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# Soil water content, penetration resistance, crumb ratio and soil carbon restoration through conservation agriculture: An overview

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## Abstract
Maintenance of soil physical health at its optimum level is essential for sustainable crop production and rational use of natural resources without jeopardizing their quality. The ongoing conventional tillage practices for crop production using intensive ploughing and removal of crop residue from the field have resulted in an increase in surface crusting, soil compaction, soil erosion, decrease in water infiltration and ultimately aggravation of the overall soil physical health deterioration. Conservation tillage can improve soil physical structure and water storage, protect moisture, and increase crop yield. However, the long-term adoption of a single tillage method may have some adverse effects on soil and ecological environment, although crop yields have increased. Through informed allocation of soil tillage techniques, the combination and configuration of soil tillage measures, such as rotary tillage, sub-soiling, and no tillage may reduce the shortcomings of traditional long-term farming. Throughout the world, degradation of soil has become an environmental problem which limits the sustainability of agriculture and decreases soil productivity. The main reason of degradation is either over cultivation or the utilization of improper tillage methods. Therefore, tillage practices play a crucial role in chemical, biological and physical properties of agricultural soils. This role was determined often by using indicators of soil quality such as bulk density, aggregate stability, plant available water, organic carbon content, soil compaction and other properties.

The NT treatment had the highest effect at 0–10cm depth, while the effect for the ST treatment was highest at 0–30cm. SOC storage decreased with soil depth, with a significant accumulation at 0-20cm depth. Tillage system change influenced SOC content, NT, ST, and BT showed higher values of SOC content and increased 8.34, 7.83, and 1.64 MgCha$^{-1}$, respectively, compared with CT. Across treatments, aggregate-associated C at a depth of 0–10cm was higher in the NT and ST treatments than in the MP and CT treatments. The advantage of the NT treatment weakened with soil depth, while the amount of aggregate-associated C remained higher for the ST treatment. There were more macro-aggregates in the ST and NT treatments than in the MP and CT treatments, while the MP and CT treatments had more micro-aggregates. The sum of macro-aggregate contributing rates for soil organic C (SOC) was significantly superior to that of the micro-aggregates. However, bulk density (Db) of the 10- to 20-cm soil layer was highest under puddled treatments (1.74–1.77 Mg m$^{-3}$) and lowest under ZT treatments (1.66–1.71 Mg m$^{-3}$). Likewise, soil penetration resistance (SPR) was highest at the 20-cm depth in puddled treatments (3.46−3.72 MPa) and lowest in ZT treatments (2.51–2.82 MPa). Furthermore, it has been found that porosity decreased in the order disc harrow tillage (49.90%) follow by disc plough tillage (42.62%) and zero tillage (41.17%) respectively. Meanwhile, infiltration capacity increased in the order zero tillage (24.40 cm/hr) follow by disc plough tillage (32.30 cm/hr) and disc harrow tillage (39.40 cm/hr). On the basis of conservation tillage to maintain an adequate amount of crop residue on the soil surface, less traffic and less manipulation of the land might be the benefits. However, rotary tillage can effectively improved soil structure and reduced soil bulk density, where N ↔ S treatment soil bulk density is low and in 0–60 cm soil layer averaged 1.31 g/cm$^3$. Different tillage treatments could be used during the fallow period to store additional soil moisture: the N ↔ S treatment showed good water storage effect.

**Keywords:** Conservation tillage, soil porosity, bulk density, soil organic matter

## Introduction
Soil quality indicators can be used to evaluate sustainability of land use and soil management practices in agro-ecosystems. Soil quality indicators can be defined as the soil processes and properties that are sensitive to changes in soil functions. Karlen (2004) also expresses that soil quality assessment is simply a tool focused on dynamic soil properties and processes that are useful for assessing the sustainability of soil management practices.

Tillage practices modify soil structure by changing its physical properties such as soil moisture content, soil bulk density and soil penetration resistance, etc. Annual disturbance and pulverizing caused by conventional tillage produces a finer and loose soil structure as compared to conservation tillage, which leaves the soil intact. This difference results in a change of number, shape, continuity and size distribution of the pores network, which controls the ability of soil to store and transmit air, water, agricultural chemicals and crop growth. This in turn controls erosion, runoff and crop performance. Changes in soil penetration resistance affect the seedling emergence, plant population density, root distribution and crop yield. Conservation tillage often results in decreased pore space, increased soil strength and stable aggregates (Horne *et al*., 1992). The pore network in conservational tilled soil is usually more continuous because of earthworms, root channels and vertical cracks (Channel, 1985). Therefore, conservation tillage may reduce disruption of continuous pores.

Soils store climatically significant amounts of carbon (C) as soil organic matter, globally about 2.3 times greater than the C in atmospheric $CO_2$ and 3.5 times greater than the C in all living terrestrial plants. However, prolonged cultivation accelerates the decomposition of soil organic matter and can cause the loss of 20–67% of the soil C in an agricultural field (Wei *et al*., 2015) [67]. Between 1850 and 1998, global agricultural cultivation led to the release of ~78 Gt of C from soil as $CO_2$ to the atmosphere, with ~133 Gt of soil C released since the beginning of agriculture. Since the current global annual $CO_2$ emissions from fossil fuels and all other sources are ~10 Gt of C (Olivier *et al*., 2016) [53], soil C sequestration has thus been proposed as a plausible partial climate mitigation strategy that might buy time while low-carbon technologies are being developed and adopted (Lal, 2004) [37]. Indeed, a recent international initiative has set a target of increasing global soil organic matter by 0.4% per year to help negate some greenhouse gas emissions (Minasny *et al*., 2017) [45]. Abandoned agricultural lands have been a particular area of interest for carbon capture and storage (Silver *et al*., 2000) [60] because of their high potential capacity for C sequestration (Minasny *et al*., 2017) [45].

Compaction of agricultural soils is a threat to soil productivity worldwide leading to soil desiccation and degradation manifested by poor crop production and detrimental environmental conditions. Soil compaction affects soil structure by destroying it. It also reduces soil porosity and water infiltration and air exchange and makes root penetration difficult and this leads to low crop yield (Wolkowski and Lowery, 2008). The vulnerability of soil to compaction is attributed to various factors. These are soil texture, moisture content and plasticity, vehicle weight and its speed, ground contact pressure and number of passes (Materechera, 2009) [41] [41]. Compaction is becoming a threat in agriculture mainly due to the increasing weight of farm machinery (Materechera, 2009) [41]. Soil compaction effects on soil properties in arid and humid regions vary due to different soil properties like soil moisture content. In arid regions high temperatures lead to high evaporation rates resulting in decreased moisture content manifested by formation of a hard pan and/or compaction. As the soils get drier especially in areas characterized by clays the soil become more compact. Moreover, soil penetration resistance increases as soil water potential decreases (Kondo and Dias Junior, 1999). Similarly compaction of soils is usually excessive when tillage is performed under wet conditions (Materechera *et al*., 2009) [41]. Soil tillage can improve or deteriorate soil physical properties (Bogunovic *et al*., 2018) [13]. Poorly managed soils become vulnerable to the climate extremes (Jug *et al*. 2018) [32]. Therefore, excessively wet or too dry soil requires adoption of appropriate soil management (Szalai and Lakatos, 2013) [64]. Current research reveals that in the rainy season intensity of rains on ploughed soils cause physical soil deterioration (Jug *et al*., 2018) [32], like settling, reducing the depth of the loosened layer, crumbs disintegration and surface siltation (Gallardo-Carrera *et al*., 2007) [25]. After drying, conventionally tilled soils rapidly lose moisture, while soil compaction in-creases with higher content of dust (Dekemati *et al*. 2019) [19]. On the other hand, no-tillage (NT) or conservation tillage practices preserve soil quality (Rodrigo-Comino 2018) [58]. Such management in long-term improves soil aggregation (crumb to dust ratio), soil organic matter, while topsoil compaction could increase or decrease (Bogunovic *et al*., 2018) [13] depending the climate and soils. Moreover, Dexter *et al*. (2007) [22] noted that in extreme seasons, penetration resistance varies widely under the soil water dynamics, which affects soil physical state and crop performance. When the drought becomes persistent, soil continuously loses its moisture content, penetration resistance increases, crumbling declines, but the proportion of dust increases (Morris *et al*., 2010) [48]. When soil becomes too wet or too dry, the penetration resistance (SPR) varies widely (Dexter *et al*., 2007) [22], between the seasons. The crumbling process tends to drop in the extreme seasons; however, crust formation occurs more frequently (Gallardo-Carrera *et al*., 2007) [25]. Studying the soil physical factors (e.g. crumb ratio (SC) and crusted area (CA)), they are highly exposed to the weather phenomena and require more attention in the future (Bogunovic *et al*., 2018, Jug *et al*., 2018) [13, 32]. This article reviews the tillage types effects on compaction in semi-arid conditions by determining soil physical health and associated processes for successful crop production.

**Soil bulk density**

Bulk density can be used as a measure of a soil's compaction and indicates the effect a soil is likely to have on seedling emergence, root growth and thus crop production (Blanco-Canqui and Ruis, 2018) [12]. It can also indicate properties such as porosity and likely water infiltration (Blanco-Canqui and Ruis, 2018) [12]. Bulk density, has been observed to increase (Blanco-Canqui and Ruis, 2018; Somasundaram *et al*., 2019) [12, 62], decrease (Blanco-Canqui and Ruis, 2018) [12], and be no different under CA systems (Blanco-Canqui and Ruis, 2018) [12]. Where greater bulk densities are observed, these are generally attributed to reduced soil disturbance and subsequent soil settling in the absence of tillage, and the repeated trafficking of the soil by agricultural machinery (Blanco-Canqui and Ruis, 2018) [12]. However, this is not necessarily associated with decreased crop growth due to the maintenance of stable macro-pores in CA soils, which can provide pathways for root growth and water infiltration (Soane *et al*., 2012) [61]. Initially greater bulk densities may also decline over time as SOC improves (Blanco-Canqui and Ruis, 2018) [12]. However, in some instances, increases in bulk density do limit production, this may occur because the greater soil strength under compacted conditions limits root growth and thus water and nutrient uptake and/or because it can lead to decreased air permeability and a reduction in oxygen concentrations for plants during wetting events

(Nyagumbo *et al*., 2016) [51]. Where decreases in bulk density are observed, these are generally associated with increased addition of organic residue, and associated increases in soil faunal activities (Blanco-Canqui and Ruis, 2018) [12].

Keller *et al*. (2019) [34] revealed that the increase in bulk density at around 0.2m depth of the arable soil marks the average depth of the plough pan. Bulk density in the upper subsoil (0.3m to about 0.5m depth) increased from about 1.1–1.2 Mg $m^{-3}$ in the unmanaged soil to 1.3–1.4 Mg $m^{-3}$ in the arable field due to wheeling during ploughing. Fig. 1 reveals compaction of the arable field down to almost one metre depth. Our simulations show that subsoil compaction may be caused by two factors: high wheel loads of farm implements and effects of conventional ploughing that require driving the tractor in the plough furrow, i.e. applying stress directly to the exposed subsoil.

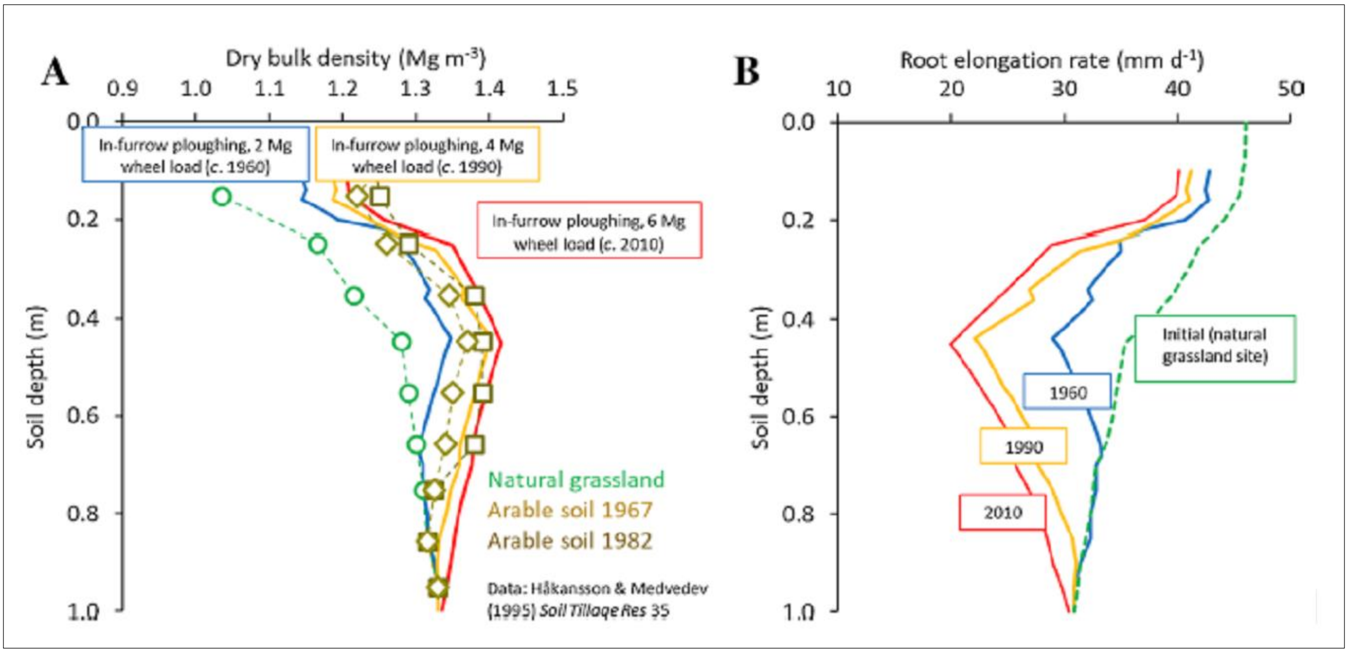



**Fig 1:** The evolution of bulk density in an arable soil caused by increase in machinery weight [Source: Keller *et al*., 2019] [34]

Li *et al*. (2020) [31] observed that soil bulk density is the main physical indicator reflecting soil structure, gas permeability, water permeability, and water retention capacity. With the increase in soil depth, soil bulk density of each rotation mode showed an increasing trend. That is, the average soil bulk density of the 6 tillage patterns in the 0–20, 20–40, and 40–60 cm soil layers was 1.3, 1.4, and 1.5 g/$cm^3$, respectively, and there was a significant difference in soil bulk density between different tillage models, as shown in Fig. 2. Because of the different soil cultivation methods used in the spring maize planting year under the RT mode, the soil bulk density of the 0–20, 20–40, and 40–60 cm soil layers showed an inter-annual variation trend. The soil bulk density of each soil layer in N ↔ S, S ↔ R and S ↔ S treatments decreased to varying degrees compared with BT treatment, the average decrease of bulk density of 0–20 cm soil layer was 2.16%, 1.67% and 0.63%, respectively. Compared with BT treatment, the soil bulk density of R ↔ N, N ↔ N and R ↔ R treatments under the 0–20 cm soil layer showed an increasing trend, and the increase rates were 0.2%, 2.5%, and 1.4%, respectively. In the five experimental years, compared with before the experiment, the soil bulk density with N ↔ S, S ↔ R, R ↔ N, N ↔ N, S ↔ S, and R ↔ R tillage treatments in the 20–40 cm soil layer was decreased by 8.1%, 7.3%, 5.2%, 4.3%, 6.3% and 4.8%, respectively. Soil bulk density decrease was most significant in N ↔ S ($P < 0.05$). In the 40–60 cm soil layer, the soil bulk density of N ↔ S, S ↔ R, R ↔ N, and S ↔ S decreased with time, which was 5.2%, 4.2%, 2.9%, and 3.3%, respectively. N ↔ N increased by 0.6% compared with the soil bulk density before the test.

