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Variation of porosity, pore size distribution and soil physical properties under conservation agriculture

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ABSTRACT

For sustainable crop production and maintenance of soil health, conservation agriculture (CA) practices provides an opportunity for improving soil structure and physical health, nutrient and water use efficiency, soil organic carbon and mitigation of greenhouse gases emission from agriculture. CA is primarily based on four crop management practices such as minimum soil disturbance or no-tillage; permanent or semi-permanent retention of crop residue; crop rotation and control traffic. Different CA management practices affect crop yield as well as soil properties. CA makes necessary modifications in different soil hydro-physical properties, viz. increase in soil water infiltration, reduction in water runoff and soil loss, and reduction in evaporation loss. No tillage (NT), residue retention and crop rotation combined effect the soil organic carbon concentration. Different crop rotations and residue retentions and crops with different rooting depths used in CA practices have proved to reduce the compaction constraints.CA can help to mitigate GHG emissions, viz methane (CH_4) and nitrous oxide (N_2O) from agriculture by improving soil C sequestration, enhancing soil quality, nitrogen and water use efficiencies, and decreasing fuel consumption. But effect of CA and conventional agricultural practices of porosity and pore size distribution is very much limited. When CA is practiced for six to ten years there is improvement in soil structure, porosity and pore size distribution, macro-micro faunal activity, and organic matter content..The soil under ZT has the lowest porosity as compared to conventional management practices. The highest porosity and the maximum connected pores are frequently seen in conventionally tilled soil. In this paper, an attempt has been made to review the variation of porosity and pore size distribution and other soil physical properties under conservation agricultural practices.

Key words: Conservation agriculture, No tillage, Pore size distribution, Porosity, Soil organic carbon

For sustainable crop production and balanced use of natural resources, it is essential to maintain optimum soil physical health without hampering their quality. Presently, the conventional tillage (CT) for crop cultivation which involves rigorous ploughing and elimination of crop residue after harvesting, increases soil compaction and surface crusting, accelerated soil erosion, decline in water infiltration into the soil, and eventually leads to overall degradation in soil physical health. So, to overcome these antagonistic effects of CT on soil health, several agricultural scientists throughout the world have mentioned conservation agriculture (CA) as an answer. Food and Agricultural Organization of the United Nations define conservation agriculture (CA) as: "CA is a concept for resource-saving agricultural crop production technology that aims to achieve acceptable profits together with high as well as sustained production levels while simultaneously conserving the environment" (FAO 2007). Different CA management practices affect crop yield as well as soil properties. CA makes necessary modifications in different soil hydro-physical properties, viz. increase in soil water infiltration, reduction in water runoff and soil loss, and reduction in evaporation loss. No tillage (NT), residue retention and crop rotation combined effect the soil organic carbon concentration. Balanced application of inorganic fertilizer and organic amendments greatly influence the accumulation of organic matter in soil and also influence the soil physical environment (Hati *et al.* 2007). Study conducted by Bhattacharyya *et al.* (2006) reported the significant increase in laboratory estimated saturated hydraulic conductivity under zero-tilled plots (1.13 and 1.07 cm/hr at 0-15 and 15-30 cm soil layers respectively) after rice harvest. But effect of CA and conventional agricultural practices of porosity and pore size distribution is very much limited. When CA is practised for six to ten years there is improvement in soil structure, porosity and pore

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size distribution, macro-micro faunal activity, and organic matter content. The soil under ZT has the lowest porosity as compared to conventional management practices. The highest porosity and the maximum connected pores are frequently seen in conventionally tilled soil. Soil porosity is very important for transport and storage of water and nutrients in the soil. Hence, it is essential to understand soil pore characteristics. Water storage and transmission depend on the pore geometry and pore size distribution of soil (Eynard *et al.* 2004). Pores with diameter of <7.5 µm are suitable for retaining plant available water, whereas pores >150 µm can drain water freely with gravity (Azooz *et al.* 1996). A good soil structure and porosity can be achieved by following CA practices (Bhattacharyya *et al.* 2006). Till now the studies on the effects on different management practices including CA are very limited.

