-à-vis CT systems.

The soil health effects of CA differ significantly between sites, depending on local conditions like soil type, production system or climate. However, most of data on soil health have been collected in single-site experiments, which mean the same environmental conditions, soil, and climate. The adoption of CA in South Asian countries still remains low (about 2.5 Mha). We suggest that CA system should be promoted to achieve soil health benefits, and higher crop productivity with less input costs. The direct livelihood benefits to farmers will vary between regions. CA system also plays an important role in mitigation and adaptation of climate change thereby can lead to sustainable crop production in the long run in South Asia. Any contribution to climate change mitigation should be regarded as additional benefit for promoting the CA practices.

10.2 Knowledge gaps and future research opportunities

The assessment of soil health requires identification and quantification of critical soil attributes, which will likely need to be site-specific. The impacts of CA practices on soil health are still a matter of discussion since studies in different soil types and climate conditions have led to inconsistent results. The soil health improvement caused by crop diversification; the third principle of CA is often overlooked, warrants further assessment, especially in view of the potential multiple benefits it can deliver. Toor et al. (2021) identified four major gaps in our knowledge on soil health assessment under CA system. These gaps included, (1) Inability of soil health parameters to factor in site/soil type information and provide standard, calibrated assessment; (2) Lack of correlations between measured soil health indices to climate, soil, management, pests, and disease parameters so as to be able to predict crop yields. Establishing a relationship between improvements in soil health and crop yields will be appealing to farmers to adopt CA; (3) Lack of consistent sampling techniques and protocols in soil assessment procedures; and (4) Lack of information on societal needs like carbon sequestration, food production, and nutrient reductions due to improvement in soil health. The important areas for future research in evaluating changes in soil health and C sequestration in CA systems are listed below.

- Given the significant variation across agro-ecologies, more research is still needed in each agro-ecology so as to avoid generalization based on a limited number of trials.
- There is a lack of consistency in selecting key indicators of soil health assessment in agricultural fields under CA in the South Asian countries. The key indicators of soil health will differ among cropping systems and for irrigated and rainfed ecosystems. More information is needed to decide minimum data sets for calculating soil health index in different soil types, cropping systems and ecoregions. Choosing a minimum data set should be done carefully to also include those sensitive to climate change drivers.
- After the selection of the appropriate soil health indicators, operating procedures for various analyses should be standardized. Variation in procedures for an indicator measurement (e.g., SOC measured by different techniques) is a drawback that needs to be addressed by scientific community. More research is needed to recommend a standard approach for soil sampling, soil depth, number of replicates, methodology and different types of equipment, and choice of key parameters of soil health. Again, effect of CA on changes in soil health below 15 cm depth is not addressed properly.
- Presently, limited information is available on the changes in soil biological parameters and rhizospheric biodiversity under CA systems. Systematic studies are therefore, recommended on the dynamics of soil biology (community structure of microbes, microbial dynamics and microbial mediated processes). Future studies should be conducted on contribution of belowground (roots, rhizodeposition) on soil biological properties under CA practices using advanced measurement techniques. Soil biological health assessment requires development of new tools and methodologies for quantifying soil biological properties and processes (i.e., genomics, DNA and RNA sequencing). Visible-near-infrared technique can be used to successfully estimate biological SHI indicators, such as SOC, total N, β-glucosidase activity, active C fraction, MBC, POC, and soil respiration (Cho et al., 2017; Veum et al., 2017).

- Future opportunities to advance soil health assessment on a large scale include development of low-cost in situ sensors that can quickly and efficiently provide estimates for several indicators including SOC, BD, pH, soil depth, soil WHC, and EC. Toor et al. (2021) suggested the need to explore the potential of using inelastic neutron scattering to monitor SOC changes and the use of imaging techniques such as X-ray and electron microscopy to elucidate soil processes.
- Where a significant increase in SOC stock is measured, it is essential to assess the impact of CA system on net additional transfer of C from atmosphere to soil, and hence measure the real climate change mitigation, rather than a spatial redistribution of organic C in soil. Models (such as CENTURY, and Roth C) can provide precise and unbiased estimates of long-term changes in SOC in CA system under different ecologies. The use of decision support systems such as DSSAT and APSIM may be employed after proper calibration and validation to predict the long-term effects of CA on crop yields, SOC and soil health.
- There is a need to identify processes of soil C sequestration and assessing the residence time of C thus sequestered. It is essential to calculate critical and saturation level of SOC for estimation of SOC saturation deficit under different agroclimatic conditions and soil types to identify key spots for enhancing C sequestration. It is important to identify most important site-specific key factors governing C sequestration. Rooting system of different crops under CA systems need to be studied, as the roots play a greater role in carbon recycling and sequestration in soil.
- Long-term studies should be conducted with different soil types, cropping systems and residue load under variable environments for improving the knowledge regarding carbon sequestration potential and soil health in CA system.
- In CA systems, mechanisms and pathways of nutrient losses are not fully understood. The precise information on nutrient dynamics is important for managing nutrients in an efficient way under CA system.
- Establishing a clear relationship between improvements in soil health and crop yields will generate more interest of farmers and help promote CA in South Asia. There exists tremendous scope to measure soil health parameters under different climate, soil types, cropping systems, pests, and disease.
- More studies are needed to quantify of C footprints and GHGs (CO_2, CH_4, and N_2O) emission through the adoption of CA practices by conducting life cycle analyses of carbon under diverse soils, cropping systems

and ecoregions. Future refinements of the estimates may include field measurements of GHG emissions and N losses via NH_3 volatilization and NO_3^- leaching under CA vis-à-vis conventional farming systems.

- Presently, there are few long-term (10 or more years) studies on the effects of CA on soil health across different cropping systems in the South Asia. We recommend to maintaining and setting up long-term CA experiments on key soil types and agroecological regions to quantify the influence of CA on the soil health including nutrient cycling, C sequestration, ecosystem services and system productivity.

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