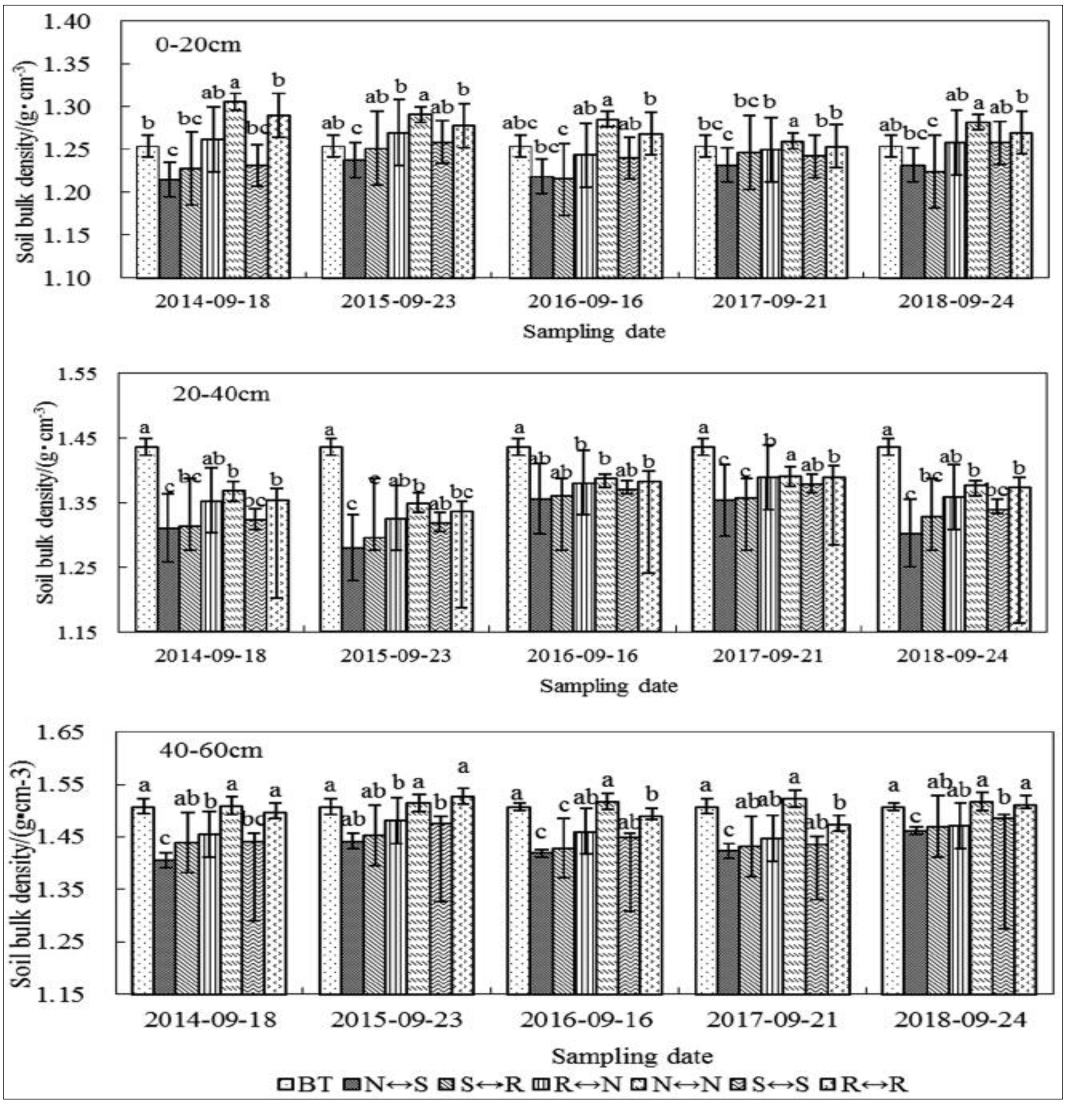



**Fig 2:** Effect of different rotational tillage treatments on soil bulk density at 0–60 cm soil layer of spring corn field after harvesting l[Source: Li *et al*., 2020] [31]

Md. Khairul *et al*. (2014) [42] bulk density was decreased due to tillage practices. The highest Bd reduction (6.41%) was found in ZT followed by MT (3.95%), while DT showed the lowest reduction (Figure 3a). The soil particle density was decreased after four years of study. The highest decrease was noted in ZT and the minimum was in DT (Figure 3b).

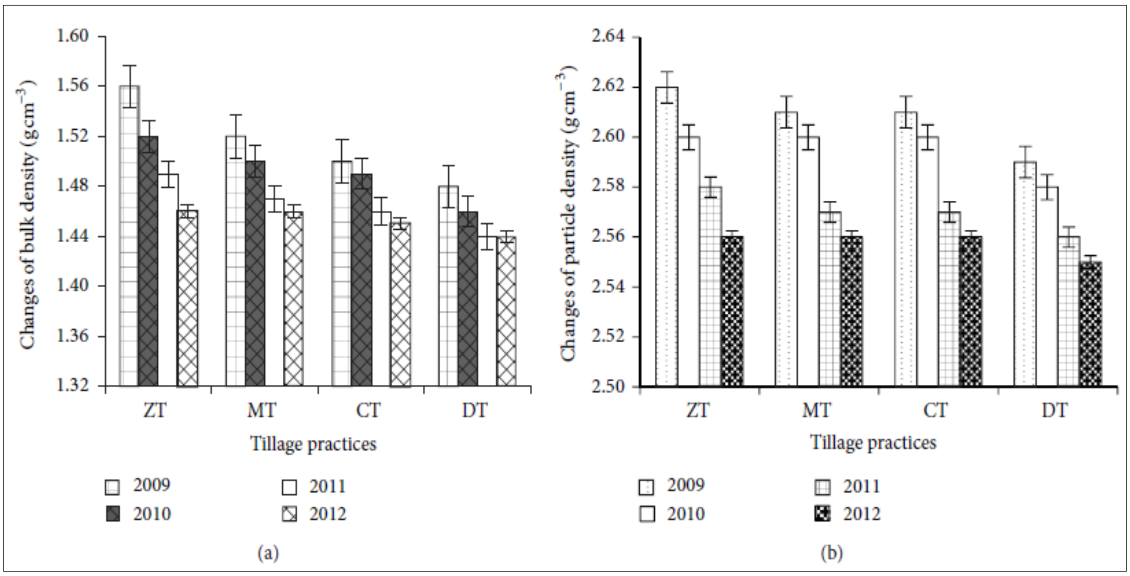
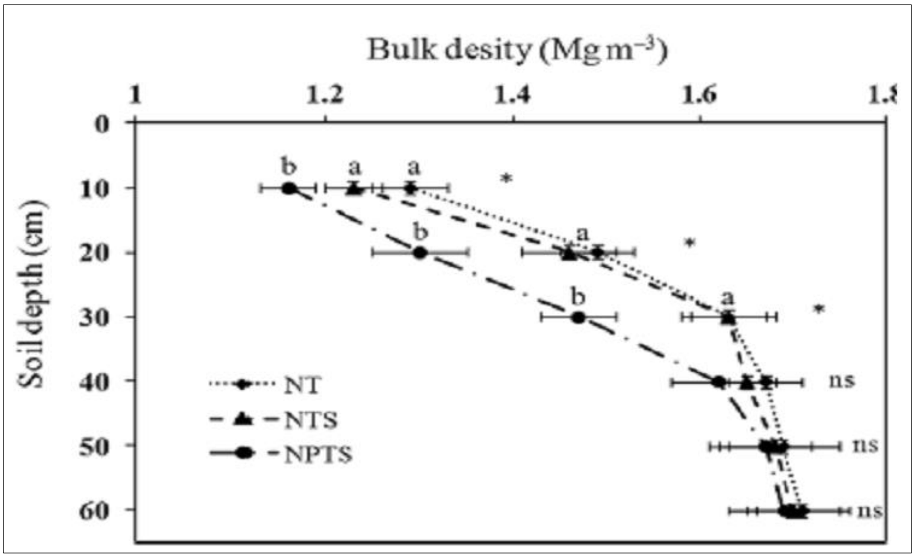



**Fig 3:** Change in bulk density (a) and particle density (b) as influenced by different tillage practices. ZT: zero tillage, MT: minimum tillage, CT: conventional tillage, DT: deep tillage [Source: Md. Khairul *et al*., 2014] [42]

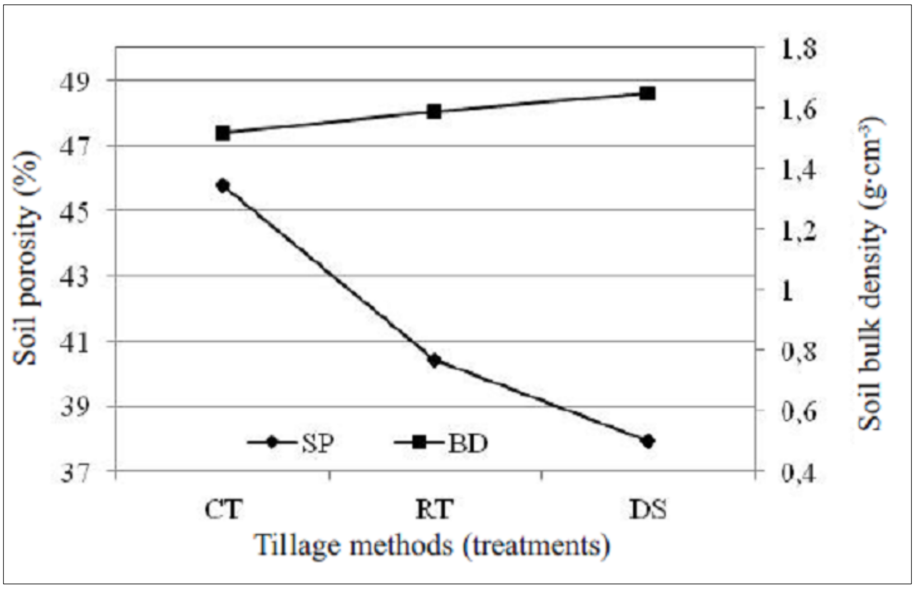
Ye *et al*. (2019) [68] indicated that soil bulk density was significantly higher in the 0–30 cm soil layer under NT and NTS compared to NPTS (Fig. 4a). However, the 0–30 cm layer soil bulk density values for NT and NTS were similar. The soil bulk densities in NPTS were 10.0%, 12.8% and 9.8% less for the 0–10, 10–20, and 20–30 cm layers, respectively, than the values recorded for the NT treatment. Soil bulk density gradually rose as the soil depth increased, regardless of tillage practice and straw management treatments. There was no apparent difference in soil bulk density among the three treatments in the 30–60 cm layer.

Akbolat and Kucukalbay, (2014) [2] also found that mean soil porosity and bulk density of the treatments are presented for soil depths of 0-10, 10-20, and 20-30 cm in Fig. 4b. Soil porosities for the CT, RT, and DS treatments were 45.7%, 40.4%, and 37.7%, respectively. According to treatments, bulk density values in the same order were determined to be 1.52, 1.59, and 1.65 g cm3. Lower porosity and higher bulk density values were determined for the DS treatment not tilled at the soil depth of 30 cm than for the other treatments.




A

**Fig 4a:** Soil bulk densities at different soil depth under three tillage and crop residue management strategies [Source: Ye *et al*., 2019] [68]