Principles of CA

Conservation agriculture is mainly based on four crop management practices-

- Minimum soil disturbance or no-tillage
- Permanent or semi-permanent retention of crop residue
- Crop rotation
- Control traffic

Different components are practices involved in CA practices have been presented in Fig 1.

Minimum soil disturbance or no-tillage

This principle of CA leads to the following effects on the soil. As the soil is never tilled which leads to improvements in soil structure and less soil erosion, an increase in organic matter content, cropping intensities and crop yields**.** Kassam and Friedrich (2009) reviewed that CA practices improve soil biological activity through minimum tillage along with residue retention, which helps to form more stable aggregates with the adequate percentage of various sizes of pores, permitting better water infiltration and air movement.

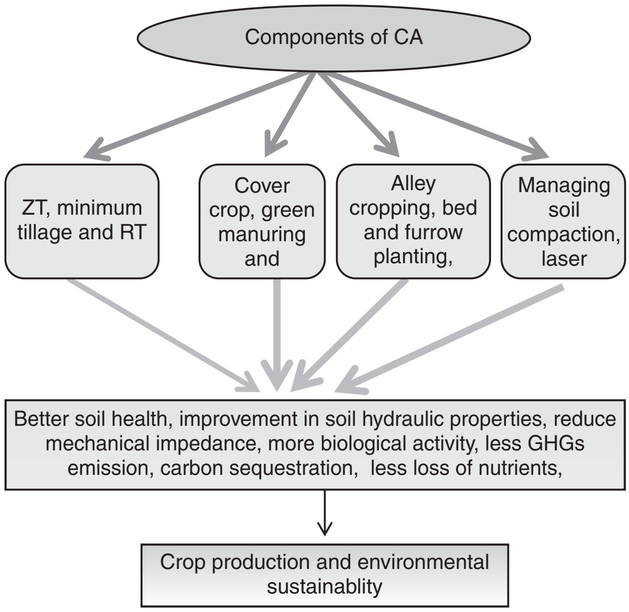

Fig 1 Different components and practices of CA (Pramanik *et al.* 2019).

Permanent or semi-permanent retention of crop residue

Crop residue act as a protective cover over the soil surface supports to suppress weeds, guards the soil from extreme weather effects, aids to preserve soil moisture, and evades soil compaction. Ghosh *et al.* (2010) reported that a permanent soil cover is essential to protect the soil from the harmful impact of rainfall and sunshine and helps to enhance the microbial population in the soil with a continuous supply of "food"; and modify the soil microclimate and generates an ideal condition for growth and proliferation of soil organisms as well as plant roots. This leads to better soil aggregation, enhanced soil biological activity, and better biodiversity and more carbon sequestration.

Crop rotation

Crop rotation is not only essential to offer a diverse "diet" to the soil microorganisms, but also it helps in for extracting nutrients from deeper soil layers that have been percolated to deeper layers. Furthermore, crop diversification leads to an enhancement of soil flora and fauna diversity. Cropping sequence and inclusion of legumes in crop rotations help in minimizing pest instance, through disruption of life cycle, biological nitrogen fixation, control of off-site pollution and enhancing biodiversity (Dumanski *et al.* 2006).

Control traffic

Controlled traffic farming (CTF) limits any traffic movement in the field in the same tracks. Though these paths are heavily compacted, but there is no compaction in rooting zone which results in better soil structure and greater yields. The superior plants growth of next to the tracks can effortlessly compensate the border effects. The border is the area which is lost in the traffic zones. In CTF, the gross yields are generally higher as compared to conventional farming with haphazard traffic (Kerr 2001). ZT can control soil compaction as because heavy machinery movement in field in the cropping area is entirely avoided. In CTF, there is lots of fuel savings as the machinery tyres move on the compacted tracks in the field (RWC-CIMMYT 2003).

Conservation agriculture production systems are used throughout the world. There are currently over 10 Mha of arable cropl and under CA system in Asia, – corresponding to about 6.5% of the worldwide CA area – mainly located in China (65.4% of the total Asian CA area) followed by Kazakhstan (19%) and India (around 15%) (FAO 2017).

CA and soil physical properties

Bulk density and total porosity under CA lucid

Bulk density is one of the most important soil physical

Table 1 Extent of adoption of conservation agriculture worldwide (> 100000 ha)

Country	CA area (ha)	Country	CA area (ha)	Country	CA area (ha)
USA	26500000	Bolivia	706000	New Zealand	162000
Argentina	25553000	Uruguay	655100	Finland	160000
Brazil	25502000	Spain	650000	U. Kingdom	150000
Australia	17000000	Ukraine	600000	Zimbabwe	139300
Canada	13481000	S. Africa	368000	Mozambique	152000
Russia	4500000	Venezuela	300000	Colombia	127000
China	3100000	France	200000	Others	409440
Paraguay	2400000	Zambia	200000	India	2000000
Kazakhstan	1600000	Chile	180000	Total	112755100

Source: FAO, 2011c, http://www.fao.org/ag/ca/6c.html

parameter which determines soil compactness. The bulk density greatly depends on inherent soil qualities as well as with management practices. Gantzer and Blake (1978) have reported that zero tillage (ZT) having higher bulk density as compared to CT. Bautista *et al.* (1996) found that zero-tillage with residue retention reduced bulk density (BD) significantly in a semi-arid ecosystem. Several researchers (Ehlers 1983; Pikul *et al.* 1990; Sauer *et al.* 1990) have found that, on many soils, converting from a CT to a ZT cropping caused an increase in BD and decrease in porosity in ZT. Mielke *et al.*(1986) has done a study for comparing bulk density between ZT and moldboard plow systems by taking seven soils at two depths (14 combinations), they have shown that in six instances a greater bulk density for the ZT, in one instance a greater BD for the moldboard plow system, and no BD differences between these systems in seven instances. There appears to be a tendency for greater bulk densities in ZT. Another study by Horne *et al.* (1992) shown that lower BD at a depth of 3–7 cm in ZT than in CT, there was no significant changes in the deeper layer.The long-term retention of crop residue helps to decrease BD and increase the effective. The effect of additional residue kept on the surface for reducing BD is very prominent in the 0–3 cm and to a lesser range in the 3–10 cm soil depth (Blanco- Canqui and Lal 2007).

The physical consolidation of soil particles against an applied force is called soil compaction. The soil compaction results in reduction in porosity, restriction of air and water movement and depletion of soil structure. The reason behind compaction in agriculture is the heavy use of farm machinery and the applied pressure of wheels. The tillage practices under inappropriate moisture leads to increase in compaction. The use of same cropping sequence and equipment year after year in conventional tillage causes the formation of sub soil compaction. Different crop rotations and residue retentions and crops with different rooting depths used in CA practices have proved to reduce the compaction constraints.

Hydraulic conductivity and infiltration under CA

The conduction of water within a soil profile against the hydraulic gradient is termed as Hydraulic Conductivity. The hydraulic conductivity of soils affected by various factors such as parent material, topography and climate etc. one of the important role is played by the tillage practices as it automatically effects soil bulk density and porosity. Obi and Nnabude (1988) and Celik (2011) showed the effects of tillage practices on hydraulic conductivity found various results like either a no major change or a negative impact. McGarry *et al.* (2000) showed that zero tillage practices improved the hydraulic conductivity of soils. The probable reason for the increased hydraulic conductivity of no tilled soils were improved pore size distribution, pore diameters and pore continuity and an increased in numbers of macropore (Cameira *et al.* 2003). Logsdon *et al.*(1995) showed that the increase in hydraulic conductivity was due to the greater activity of fungi and buildup of organic matter due to the deposits applied on the field. Soil infiltration is another soil physical property also affected by CA practices and it defined as the downward entry of water from the soil surface. The infiltration characteristic of the soil is important for defining the results of different tillage, conservation, irrigation, practices of a particular region (Sumathi and Padmakumari 2000).