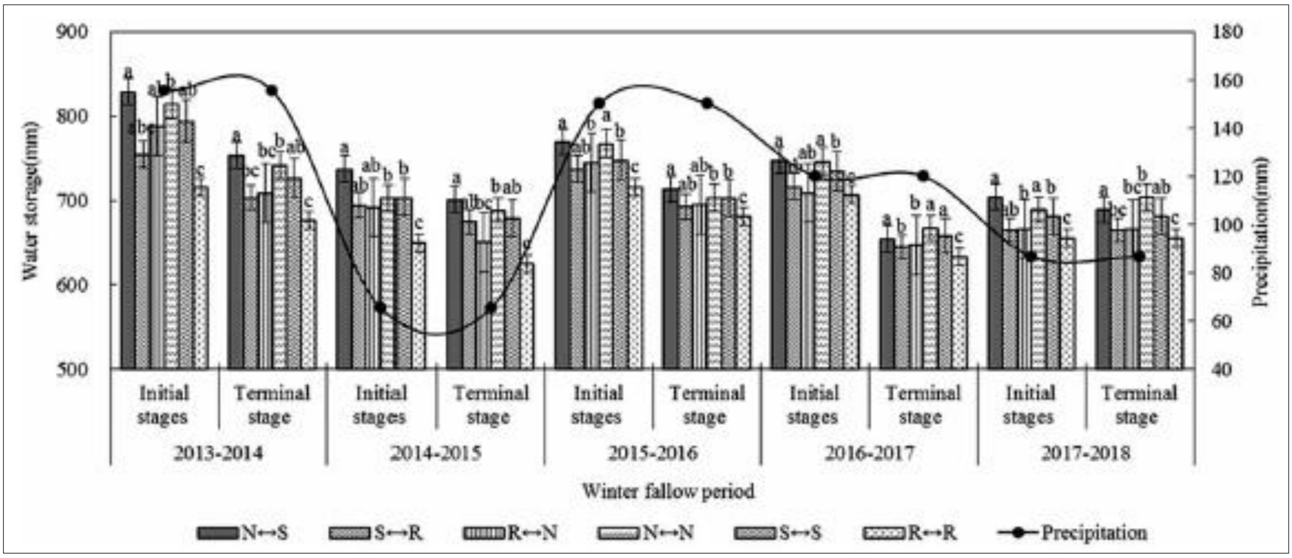

B

**Fig 4b:** Soil porosity (SP) and bulk density (BD) of tillage methods [Akbolat and Kucukalbay, 2014] [2]

## Soil water storage

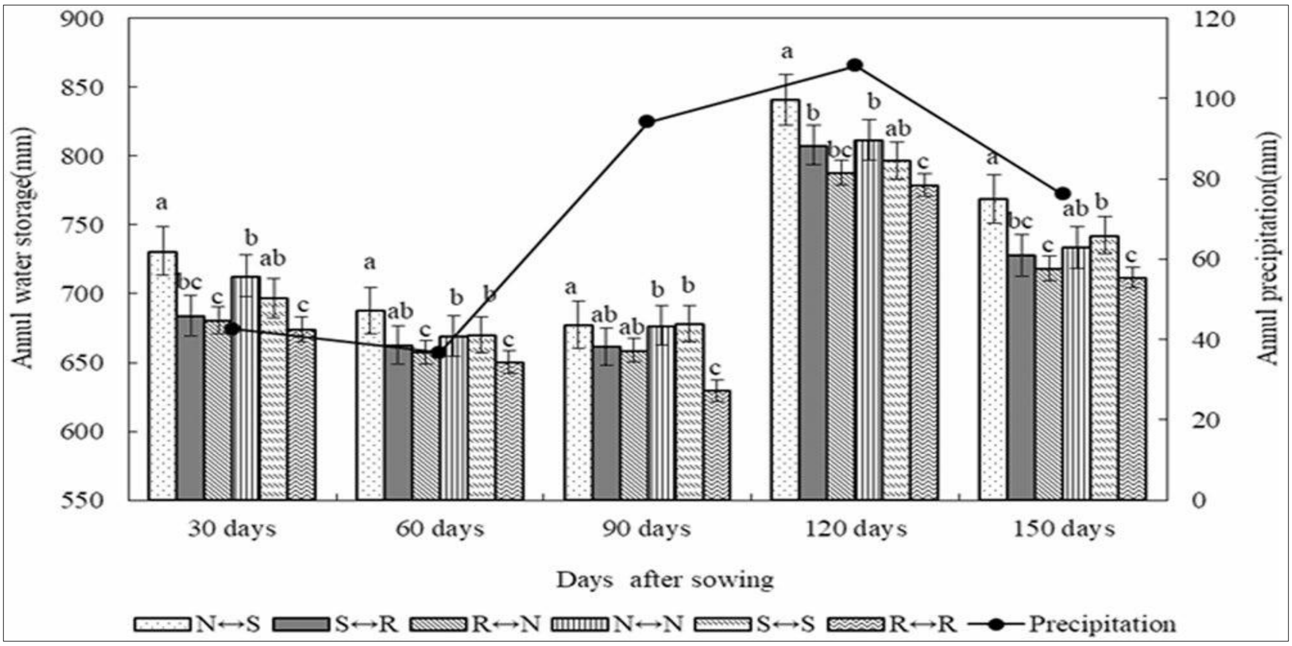
Li *et al*. (2020) [31] reported that different tillage treatments during the rest period could effectively increase the soil water storage capacity of farmland (Fig. 5a). The average soil water storage in the 0–300 cm soil layer at the end of different tillage activities was N ↔ S (705.4 mm)> N ↔ N (698.1 mm)> S ↔ S (689.4 mm)> S ↔ R (676.2 mm)> R ↔ N (67.3.6 mm)> R ↔ R (654.3 mm). The average soil water storage in each 0–300 cm soil layer was higher than that in the traditional tillage R ↔ R treatment. At the end of the 2013–2014 trial year, the soil water storage capacity of N ↔ S, S ↔ R, R ↔ N, N ↔ N, and S ↔ S was significantly higher than that of the control R ↔ R treatment, and increased by 11.5%, 4.1%, 4.9%, 9.7%, and 7.5%, respectively. In 2014–2015, because of lower rainfall during the rest period, the soil water storage capacity of each treatment was lower than that of the previous rest year, which was 4.0% to 12.1% higher than that of the control R ↔ R treatment. Compared with R ↔ R, the soil water storage capacity of N ↔ S, S ↔ R, R ↔ N, N ↔ N and S ↔ S increased by 4.8%, 1.8%, 2.1%, 3.4% and 3.2% respectively in 2015–2016, the soil water storage capacity of N ↔ S, S ↔ R, R ↔ N, N ↔ N and S ↔ S was increased by 3.4%, 1.8%, 2.2%, 5.3% and 3.9%respectively in 2016–2017, the soil water storage capacity of N ↔ S, S ↔ R, R ↔ N, N ↔ N, and S ↔ S was increased by 7.3%, 1.4%, 1.6%, 5.1% and 3.9% respectively in 2017–2018. In different rest years, the water storage effect in the N ↔ S rotation mode was better.

However, during the entire spring maize growth period, soil water storage was higher N ↔ S, S ↔ S, and N ↔ N, and there were significant differences between the treatments and the control R ↔ R treatment. During the entire growth period of spring maize, the average water storage capacity of 0–300 cm soil layer was 52.2, 19.9, 11.7, 32.1, and 27.9 mm higher than that of the control R ↔ R. From 30 days to 90 days after sowing, primarily because of the rapid growth of maize, the water storage capacity of different treatments decreased significantly, and the N ↔ S treatment decreased the most (Fig. 5b). At 120 days after sowing, the water storage capacity of each treatment significantly increased, mainly because the rainfall increased and the soil moisture recovered during this period. The soil water storage was the highest in the N ↔ S treatment, which was significantly different from that of other treatments. The entire growth period of corn, compared with R ↔ R treatment, N ↔ S, S ↔ R, R ↔ N, N ↔ N and S ↔ S treatments average soil water storage in 0–300 cm soil layer increased by 37.8 mm, 43.5 mm, 37.8 mm, 20.8 mm and 37.6 mm, respectively.




A

**Fig 5a:** Effect of different rotational tillage treatments on soil water storage at 0~300 cm soil layer during leisure period [Source: Li *et al.*, 2020] [31]

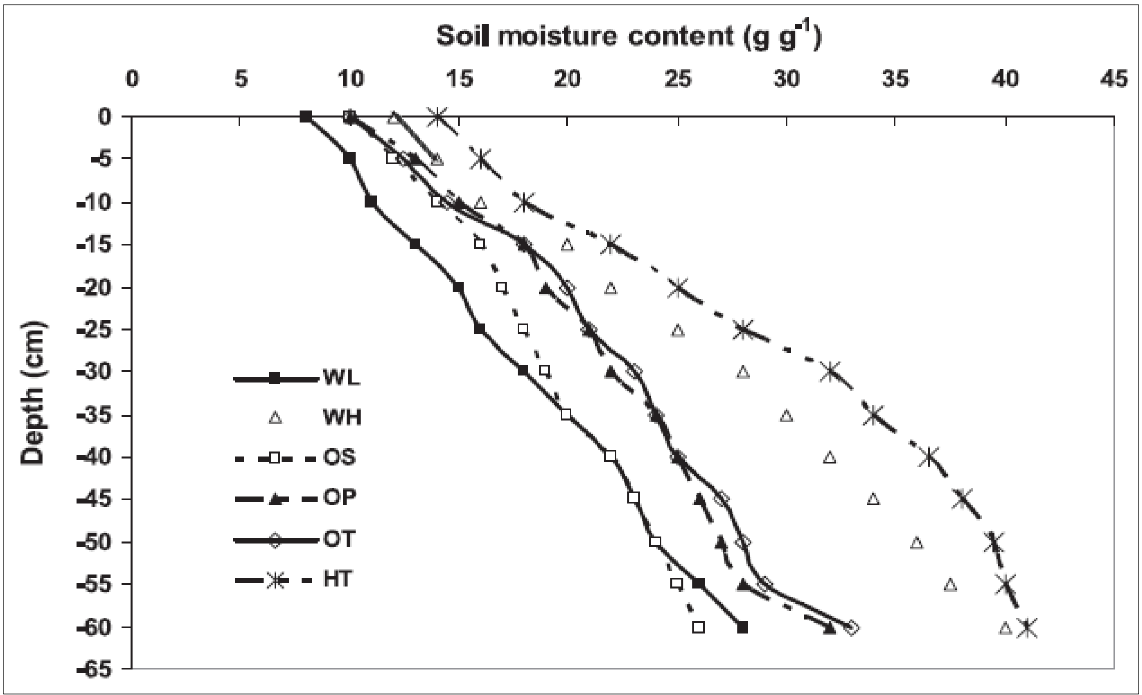



B

**Fig 5b:** Soil water storage changes in 0–300 cm soil layer of different tillage treatments after the sowing of maize field in 2014–2018.

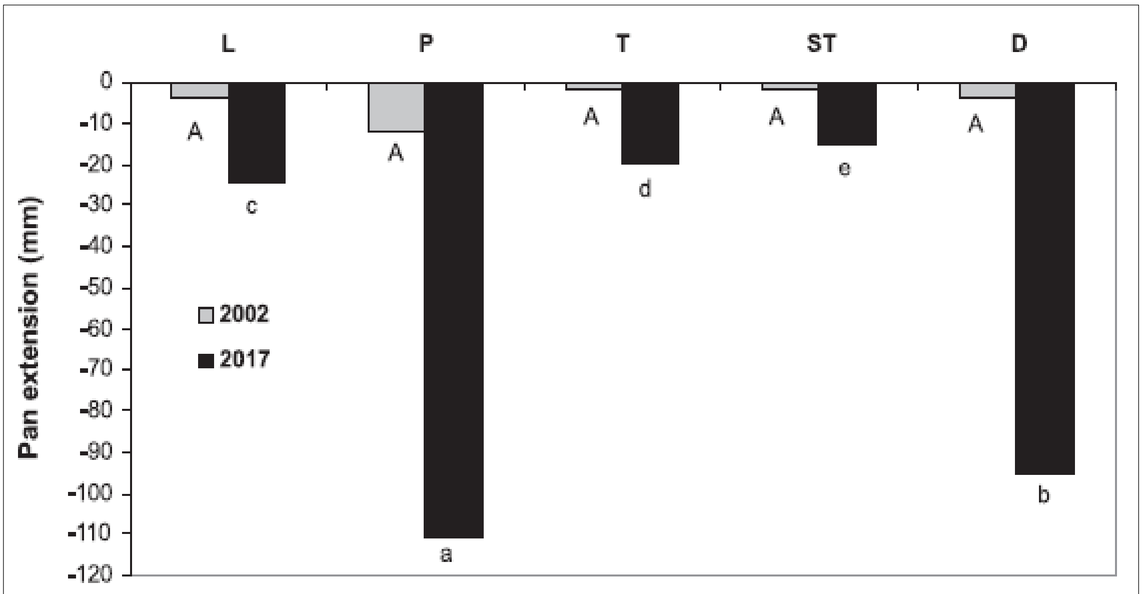
Dekemati *et al*. (2019) [19] revealed that loosening is more effective at dry (OS), and ploughing at moistened (OP) soil conditions. Moisture optimum (OT) means a soil state that produces the slightest damage during cultivation. This soil moisture range of the soil is close to the recommended moisture of soil for ploughing (Fig. 6a). Likewise, the lower limit of cultivation (WL) and the recommended moisture content for soil loosening (OS) are almost the same. In the last three years, the autumnal season was wet, which justified the inclusion of the HT to the moisture variants. Dexter and Bird, (2001) [21] have attributed great importance to research soil moisture ranges for workability. Obour *et al*. (2017) [52] stated that knowledge of soil workability is important for scheduling tillage operations and for reducing the risk of tillage-induced structural degradation of soils. A tillage operation in a given moment is to adapt to the soil moisture content for decreased tillage-induced damage. Improving soil workability requires the continuous conservation of the factors, especially the organic matter content.

Tillage-induced compaction is one of the negative results of the soil disturbance by cultivation tools (Bogunovic *et al*., 2018) [13]. Birkás *et al*. (2004) [8] noted the use of a plough and disk support pan formation. The plough and the disk pan compaction have occurred in soil since the beginning of the experiment (Fig. 6b). At the beginning of the experiment, the extension of the plough pan was quite slight (10-13 mm) and similarly narrow (3.5 mm), below the edge of the disk tillage (Birkás, 2010) [9].




A

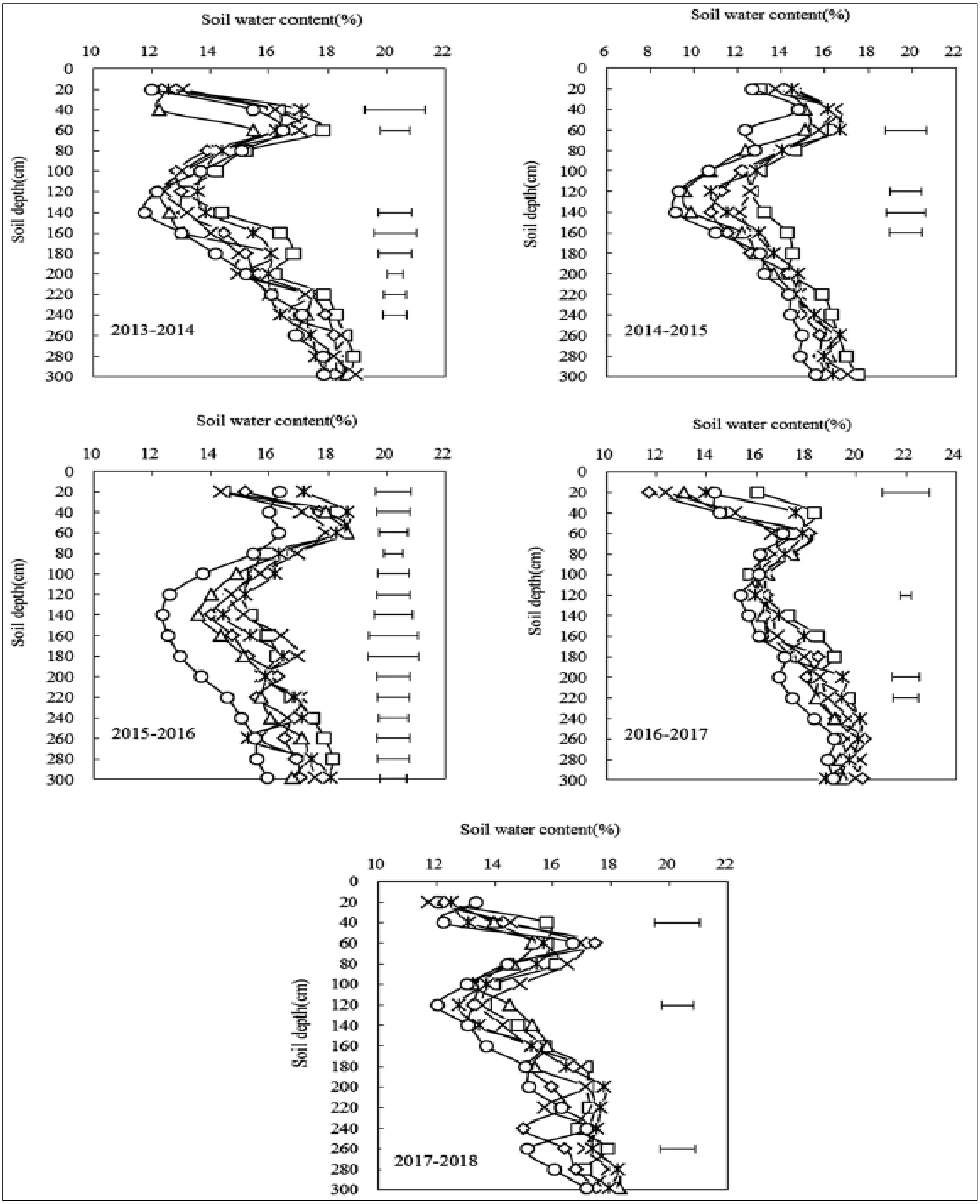
**Fig 6a:** Soil moisture contents for different workability of soil (WL: workability, lower water level; WH: workability, highest water level; OS: optimal for sub-soiling; OP: optimal for ploughing; OT: optimal level for tillage; HT: highest water level for tine tillage).