Soil carbon, different pools of SOC and sequestration under CA

The most important soil quality indicator is the soil organic carbon (SOC) specially the concentration of SOC at the surface soil. The soil organic carbon plays a great role in nutrients holding, reducing soil erosion and improving water infiltration.The distribution of SOC in the profile is affected by tillage practices and SOC content. The SOC content in the surface layer is higher in case of ZT compared to CT (Chakrabarti *et al.* 2014, Pathak *et al.* 2017), whereas a higher SOC content is found in the lower soil layers of tilled fields with residue incorporation (Fig 2). Crop residues are forerunners of the SOC pool, and maintenance of more crop residues on the soil is linked with an increase in SOC content (Bhattacharyya *et al.* 2012a). The rate of crop residues decomposition is not only dependent on the amount retained, but also on soil properties and the

Fig 2 Huge residue addition in CA causes more SOC.

chemical composition of the residues. Das *et al.* (2013) showed that plots under CA had around 33% more labile SOC (Pool II) than CT plots (2.01 g C kg–1) in the 0- to 5-cm soil layer. Conservation agriculture is a system and not a single component. Dou *et al.* (2008) observed that CA significantly ($P < 0.05$) improved SOC content and they compared the proportion of all labile SOC pools with CT, particularly for 0-15 cm soil layer, after 20 yrs. of CA adoption in south-central Texas. They found significantly higher labile SOC pool in CA and that was possibly owing to greater biomass C.

Greenhouse gas emission under CA

The different agricultural management practices can regulate soil nitrogen and carbon dynamics and thereby, influencing the greenhouse gases (GHGs) like nitrous oxide (N2O) and carbon dioxide (CO_2) emissions (Gu *et al.* 2013; Vidon *et al.* 2016). CA can help to mitigate GHG emissions from agriculture by improving soil C sequestration, enhancing soil quality, nitrogen and water use efficiencies, and decreasing fuel consumption (Drury *et al.* 2012). Carbonell-Bojollo *et al.* (2019) reported that CT increased the CO_2 emissions compared to CA and established that in CA , where mechanical soil disturbances through tillage is escaped, could be a feasible alternative to mitigate climate change. Dendooven *et al.* (2012) reported that the cumulative greenhouse gases (GHGs) emission were similar in CA and CT for both the years, but the net global warming potential (GWP) of CA was -7729 kg CO_2 ha^{-1} y^{-1} in 2008-2009 and -7892 kg CO_2 ha^{-1} y^{-1} in 2010-2011, on the other hand, in CT GWP was 1327 and 1156 kg CO_2 ha^{-1} y^{-1}. They concluded that the contribution of CA to GWP was small as compared to CT. Wang *et al.* (2011) found that when rice husk biochar was applied in the field at the rate of 50 t ha^{-1}, N_2O emissions was decreased by 73.1%. Reduction of N_2O emissions on biochar application may be due to more soil pH and improved soil aeration (Cavigelli and Robertson 2001). Plant residues with a low C: N ratio normally induce relatively high N_2O emissions (Huang *et al.* 2004) when soils remain aerobic, but soil N_2O production is depressed when soil conditions become anaerobic (Li *et al.* 2013). ZT has been found to enhance SOC and the better soil physical properties have caused to the reduced N_2O emissions as compared to CT in Eastern Canada (Drury *et al.* 2006, 2012). Utomo (2014) showed that long-term CA of corn reduced CO_2 emission and increased carbon sequestration both in biomass and soil. Release and capture of greenhouse gases are strongly affected by pore network connectivity (Quigley *et al.* 2018, Steffens *et al.* 2017). Mangalassery *et al.* (2014) showed that ZT reduces soil porosity by 33%, which led to 21% reduction in potential CO_2 efflux. Although the processes of GHG production and emission are mainly biological, soil physical conditions influence biology by their effect on the physical environment (Gregorich *et al.* 2006). Smith *et al.* (2003) reviewed the interactions between soil physical properties and biological processes at the Scottish Agricultural College (SAC) and subsequently at the University of Edinburgh. They emphasized the importance of gas diffusivity for methane (CH_4) oxidation rate and the influence of temperature and water-filled pore space (WFPS) on nitrous oxide (N_2O) production by denitrification and on N_2O emission. Conen *et al.* (2000) subsequently identified the three key factors for N_2O emission from agricultural soils as WFPS, temperature and topsoil mineral N content. Others have shown the importance of soil temperature and moisture content for fluxes of the transient greenhouse gas nitric oxide (NO) (Skiba *et al.* 1997) and of carbon dioxide (CO_2) (Franzluebbers *et al.* 1995). Bouckaert *et al*. (2013) reported that higher rate of decomposition of plant materials were found in 15-60 mm pore neck diameter whereas lower rate of decomposition were found in < 4 mm and 60-300 mm pore neck diameter classes. Thomsen *et al*, (1999) found that water is one of the main factor responsible for soil organic carbon turnover and they also reported that the effect of texture is indirect, pore size distribution of soil mainly controlled by soil structure.

Porosity and pore size distribution under CA

There are different sizes and shaped pores are present in the soil, and their characteristics influence greatly on the physical, chemical and biological behaviour of the soil. The pores of different dimensions are developed due to different abiotic (e.g. traffic and tillage, wetting and drying, freezing and thawing, etc) and biotic (e.g. burrowing of macro and microfauna, root growth) factors (Kay and VandenBygaart, 2002). The alteration of pore characteristics in the spatio-temporal scale can be done by following different tillage practices. The changes of pore characteristic are mainly depending on the magnitude, frequency, and form of stresses that have been imposed on the soil, applications of crop residue and the population of microorganisms. Many earlier studies on the effects on different management practices on soil porosity and pore geometry have been done either qualitatively or limited to the bulk analysis of disturbed soil samples from the field. X-ray μCT offers a non-destructive way of assessing the structural and pore properties of soil in three-dimensions (3D).This technique has been applied to characterize soil hydraulic properties (Périard *et al.* 2016), quantify the pore network geometry (Baveye *et al.* 2002), assessseed-soil contact (Blunk *et al.* 2017) and to visualize undisturbed root architecture in soils (Tracy *et al.* 2010).

Different agricultural operations affect pore-size distribution, pore connectivity and tortuosity. Tillage by heavy machinery reduces the macroporosity, disrupt pore continuity and affects biopore formation (Boersma and Kooistra 1994). Piccoli *et al.* (2017) reported that CA practices clearly influenced the ultramicroporosity class (0.1–5 μm) (1·86E01 vs 1·67E01 μm μm^{-3}) which is totally linked to SOC content of soil.Vanden Bygaart *et al* (1999) showed that ZT practices decreased 30- to 100-μm pores number of with a net increase in 100- to 500-μm diameter pores within 4 years of ZT practice.

The desirable soil structure is vital for getting good physical characteristics, which make agriculturally sustainable. Pires *et al.* (2019) employed X-ray CT to evaluate the effect of three different tillage systems (i.e ZT; RT, reduced tillage; and CT) in an Oxisol with a porous structure. They have used 0-10 cm depth undisturbed soil core for scanning through X-ray CT. The results have been showed that the soil under ZT has the minimum porosity as compared to RT and CT. The maximum porosity and the most connected pores have been seen in CT.

Yang *et al.* (2018) used different soil amendments like straw mulch, superabsorbent polymer (SAP) and organic fertilizers for improving soil structure and porosity. They have used X-ray CT to determine the number, size, location, and morphology of pores. They have found out that combines the application of amendments improves soil pore structure more effectively as compared to individual applications. They have also reported that the application of both straw mulch and organic manure improving soil porosity and soil structure more effectively as compared to other combinations.

Recently, X-ray computed tomography gives a novel way to study soil pore structure. X-ray CT data represented as grayscale images and the proper selection of segments to binarized, it has a great influence on the soil structure characterization. Torre *et al.* (2017) used μ-CT for the visualization of soil structure under different tillage treatments namely Chisel plough, Moldboard plough, and Roller. By comparing μ-CT data for all three treatments, they have concluded that moldboard produces a higher complex soil structure as it physically removes the soil. Chisel disrupts the soil aggregates and finally, Roller is an intermediate case with a scaling character mainly in the lower gray values of the soil image. Mangalassery *et al.* (2014) showed that soil porosity obtained by X-ray CT was considerably higher in CT (13.6%) than ZT soil (9.6%). They also reported that the porosity was 46.9% higher in 0–10 cm of tilled soils than in ZT soils and pores in CT were twice as large (0.52 mm^2) as those in ZT soils (0.27 mm^2).