B

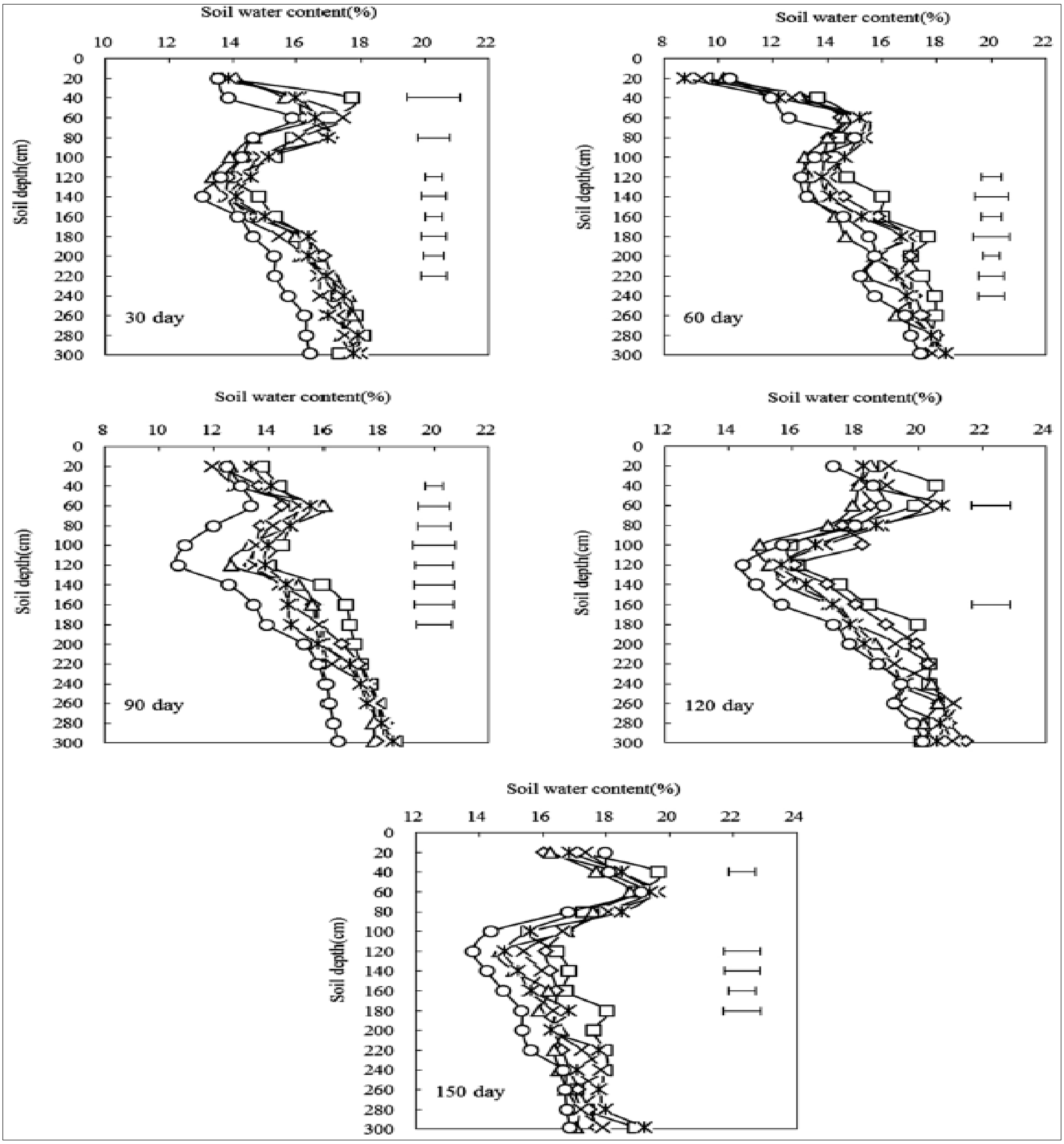
**Fig 6b:** Tillage pan occurrence and extension in the first and 16th years (L: loosening, P: ploughing, T, ST: tine tillage, D: disk tillage);

Li *et al*. (2020) [31] also found that the soil water content of each treatment in the 0–300 cm profile soil has a similar trend, with a small increase in the 0–60 cm soil, a decrease in the 60–120 cm soil, and an increase in the 120–300 cm soil, but the soil water content in the 40–60 cm soil layer of each treatment has always maintained a high level. In the 0–300 cm soil layer, the average water content for each treatment soil was N ↔ S > S ↔ S > S ↔ R > N ↔ N The soil water content during the rest period was greatly affected by precipitation, and the difference varied among years. The soil water content of each treatment in the 0–300 cm profile soil has a similar trend, with a small increase in the 0–60 cm soil, a decrease in the 60–120 cm soil, and an increase in the 120–300 cm soil, but the soil water content in the 40–60 cm soil layer of each treatment has always maintained a high level. In the 0–300 cm soil layer, the average water content for each treatment soil was N ↔ S > S ↔ S > S ↔ R > N ↔ N (Fig.7a).




A

**Fig 7a:** Effects of different tillage treatments on soil water content in 0–300 cm depth during the leisure period of maize field.



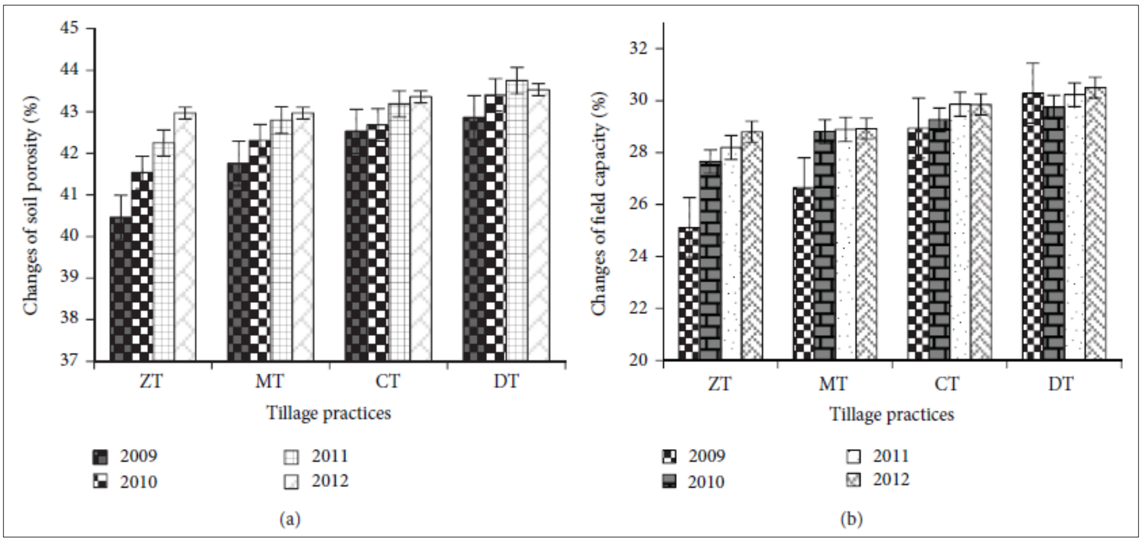

B

**Fig 7b:** Effects of different tillage treatments on annual soil water content in 0–300 cm depth of maize field after the sowing.

During the entire spring maize growth period, the soil water content fluctuated less during each period. Only 90 days after the maize was planted (large trumpet period), the soil water content decreased significantly, and the soil water content remained basically stable in other periods (Fig. 7b). The soil moisture content fluctuated from 13.0% to 18.1% 30 days after sowing of spring maize; there were significant differences among the tillage treatments, primarily in the 20–40 cm, 60–80 cm, and 120–220 cm layers, and the treatment room. There were significant differences 60 days after sowing because of reduced rainfall at the beginning of the growing period and the need for crop growth. Compared with 30 days after sowing, the soil water content decreased, and the fluctuation range was 8.8% to 18.3%. The significant difference between the tillage treatments was mainly in the deep layer at 120–240 cm. At 90 days after sowing, the soil water content fluctuated from 10.7% to 18.5%. The significant difference between the tillage treatments was only at 20–40 cm and 40–60 cm in the soil surface, and 80–180 cm in the deep soil. After 120 days of sowing, the maize grew faster. The soil moisture in the 40–60 cm surface layer and the 140–160 cm deep soil layer was significant. During the whole spring maize growth period, the soil water content under each treatment was higher than that of the control R ↔ R, and the N ↔ S treatment had the highest soil water content.

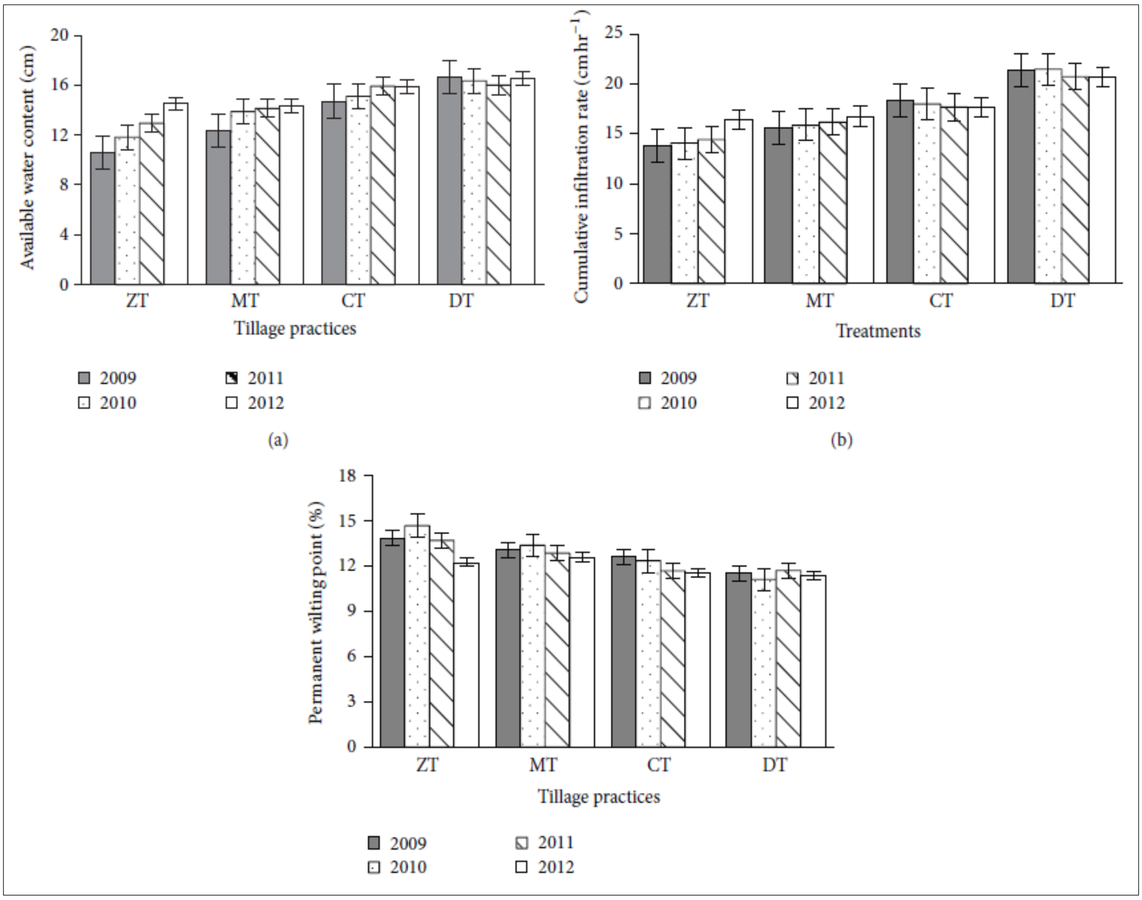
Md. Khairul *et al*. (2014) [42] reported that after four years of cropping cycles, porosity was increased from the initial value (6.2, 2.9, and 0.69% increase in ZT, MT, and CT, resp.) (Fig.8a). the field capacity (FC) was also increased due to different tillage practices. The highest FC increase (14.65%)

was found in ZT followed by MT (8.52%). CT showed the lowest increase of field capacity from the first year value (Fig. 8b). However, permanent wilting point (PWP) was also influenced by the different tillage practices. After four years, the permanent wilting point was decreased due to tillage practices (Fig. 8c). The highest reduction (11.91%) was found in ZT followed by CT (8.32%) and the lowest reduction (1.13%) in DT. After four years of experimentation, the result showed no significant variation in available water content (AWC) due to different tillage treatments whereas AWCs were significant after completion of the first and second cropping cycles. In the end of the study, maximum available water content (AWC) was found in the deep tillage (16.50 cm) and the minimum AWC (14.30 cm) in ZT.




A

**Fig 8a:** Change in soil porosity (a) and field capacity (b) as influenced by different tillage practices (year most recent first). Notes: ZT: zero tillage, MT: minimum tillage, CT: conventional tillage, and DT: deep tillage.




B

**Fig 8b:** Effect of tillage practice on available water content of soils (a), cumulative infiltration (b), and permanent wilting point (c), ZT: zero tillage, MT: minimum tillage, CT: conventional tillage, and DT: deep tillage

### Soil crumb ratio

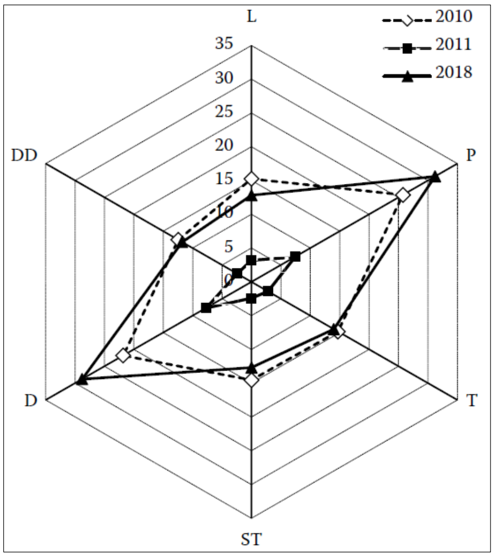
The ratio of crumb in soils under conservation tillage is one of the basic soil quality indicators (Nimmo 2004). Therefore, the use of proper tillage management (that is ST, T, L or DD) helps create surface state that may mitigate the exposure to the climate damages including crumb breakdown (Morris *et al*. 2010) [48]. Moreover, Muršec *et al*. (2018) paid attention to the structural stability of soil aggregates. Investigation of differences in soil aggregation between irrigated and rain-fed soils may become a new challenge for future, considering frequency of drought periods in the region.

**Table 1:** Soil water content (SWC); bulk density (BD); soil penetration resistance (PR); soil crumb (SC) and crusted area (CA) under L (loosening); P (ploughing); T (tine tillage); ST (shallower tine tillage); D (disk tillage) and DD (direct drilling) in three selected years Source: Bogunovic *et al*. (2019) [14].

| Soil property | Year | Depth (cm) | Treatment | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | L | P | T | ST | D | DD |
| SWC (weight %) | 2010 | 0–60 | $27.5^{aA}$ | $26.8^{aA}$ | $27.5^{aA}$ | $27.6^{aA}$ | $26.7^{aA}$ | $27.5^{aA}$ |
| | 2011 | | $26.3^{aB}$ | $25.8^{aB}$ | $27.1^{aB}$ | $26.9^{aB}$ | $25.7^{aB}$ | $27.0^{aB}$ |
| | 2018 | | $23.3^{aC}$ | $22.6^{aC}$ | $23.9^{aC}$ | $23.9^{aC}$ | $22.7^{aC}$ | $24.2^{aC}$ |
| BD ($g/cm^3$) | 2011 | 0–40 | $1.28^{b}$ | $1.25^{b}$ | $1.27^{b}$ | $1.30^{a}$ | $1.38^{a}$ | $1.39^{a}$ |
| PR (MPa) | 2010 | 0–50 | $2.10^{aA}$ | $2.09^{aB}$ | $2.20^{aA}$ | $2.17^{aA}$ | $2.46^{aB}$ | $2.42^{aB}$ |
| | 2011 | | $2.96^{aA}$ | $3.22^{aA}$ | $2.88^{bA}$ | $3.11^{aA}$ | $3.71^{aA}$ | $3.58^{aA}$ |
| | 2018 | | $2.61^{bA}$ | $2.76^{aA}$ | $2.71^{aA}$ | $2.78^{aA}$ | $3.21^{aA}$ | $3.29^{aA}$ |
| SC (%) | 2010 | 0–10 | $75.2^{aA}$ | $61.4^{bA}$ | $75.8^{aA}$ | $77.7^{aA}$ | $72.6^{aA}$ | $71.9^{aA}$ |
| | 2011 | | $70.4^{aA}$ | $65.7^{aA}$ | $73.0^{aA}$ | $75.6^{aA}$ | $67.3^{abA}$ | $69.1^{bA}$ |
| | 2018 | | $62.0^{bB}$ | $50.0^{bB}$ | $66.1^{aAB}$ | $69.0^{aAB}$ | $48.3^{cB}$ | $61.4^{bB}$ |
| CA (%) | 2010 | surface | $15.25^{aA}$ | $25.75^{aA}$ | $14.71^{aA}$ | $14.54^{aA}$ | $21.81^{aA}$ | $12.44^{aA}$ |
| | 2011 | | $3.19^{bB}$ | $7.39^{aB}$ | $2.79^{bB}$ | $2.41^{bB}$ | $7.73^{aB}$ | $2.46^{bB}$ |
| | 2018 | | $12.8^{bA}$ | $31.2^{aA}$ | $14.0^{bA}$ | $12.7^{bA}$ | $28.8^{aA}$ | $11.8^{bA}$ |

Values followed by the same lowercase letter within a row indicate no significant difference at 0.05 level; values followed by different uppercase letters within a column indicate a significant difference at 0.05 level

Bogunovic *et al*. (2019) [14] reported that the crust occurrence was affected by the ratio of siltation in the soil surface; however, it was influenced by the amount and intensity of the rainfalls. In the rainy season of 2010, a higher difference in CA was detected between tillage treatments (P 25.75%, and at T, ST and DD < 15%). The mean CA for months differed between 0.8% and 34.7%. In the 2011 period, the after-effects of the previous season and the lack of precipitation of the given season had affected the crust formation. CA ratios at the P and D treatments were twice larger compared to the other treatments (Fig.9). In addition, the ratio of CA assessed at P (31.7%) and D (28.8%) treatments was significantly higher than at other treatments. The lower crust ratio at L, T, ST and DD treatments may attribute to the protective effect of stubble residues remained from the previous year. The rank of tillage treatments in a three-year average was in increasing order: DD < ST < L < T < D < P, referring to the surface conservation as well as the surface exposure. Surface crust mainly depends on soil properties and weather conditions, while it often occurs due to the high amount of dusts developed by multi-traffic tillage in the top layer (Gallardo-Carrera *et al*., 2007) [25].



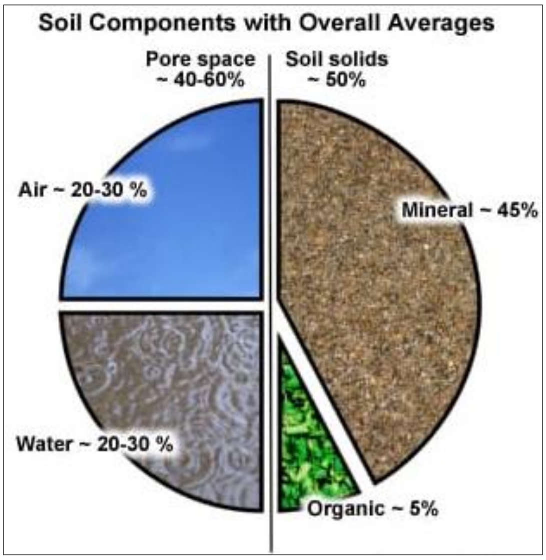




**Fig 9:** Extension of the crusted area (%) under L (loosening); P (ploughing); T (tine tillage); ST (shallower tine tillage); D (disk tillage) and DD (direct drilling) in three selected years [Source: Bogunovic *et al*., 2019)] [14]

Dekemati *et al*. (2019) [19] reported that the ratio of large soil crumb showed significant differences between tillage treatments (Fig. 10). The ratio of large crumbs reached or exceeded 40% at the T, ST and DD treatments in several years. This result is consistent with those of Kalmár *et al*. (2013) [33] who reported that increasing surface cover ratio significantly increased the large crumb formation. Birkás *et al*. (2017) [10] stated that the reduction of the crumbs in wet season is lower than in the dry season, but the chance of improvement is fairly moderate during average season. This assumption is harmonised to the findings of Gyuricza *et al*. (2015) [28] who found poor crumb formation in a Chernozem soil when the dry season replaced a rainy period.

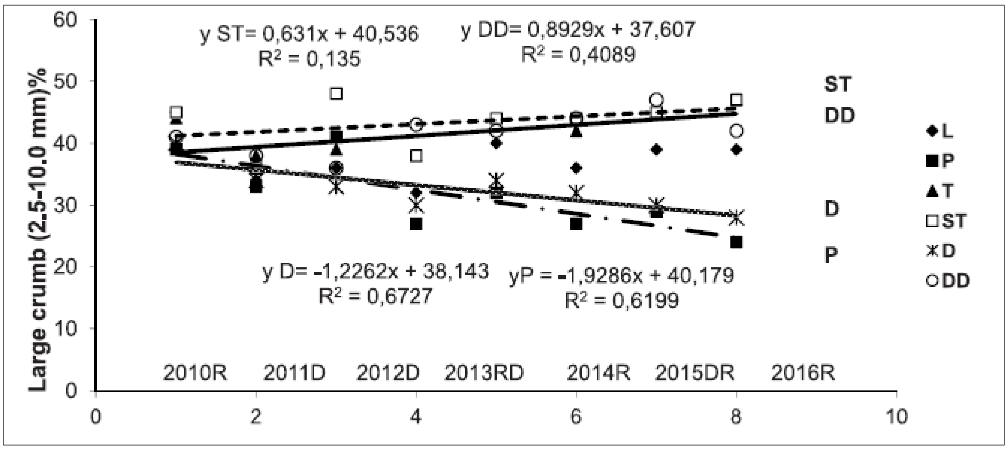



**Fig 10:** Ratio of large crumbs (2.5-10 mm) at four tillage treatments and in variable seasons (R: rainy; D: dry; RD: rainy and dry; DR: dry and rainy); L: loosening; P: ploughing; T, ST: tine tillage – deeper, and shallower; D: disk tillage; DD: direct drilling.

Dekemati *et al*. (2021) [20] reported that the dust and clod ratios were the greatest in ploughing (P) in all the three experimental years, while the crumb ratio in P was significantly lower than in DC and SC. The fine crumb ratio was significantly lower in P in 2017 and 2018 as compared to deep tine cultivation (DC) and shallow tine cultivation (SC). In 2016, P treatment achieved higher proportions of clod (+2.34%), fine crumb (+1.48%) and dust (+5.80%) compared to DC. Regarding the crumb fraction, DC showed significantly higher ratio (+9.62%) compared to P. Furthermore, P resulted significantly higher (5.8%) dust compared to DC. In 2017, the lowest ratio of clod fraction was measured in DC (13.12%), followed by SC (16.50%) and the highest (23.74%) [Fig.11]. The significantly higher crumb ratio was determined in SC and DC as compared to P, while DC showed significantly higher fine crumbs as compared to DC. In 2018, the highest clod (16.20%), dust (7.78%) and lowest crumb (37.38%) and fine crumb (38.64%) ratios were measured in P. Significant difference in clod, crumb and fine crumb fractions was found between SC and P, while in the dust fraction ratios showed significantly higher dust fraction at P as compared to DC. Thus, in SC and DC significantly higher crumb and fine crumb ratio were recorded compared to P.

Baker *et al*. (2005) [4] drew attention to the fact that conservation tillage achieves a 50–90% reduction in dust fraction, especially when the number of tillage interventions is reduced. However, crumb fraction ratios between DC and SC treatments showed no difference, while both treatments showed significantly higher crumb ratio than P. This result is not only due to the surface cover which is provided by DC and SC, but also because the other favorable soil characteristics of these tillage interventions, e.g., increased SMC, greater earthworm abundance, more intensive plant root growth.

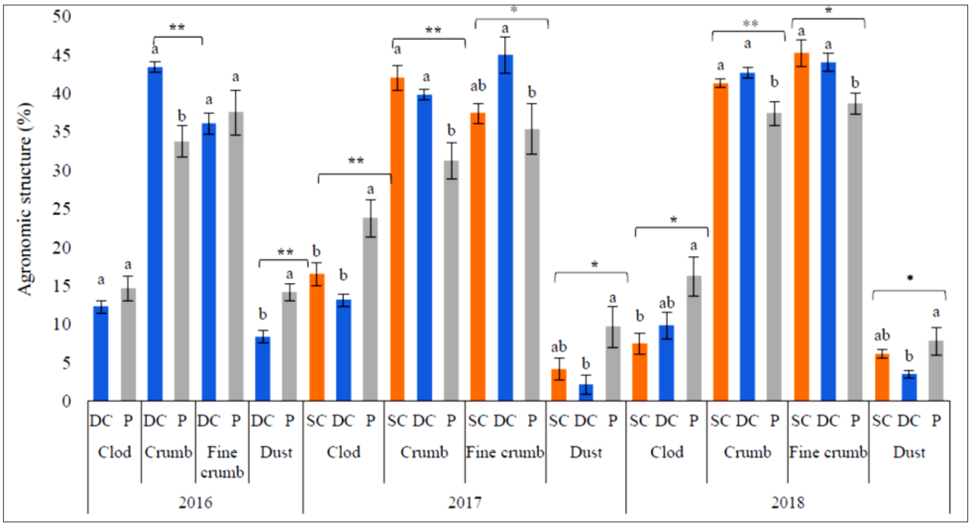



**Fig 11:** Average ratios of agronomic structure through three years (2016–2018). Treatments: P—ploughing; DC—deep tine cultivation; SC—shallow tine cultivation [Source: Dekemati *et al*., 2021)] [20]

**Soil Compaction**

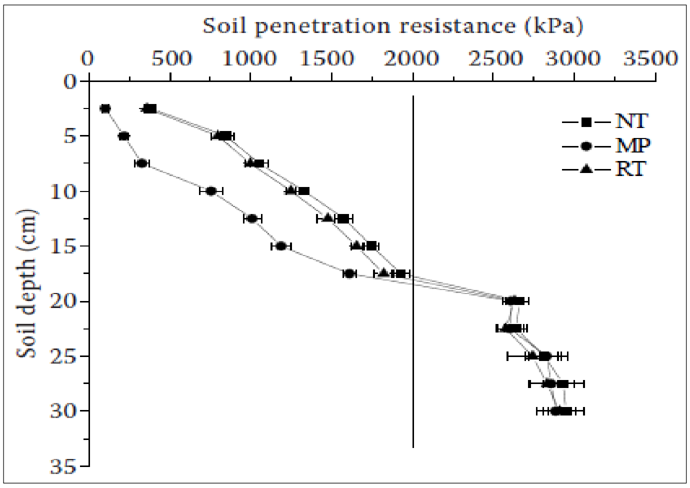
Soil compaction is the process of physical consolidation of soil particles against an applied force, often resulting in destruction of soil structure, reduced porosity, restricted water and air movement hampering root penetration and consequently decreasing crop performance. In agriculture, wheel of heavy farm machineries is the major cause of soil compaction and the magnitude of compactness increases when tillage operation is carried out at inappropriate soil moisture conditions and a larger number of tillage operations are performed. In conventional tillage, farmers adopt the same equipment and crop sequence every year which consequently develops a plough pan (compact layer) in the sub soil. Cone penetrometer is generally used to assess the compactness in field and the numerical value given by it is called cone index (CI). It directly measures the applied force, required to press the penetrometer into a soil at a desired depth or indirectly it is an index of shear resistance of the soil.

Earlier studies reflect that a higher CI value was observed in no-tillage systems compared to conventional tillage systems in upper soil layers (0–20 cm) [Bueno *et al*., 2006] [15], due to various tillage operations. Although higher CI value was recorded below the tilled layer in conventional tillage system, it might have been due to formation of plough pan layers by using the same agricultural implements over the years (Doan *et al*., 2005) [23]. Moreover, the CI value in no-tillage system was closely correlated to the soil moisture content, depth of soil and percentage of sand particles, whereas in conventional tillage system, it was closely correlated to the percentage of clay and depth of tillage operations (Kumar *et al*., 2012) [35].

Soil compaction is the increase in bulk density expressed in tons of soil per cubic meter and the accompanying decrease in pore space, resulting from the application of pressure to the soil by farm machinery, livestock trampling, raindrop impact and other means in sufficient amounts to overcome soil strength. The soil compaction involves a microscopic rearrangement and bringing of the solid particles closer to one another and consequently an increase in the bulk density of the soil (Panayiotopoulos *et al*., 1994) [54]. But the degree of compactness is a quantitative parameter and defined as “the ratio of the actual bulk density to the reference bulk density obtained by uniaxial compression of wet soil (sufficiently for drainage) at static pressure of 200 kPa” (Lipiec and Hatano 2003) [39]. Bulk density (dry soil mass per unit volume) is the most frequently used parameter to characterize the soil compaction (Panayiotopoulos *et al*. 1994) [54], but in swelling/shrinking soil, it is recommendable to determine the bulk density at the standard moisture contents (Håkansson and Lipiec, 2000) [29]. Typical resistance indicators, used nowadays, are highly precise for the soil density measurements up to the soil depth of 20 cm while for deep stratum, the stress state transducers with six earth pressure gauges that measure three dimensional stresses can be useful (Eguchi and Muro, 2007) [24]. The bulk density is difficult to measure in gravelly soils (Webb 2002) [66]. For an accurate measurement of the effects of the soil compaction on all types of the soil, the soil bulk density alone is not adequate but other soil properties such as the soil strength, soil aeration, and soil moisture should also be measured (Lipiec and Hatano, 2003) [39].

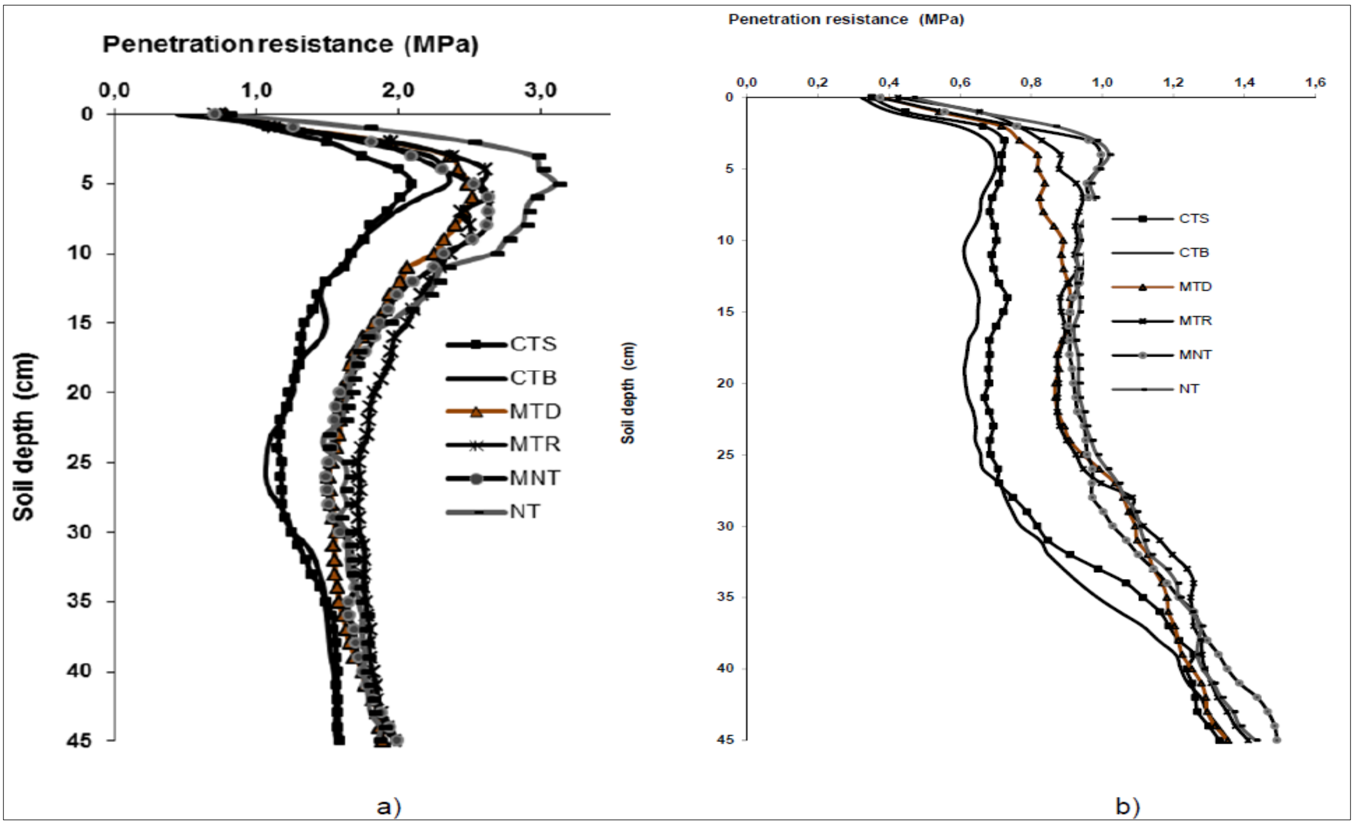
Penetration resistance is an indicator for the degree of compaction of soil. Soil compaction limits root growth and the availability of air and water to the roots. Chen *et al*. (2014) [17] observed that both NT and RT had significantly greater SPR than MP at the depths of 2.5–17.5 cm (Fig. 12a). It could be due to the cumulative soil consolidation over time under NT and RT and to the fall and spring tillage than NT and RT, respectively. This was mainly due to the retention of crop residues on the surface and less disturbance of NT and RT plots. The possible explanation was a higher volume fraction of large pores, providing greater gravitational drainage under conventional tillage when compared to conservation tillage (Kahlon *et al*., 2013). In addition, though similar SWC values at 0–10 cm were obtained from the NT and RT systems, the latter was on average 4.84% higher than the former. The reason for this situation was that capillary continuity under RT was the least disturbed due to no-tillage and controlled traffic and this accelerated the water sucking of crop roots from the surrounding soils (Li *et al*., 2007).