Bouckaert *et al.* (2013) use X-ray computed tomography for the quantification and distribution of pore in a unit pore volume and they tried to develop the relationship between pore volume and soil carbon mineralization. They have established correlation between volume of each pore neck classes and slow pool carbon mineralization rate and found out that pore neck size of 150-250, 250-350 and >350 μm having positive correlation (r) = 0.572, 0.598 and 0.516, respectively because larger pores enhancing aeration

Table 2 Effect of different CA practices on soil physical properties

Management practices	Effect on soil physical properties	References
Minimum tillage along with residue retention	Improve soil biological activity, form more stable aggregates	Kassam and friedrich (2009)
Permanent soil cover	Protect the soil from the harmful impact of rainfall and sunshine, increase microbial population	Ghosh*et al.* (2010)
Crop rotation with legume	Minimizing pest instance, enhance biological nitrogen fixation and microbial diversity.	Dumanski *et al.* (2006)
Zero tillage (ZT)	Higher bulk density	Gantzer& Blake (1978)
Zero tillage (ZT) with residue retention	Reduce bulk density	Bautista *et al.* (1996)
Zero tillage (ZT)	Improve hydraulic cinductivity	Mcgarry*et al.* (2000)
No tillage	Improved pore size distribution, increase pore diameters, pore continuity and numbers of macropore	Cameira*et al.* (2003)
Zero tillage	Increase soil organic carbon in surface layer of soil	Chakrabarti *et al.* (2014)
Plant residues with a low C: N ratio	Induce relatively high N_2O emissions	Huang *et al.* 2004
Zero tillage	Reduce N_2O gas emission	Drury *et al.* 2006 (2012)
Zero tillage	Decreased the number of micropores, increase in macropores within 4 yr of ZT practice	Vanden Bygaart *et al*. (1999)
Soil amendments like straw mulch, superabsorbent polymer (SAP) and organic fertilizers	Improve soil structure and porosity	Yang *et al.* (2018)

whereas <9.44 µm pore neck classes having negative correlation due to obstruction of microbial activity and mobility of enzymes. Rabbi *et al*. (2016) tried to investigate the effects of pore geometry on the bacterial diversity and organic carbon decomposition rate in both micro-aggregates (53–250 µm) and macro-aggregates (250–2000 µm) of soils and observed that micro-aggregates had 54% lower µCT observed porosity and 64% more occluded particulate organic carbon (oPOC) as compared to macro-aggregates but organic carbon decomposition rate constant (Ksoc) was comparable in both aggregate size ranges.

Quigley *et al.* (2018) use X-ray computed tomography to understand how different size pores affect the spatial distribution of newly added carbon immediately after plant termination and 1 month after incubation. They have found out that soil with a pore size of 40-90 µm associated with quick decomposition of newly added carbon and pore size with <40 µm associated with carbon protection. Effect of different CA practices on soil physical properties have been listed in Table 2.

Conclusions

Conventional tillage operations effects surface soil condition, porosity and pore size distribution, decreases SOC by hastening the degradation and mineralization of biomass due to more aeration and mixing of crop residues in soil, exposing previously protected SOC inside the soil aggregates to soil microorganisms. CA can be considered as a developing technology as it can manage crop residue, water, and nutrient in an efficient way. Effective management of water and nutrient, and restoration of degraded soils can lead to achieve sustainable agriculture and it can meet the food demand of a huge population.The application of both crop residue and organic manure could improve soil porosity and soil structure more effectively. By modifying the porosity and pore size distribution, CA can efficiently manage the gas exchange, water transport and SOC decomposition rates. Non-destructive method such as µCT of assessing porosity and pore size distribution could provide a better insight into the soil. CA can also help to mitigate GHG emissions from agriculture by improving soil C sequestration, modifying the porosity and pore size distribution, enhancing soil quality, nitrogen and water use efficiencies, and decreasing fuel consumption. Incorporation of nitrogen-fixing legume crops in crop rotation can meet a considerable amount of nitrogen requirement of crops. The adoption of CA can improve soil structure, aggregation, SOC, infiltration rate, soil moisture content and mitigate GHGs emissions.

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