Barut and Celik, (2015) [5] reported that there were differences between means of tillage systems on soil compaction (Fig. 12b). Soil compaction values were under 2 MPa up to 45 cm depth for CTS in 2010. The lowest soil resistance values were obtained from CT and MT plots, respectively. The highest soil resistance value was in NT between the 3-15 cm soil layer and values were over 2 MPa. Penetration resistance showed a decreasing trend between 10 and 30 cm soil depth in all tillage systems (Fig. 12a). Soil compaction values were under 2 MPa up to 45 cm depth for all tillage systems (Fig. 12b).




A

**Fig 12a:** Soil penetration resistance under no tillage (NT), moldboard plow (MP) and ridge tillage (RT) systems [Source: Chen *et al*., 2014] [17]

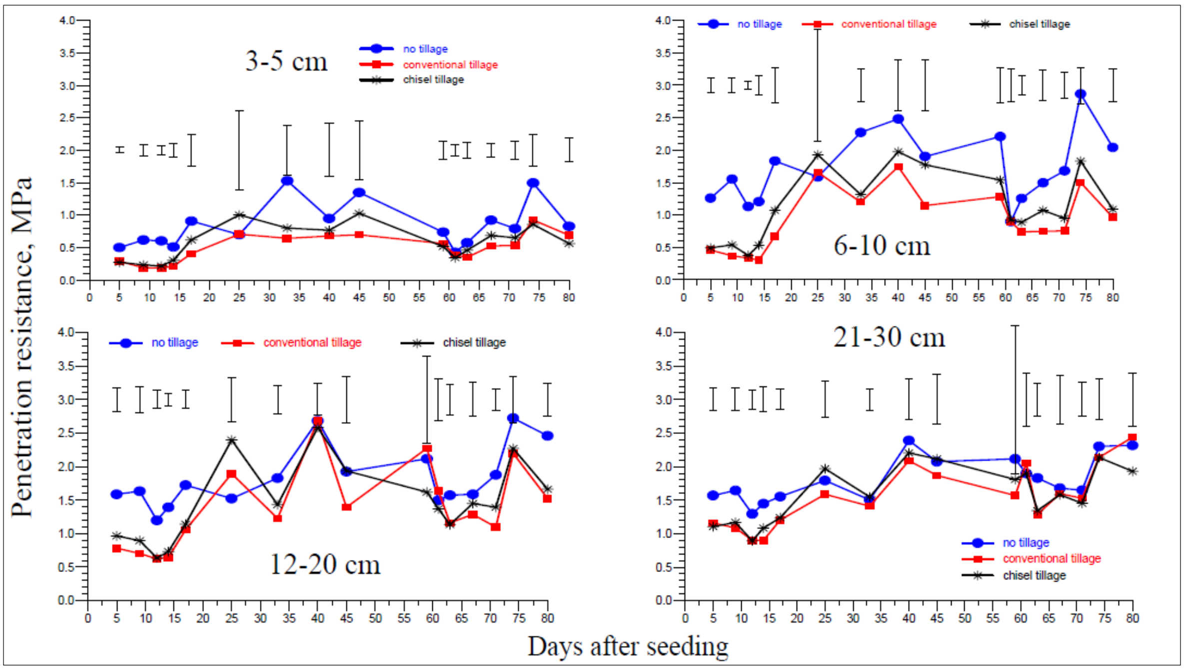



B

**Fig 12b:** Penetration resistance values for 2010 (a) and 2011 (b); CTS, conventional tillage with stubble; CTB, conventional tillage with stubble burning; MTD, minimum tillage with disc; MTR, minimum tillage with rotary tiller; MNT, minimum tillage with disc + no-tillage and NT, no-tillage [Source: Barut and Celik, 2015] [5]

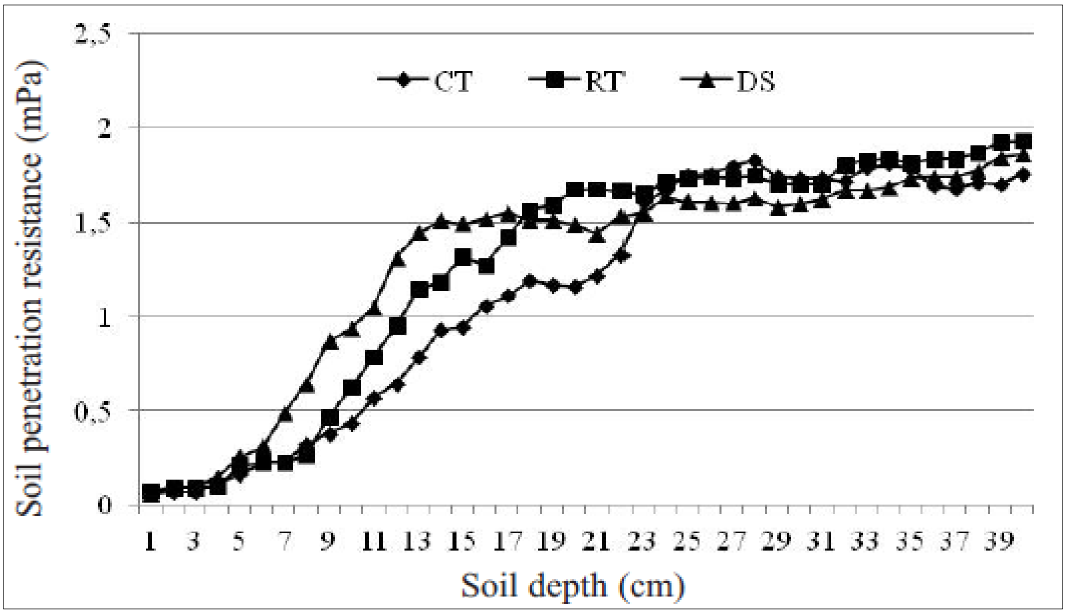
Reichert *et al*. (2004) [57] revealed that soil properties that influence PR values, moisture is the most highly variable during the crop cycle. Low PR was verified in the 3-5 cm layer, mainly in the first 10 days after the beans were sown (Fig. 13a). During all crop cycle, no-tillage presented greater PR than conventional or chisels tillage, but always below to 1.5 MPa. For the 6-10 cm layer, no-tillage presented PR values of 1.5 MPa in the first days after seeding, while the other two soil management systems had PR around 0.5 MPa. From 30 to 60 days after sowing, no-tillage presented PR of 2 Mpa (Fig. 13a), considered critical for roots growth (Taylor *et al.*, 1966) [65]. However, root growth was fast and in the first 10 days after seeding the roots already surpassed the depth of 10 cm (visual observation). The greatest variation in PR occurred for the 12-20 cm depth due to variations in soil moisture, with PR above 2.5 MPa for the three soil management systems. In the layer of 21-30 cm small variations were observed among the soil management systems. Restrictions to root growth due to high PR (above 2 MPa) during beans cycle were observed in the 6-10 cm depth, starting from 30 days after seeding for no-tillage. In the depth from 12 to 20 cm, PR above 2 MPa were observed in all soil management systems, with alternating periods with PR below 2 MPa when soil moisture increased, permitting root growth to deeper soil.

Akbolat and Kucukalbay, (2014) [2] observed that there is a distinct difference between the penetration resistances of the treatments at 0- 25 cm (plough tillage depth). Average penetration resistances of 0.76, 0.95, and 1.04 mPa were determined at a tillage depth of 0-25 cm for the CT, RT, and DS treatments. Penetration resistances were on average 1.13, 1.27, and 1.28 mPa at soil depth of 0-40 cm, respectively (Fig.13b). Similarly, (Ozpinar and Cay, 2006) [54] determined penetration resistances of 0.76 mPa and 1.03 mPa for the CT and DS treatments at a soil depth of 45 cm. Due to deep tillage of the CT treatment with plough, soil resistance and bulk density are expected to be low, whereas porosity is expected to be high. On the other hand, high penetration resistance is also expected in the DS treatment on which no tillage was carried out. Penetration resistance of the treatments was very close to each other for the part after tillage depth (25-40 cm).




A

**Fig 13a:** Soil penetration resistance during the beans cycle for three soil management systems, at four depths [Source: Reichert *et al*., 2004] [57]




B

**Fig 13b:** Soil penetration resistance as a function of tillage depth and tillage methods [Source: Akbolat and Kucukalbay, 2014] [2]

Chen *et al*. (2014) [17] compared with MP, NT and RT led to a significant BD increment at 0–20 cm depth. BD at 20–30 cm under all tillage treatments was similar (Table 2). This should be attributed to the difference in tillage intensity between conservation and conventional tillage systems. Though NT resulted in similar BD values with RT, the latter was on average 4.57% lower than the former of 0–20 cm. It was mainly attributed to the impact of different degrees of soil disturbance in NT and RT. Treatments BD varied from 1.01 to 1.38 g/cm$^3$ at 0–30 cm depth. However, Tillage treatments differed in regard to MAC in 0–20 cm depth, and MAC in NT soil was significantly lower than MP and RT (Table 2). These results are related to disturbance of soil by primary or secondary tillage, which pulverized the soil, broke clods and loosens the soil, and thus an increase in the MAC of the tilled zone (Kay and Vanden Bygaart, 2002). Water flows primarily through these pores during infiltration and drainage and consequently these pores exert a major control on soil aeration (Calegari *et al*., 2013). In addition, much of root growth is initiated in these pores (Calegari *et al*., 2013). Moreover, tillage systems resulted in significantly different values of AFP in 0–20 cm layers (Table 2). In contrast to MP, NT had a significantly lower AFP at the depth of 0–20 cm. AFP was significantly higher in RT than NT soils at 0–20 cm. This result indicated that RT had greater soil aeration than NT soil. It is generally accepted that if air-filled porosity in soil is 0.10 cm$^3$/cm$^3$ or less, plant growth will be significantly limited (Wall and Heiskanen 2009).

**Table 2:** Soil bulk density (BD), soil water content (SWC), soil macro-porosity (MAC) and soil air-filled porosity (AFP) under no tillage (NT), moldboard plow (MP) and ridge tillage (RT) systems [Chen *et al*., 2014] [17]

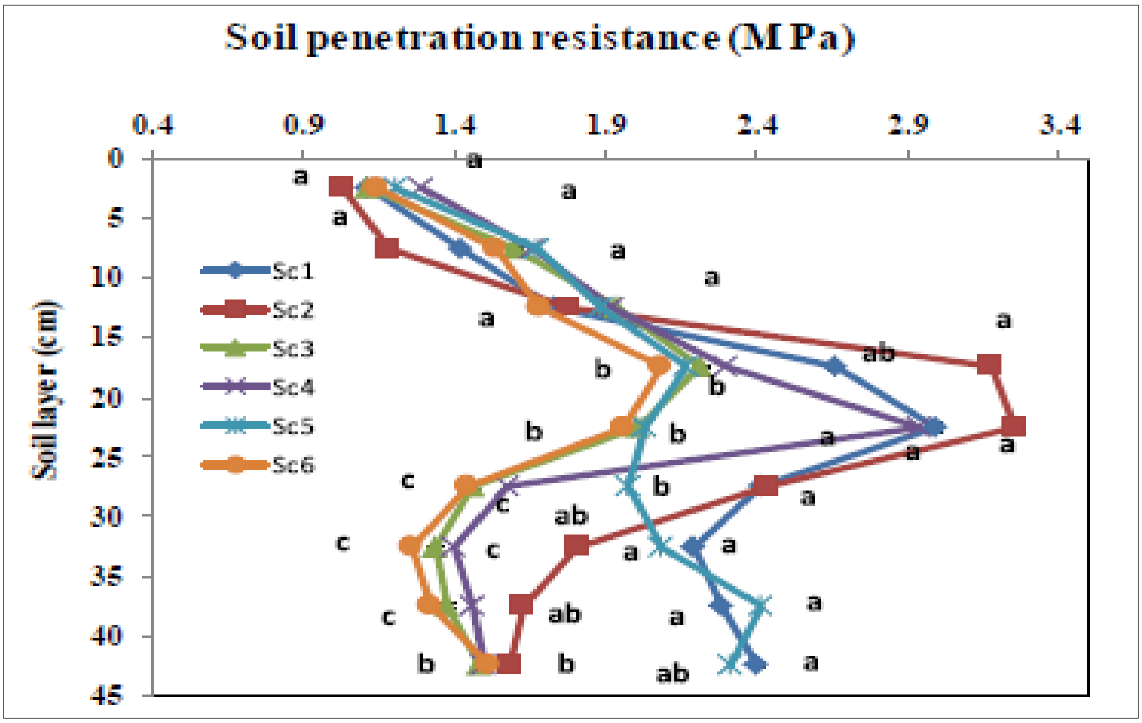
| Soil property | Soil depth (cm) | Treatment | | |
|---|---|---|---|---|
| | | NT | MP | RT |
| BD ($g/cm^3$) | 0–5 | $1.15^{a}$ | $1.01^{b}$ | $1.10^{a}$ |
| | 5–10 | $1.36^{a}$ | $1.21^{b}$ | $1.30^{a}$ |
| | 10–20 | $1.38^{a}$ | $1.23^{b}$ | $1.32^{a}$ |
| | 20–30 | $1.36^{a}$ | $1.35^{a}$ | $1.34^{a}$ |
| SWC (weight, %) | 0–5 | $30.20^{a}$ | $26.78^{b}$ | $31.65^{a}$ |
| | 5–10 | $24.78^{a}$ | $20.23^{b}$ | $25.99^{a}$ |
| | 10–20 | $16.12^{b}$ | $18.90^{a}$ | $16.87^{b}$ |
| | 20–30 | $12.36^{a}$ | $12.50^{a}$ | $12.47^{a}$ |
| MAC (%) | 0–5 | $11.78^{b}$ | $12.81^{a}$ | $12.45^{a}$ |
| | 5–10 | $10.53^{b}$ | $11.56^{a}$ | $11.16^{a}$ |
| | 10–20 | $8.80^{b}$ | $9.56^{a}$ | $9.32^{a}$ |
| | 20–30 | $7.73^{a}$ | $7.86^{a}$ | $7.67^{a}$ |
| AFP ($cm^3/cm^3$) | 0–5 | $1.24^{c}$ | $1.55^{a}$ | $1.35^{b}$ |
| | 5–10 | $0.90^{c}$ | $1.13^{a}$ | $0.98^{b}$ |
| | 10–20 | $0.87^{c}$ | $1.10^{a}$ | $0.95^{b}$ |
| | 20–30 | $0.90^{a}$ | $0.91^{a}$ | $0.93^{a}$ |

Values followed by the same letter within a row indicate no significant difference at 0.05 levels

Roy *et al*. (2022) [59] observed that 0n average, CA scenarios reduced SPR by 13–21, 32–34, 18–40, 36–42, 28–41 and 34–38% at 15–20, 20–25, 25–30, 30–35, 35–40 and 40–45 cm soil depth, respectively over farmer's practice (Sc1) (Fig. 14a). Higher SPR at 15–30 cm soil depth in Sc1 and Sc2 might be due to higher sub-surface soil compaction as widely reported in RWCS in the IGP (Gathala *et al*., 2011) [26]. Lower SPR in 15–30 cm depth under CA based scenarios (Sc3, Sc4 and Sc6) was mainly due to higher soil water content compared to Sc1 and Sc2. Similar finding was also reported by Mondal *et al*. (2019) [47] with lower SPR as obtained in subsurface soil layer under CA based systems.

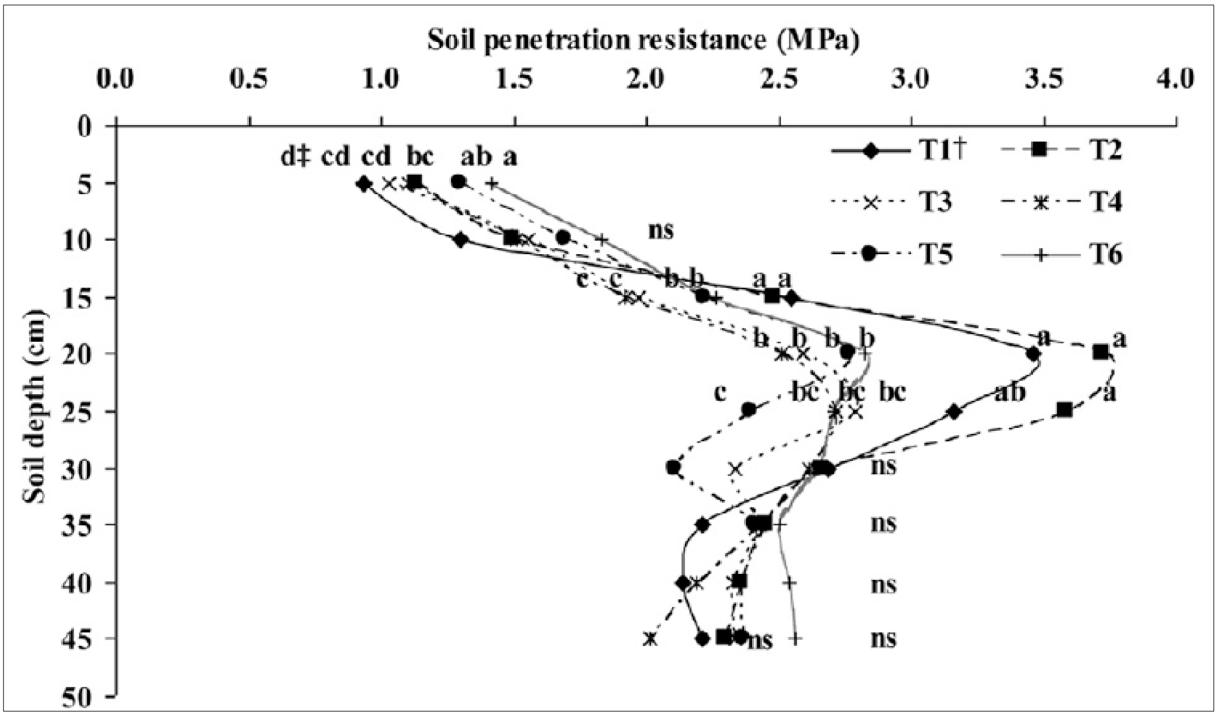
Gathala *et al*. (2011) [26] observed that the SPR increased with the increase in depth up to 20 cm, irrespective of treatment. In surface soil (5-cm depth), SPR was highest (1.3–1.4 MPa) in ZT flat beds (T5 and $T_6$) and the differences from other treatments ($T_1$–$T_4$) ranged from 26 to 51%. The $T_2$ (puddled TPRAWD/ZT wheat) had 20% higher SPR than $T_1$ (puddled TPR/CT wheat) and $T_5$ and $T_6$ (ZT flat) had 28% higher SPR than $T_3$ and $T_4$ (raised beds). However, unlike Db, SPR of raised bed DSR ($T_3$) was similar to raised bed TPR ($T_4$). In subsurface soil (15- and 20-cm depth), the trend of SPR was reverse to surface soil, and it was higher in puddled ($T_1$ and $T_2$) than in the rest of the treatments ($T_3$–$T_6$) (Fig. 14b). At 15 and 20 cm, SPR was 9 to 25% and 24 to 33% lower in $T_3$–$T_6$ than $T_1$ and $T_2$, respectively. At the 15-cm soil depth, SPR of raised beds ($T_3$ and $T_4$) was lower than ZT flat beds ($T_5$ and $T_6$), but at the 20-cm depth, no differences were found. Beyond 30-cm, however, different treatments did not impact SPR.

Penetration resistance in a given soil is directly related to Db and inversely related to soil water content (Sharma and De Datta, 1986). Also in our case, SPR closely followed Db trends, as soil water content (volume basis) at the time of SPR measurements did not differ among treatments. The moisture content, on average, varied from 22 to 28% at different depths up to 30 cm. The higher SPR below tillage depth (especially in the 15- to 25-cm soil layer) under puddling/CT ($T_1$ and $T_2$) was associated with higher Db in these plots. Published studies corroborate these results that SPR remains higher under puddling than under ZT/conservation tillage (Jat *et al*., 2009) [30].




A

**Fig 14a:** Effect of long term CA practices on soil penetration resistance under different scenarios [Source: Roy *et al*., 2022] [59]

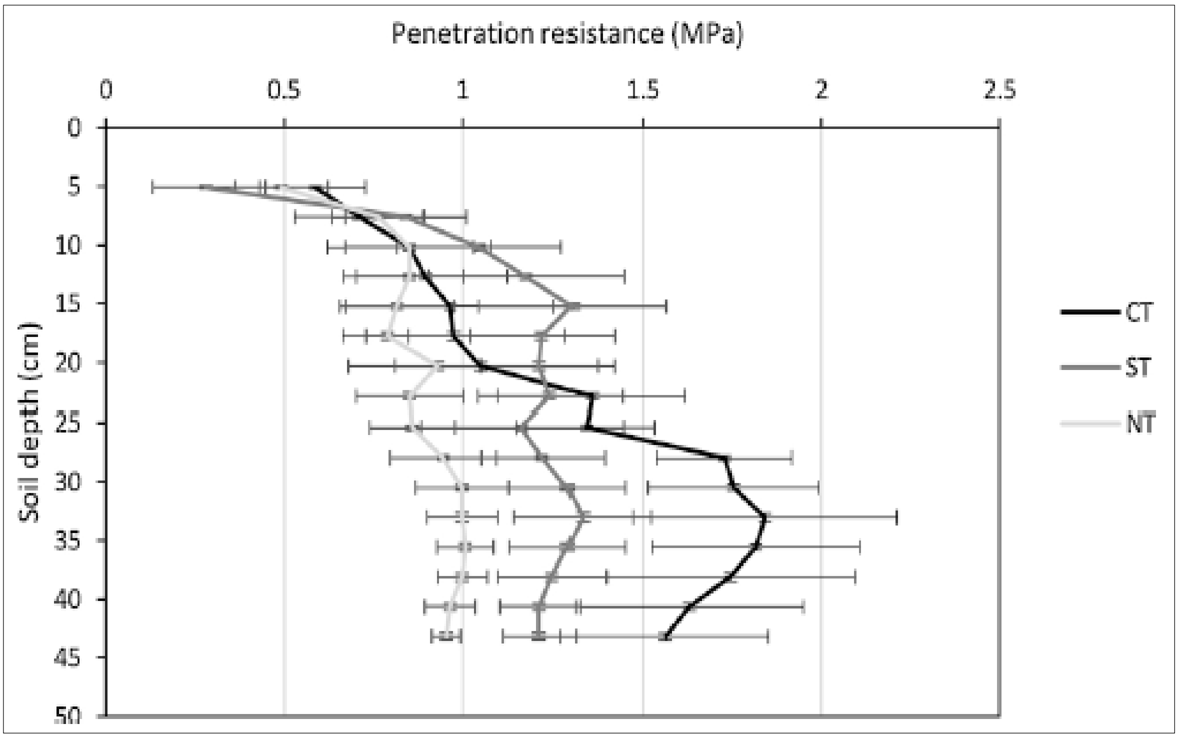



B

**Fig 14b:** Effect of tillage and crop establishment methods on soil penetration resistance (4-yr average, 2005–2006 to 2008–2009) in a 7-yr rice–wheat rotation [Source: Gathala *et al*., 2011] [26]

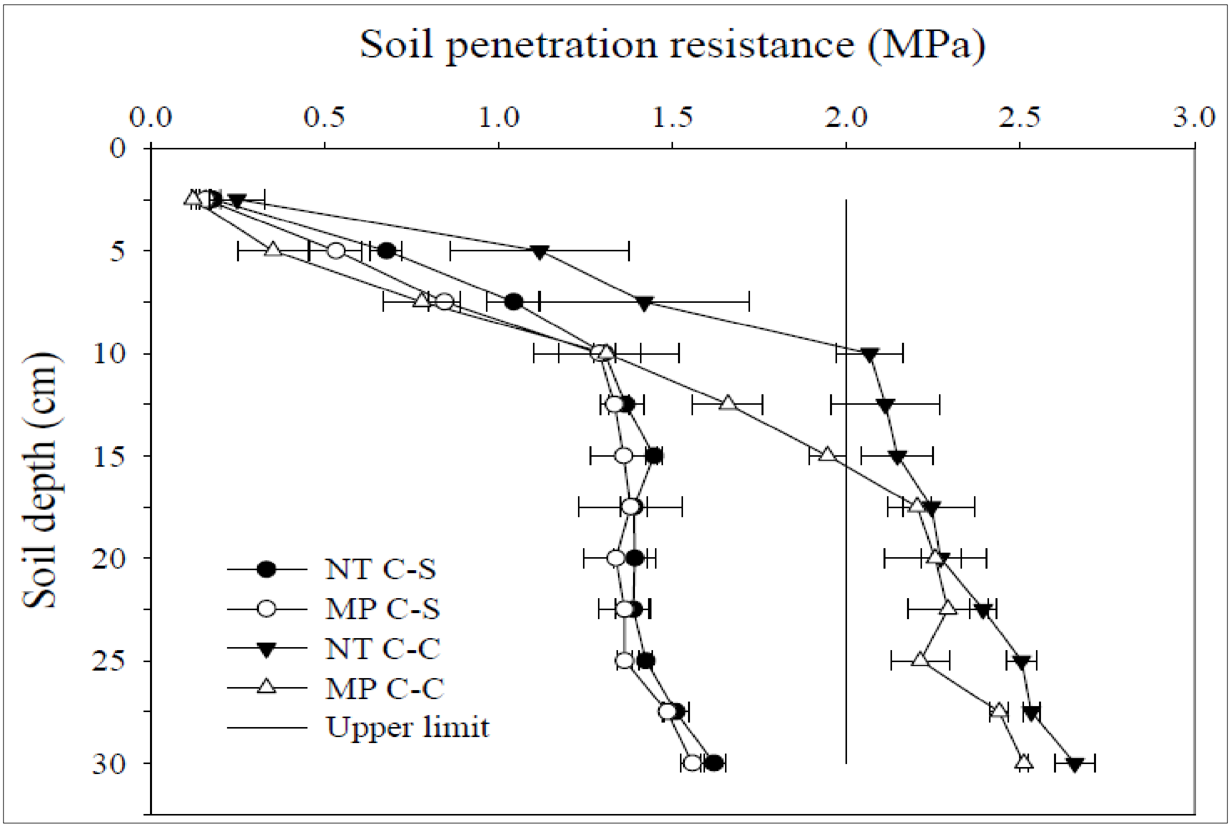
Afshar *et al*. (2019) also found that no significant differences were found between the tillage treatments in terms of PR in top layers of the soil (0–12 cm). In contrast, there were differences among tillage systems in deeper layers. No-till plots had the lowest compaction consistently throughout the soil profile. In mid layers (12–22 cm) ST showed more compaction than CT, whereas in deeper layers (22–45 cm) the PR was considerably greater in CT than that in ST and NT (Fig.15a). Regardless of the tillage system, PR did not exceed 1.8 MPa.

Chen *et al*. (2011) revealed that soil penetration resistance increased steeply with depth of the top 10 cm and 17.5 cm under both NT and MP for C-S and C-C systems, respectively (Fig. 15b). As expected, soil penetration resistance in NT soil was consistently higher than in MP soil in two crop rotation systems (Fig. 15b). For C-S system, soil penetration resistance was far below the upper limit of 2 MPa; however, the upper limit was very shallow (≈ 10 cm) under NT, slightly deeper (≈ 15 cm) under MP in C-C system (Fig. 15b). The results are probably due to accumulative soil consolidation over time under NT, and to fall and spring tillage compaction in the case of MP. Soil penetration resistance was higher in C-C than in C-S system especially obvious in NT soil, which was likely the result of lower soil water content in C-C relative to C-S system. This suggested that the C-S system did a much better work in decreasing soil strength.




A

**Fig 15a:** Effect of tillage on soil penetration resistance at various soil depths measured in the middle of the sugar-beet growing season [Source: Afshar *et al*., 2019].



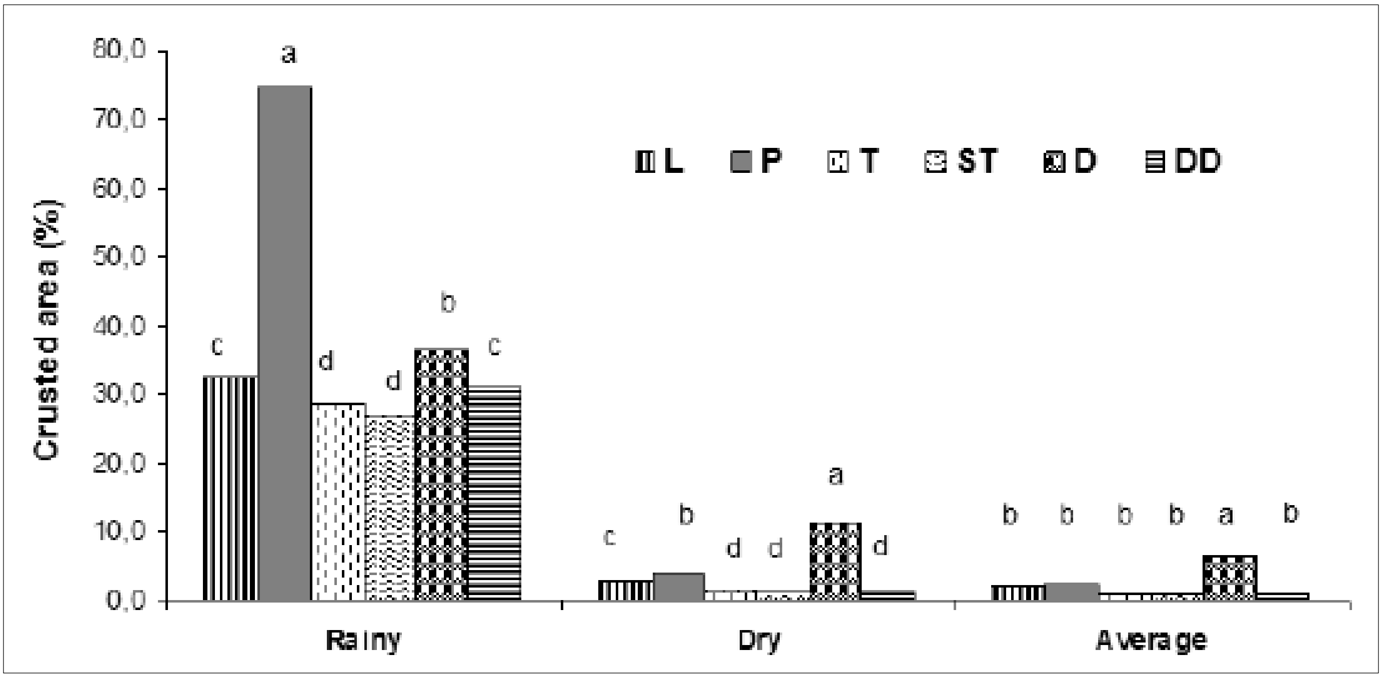

B

**Fig 15b:** Effects of tillage and crop rotation systems on soil penetration resistance. NT = no tillage; MP = mouldboard plough tillage; C-S = corn-soybean rotation; C-C = monoculture corn [Source: Chen *et al*., 2011]

**Crust Formation**

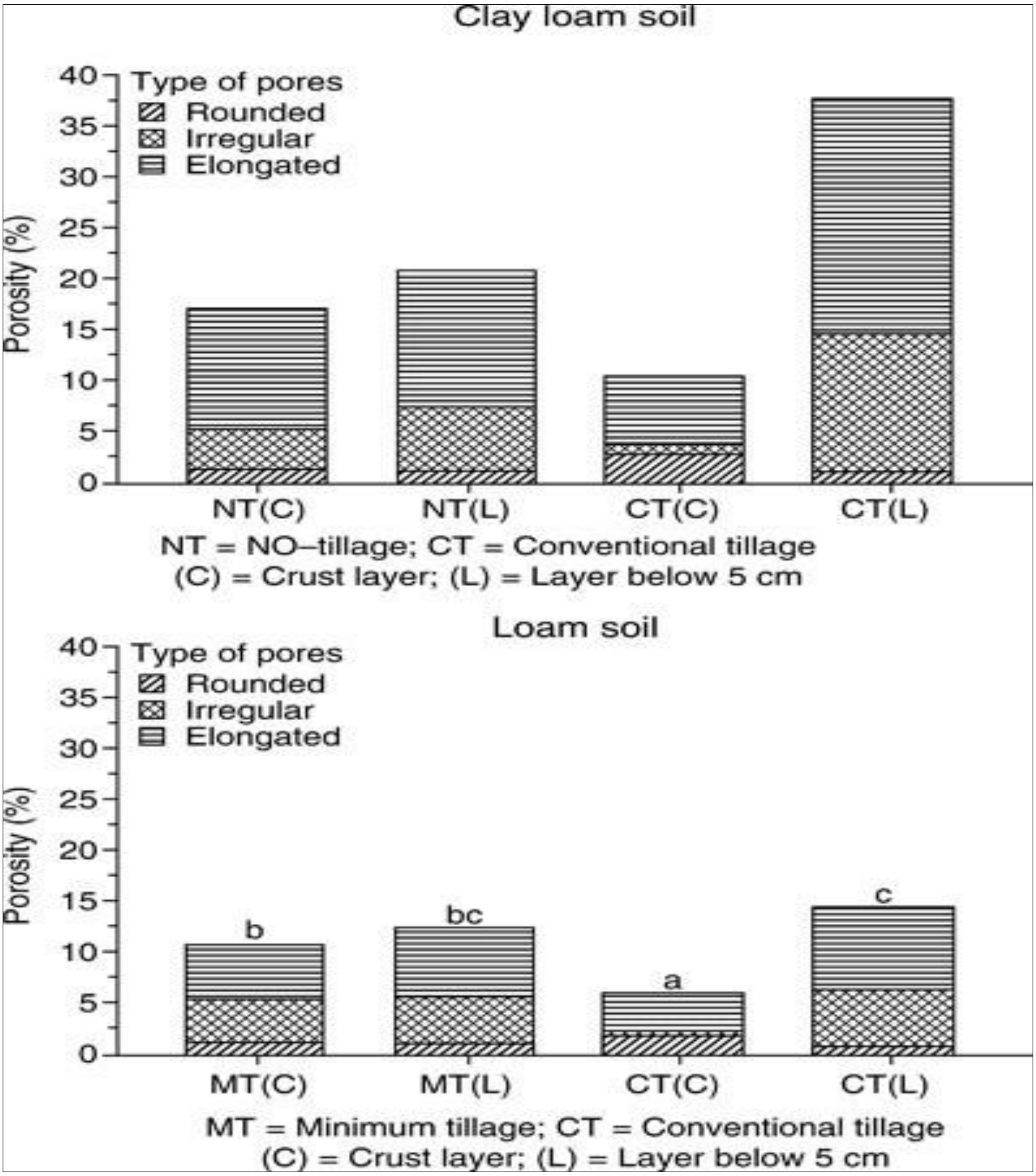
The crust occurrence was affected by the ratio of siltation in the soil surface; however, it was influenced by the amount and intensity of the rainfalls. The original reason for the crust is the high amount of dusts formed by multi-traffic cultivation on the surface. Dust forms to silty film after heavy rains and follows rapid drying that becomes a hard crust on the soil surface. The extent of the crusted area in three types of seasons (Fig. 16a). The tillage treatments had a significant effect on the crusted area in three types of seasons. The silt and then the crust formation became high on ploughed (P) and disk-tilled (D) treatments, mostly due to inadequate surface cover. The least crusted area detected on the surface of the tine tilled and direct-drilled treatments. It may be noted that the crusting occurred in the rows of the wide-row crops during the seasons and in the rows of winter cereals after wintering. According to Gallardo-Carrera *et al*. (2007) [25] a structural crust is formed from micro-particles produced by the breakdown of soil surface aggregates. They outlined that these particles are reorganized into a denser and more continuous structure by clogging pore systems in the soil. Badorreck *et al*. (2013) [3] emphasized that the reason for silting and crusting on the soil surface are negative processes and that both impede the movement of moisture, air and heat.

Mermut *et al*. (1992) [43] reported that soil tillage affected the structure and pore arrangement of the studied soil. The higher percentage of large complex pore area in the CT and RT systems compared to NT, occurred due to the tillage system employed (Fig.16b). This effect was more pronounced in the first year, where the % Comp. L pores was greater in CT and RT. Similarly, other authors have reported an increase in the percentage of large pores (>500 µm) in CT and RT systems due to soil tillage, and most of the total porosity was represented by few large-sized pores.




A

**Fig 16a:** Ratio of crusted area in three different seasons and at tillage treatments (L: loosening, P: ploughing, T, ST: tine tillage, D: disk tillage, DD: direct drilling);




B

**Fig 16b:** Effects of different tillage practices on surface crusting

Blanco-Canqui *et al*. (2006) [11] observed that soils without surface mulching of crop residue developed a 3 ± 0.7 cm thickness crust and 0.6 ± 0.5 cm width cracks during dry spell. Crust increases the surface bulk density due to consolidation of soil particles, and reduces hydraulic conductivity, which reduces air and water movement, adversely affects heat fluxes, promotes soil erosion and hampers seedling emergence (Baumhardt *et al*., 2004) [6].

Chen *et al*. (1980) [16] commented that steady state runoff indicated that seal resistance to infiltration reached equilibrium with erosive forces acting on the seal. However, the fresh soil surface needed time to surface sealing formation, so the soil surface with the antecedent soil crust was easy to reach the steady state. Neave & Rayburg (2007) [50] found that the initial crusts development was an important contributor to runoff. Under the same rainfall intensity and tillage treatment the runoff discharge rate measured in crusted soil were always significantly higher than those in un-crusted soil. The soil crusts reduced infiltration rate and increased runoff volume. In the case of an un-crusted surface, the soil was loose and soil permeability was high. Thus, runoff volume was low. Runoff rates in crusted soil were high.

**Aggregate Destruction**

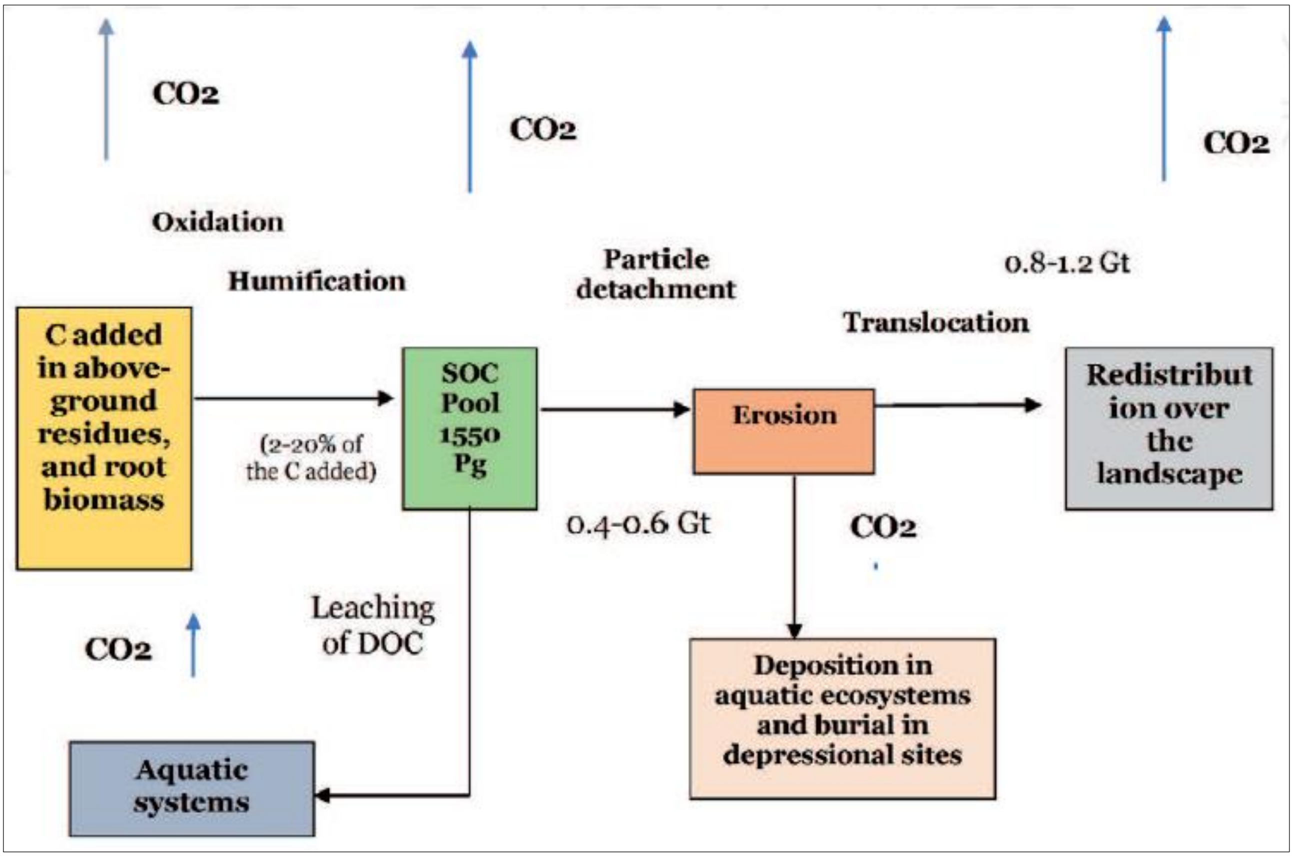
Naresh *et al*. (2015) [49] also observed that macro-aggregates are less stable than micro-aggregates and more susceptible to the disruptive forces of tillage, and > 2 mm size macro-aggregates showed the lowest percentage distribution across depths. This might be attributed to the mechanical disruption of macro-aggregates with frequent tillage operations and reduced aggregate stability. The proportion of the micro-aggregates in all treatments was small and they had the lowest OC content. However, micro-aggregates formation and the micro-aggregates within the macro-aggregates can play an important role in C storage and stabilization in the long term (Kumari *et al*., 2011) [36].

Song *et al*. (2016) [63] showed that the mean percentages of >2 mm macro-aggregates and water-stable macro-aggregates were increased by 12.77% and 43.21%, respectively, for the treatment group of rice-wheat under zero tillage compared to rice- wheat conventional tillage. In the 0–15 cm and 15–30 cm soil layers, the percentage of 2–0.25 mm water-stable macro-aggregates was increased by 25% and 40%, respectively, for the Rice-Wheat zero tillage treatment compared to the Rice-Wheat conventional tillage treatment. Thus, compared to conventional tillage, zero tillage can reduce the turnover of macro-aggregates in farmland and facilitate the enclosure of organic carbon in micro-aggregates, which enables micro-aggregates topreserve more physically protected organic carbon and form more macro-aggregates. Moreover, results showed that zero tillage resulted in higher organic carbon storage in soil aggregates in the 0–15cmsoil layer than conventional tillage primarily because conservation tillage reduces the damage to soil aggregates and increase the content and stability of associated organic carbon accordingly. The highest SOC concentration was found for the 0.25–0.106 mm micro-aggregates in the 0–15 cm and 15–30 cm soil layers.

**Soil Carbon Restoration**

Soil carbon stocks consist of soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC). Soils contain carbon in both organic and inorganic forms, i.e., oxidized carbon and non-oxidized carbon. The sum of the two forms of carbon is referred to as total carbon.

The global soil carbon, estimated to be 2500 Pg (1 Pg = $10^{15}$ g) which is nearly 3.3 times the atmospheric pool and 4.5 times the biotic pool size (760 Pg) [Lal, 2010] [38], whereas, the total amount of SOC and SIC stored worldwide are estimated to be 1550 Pg C 950 Pg in the top 1 m of soils in a dynamic equilibrium of gains and losses (Fig. 17a). Pools of C in rocks are inert and changes over the millions of years of time while pools of C in the terrestrial biosphere, atmosphere, and oceans constitute active pools that are vulnerable to anthropogenic activities. Exchange of C among these pools over a short and long period of time is known as the Global Carbon Cycle (GCC). The Global Carbon Cycle has been changing due to the increase in atmospheric C pool and decrease in biosphere and soil C pool consequently resulting in global warming. Conversion of natural to agricultural ecosystems causes 60% depletion of the SOC pool of temperate regions and 75% or more in cultivated soils of the tropics, and further creates severe soil degradation when the output of C exceeds the input.



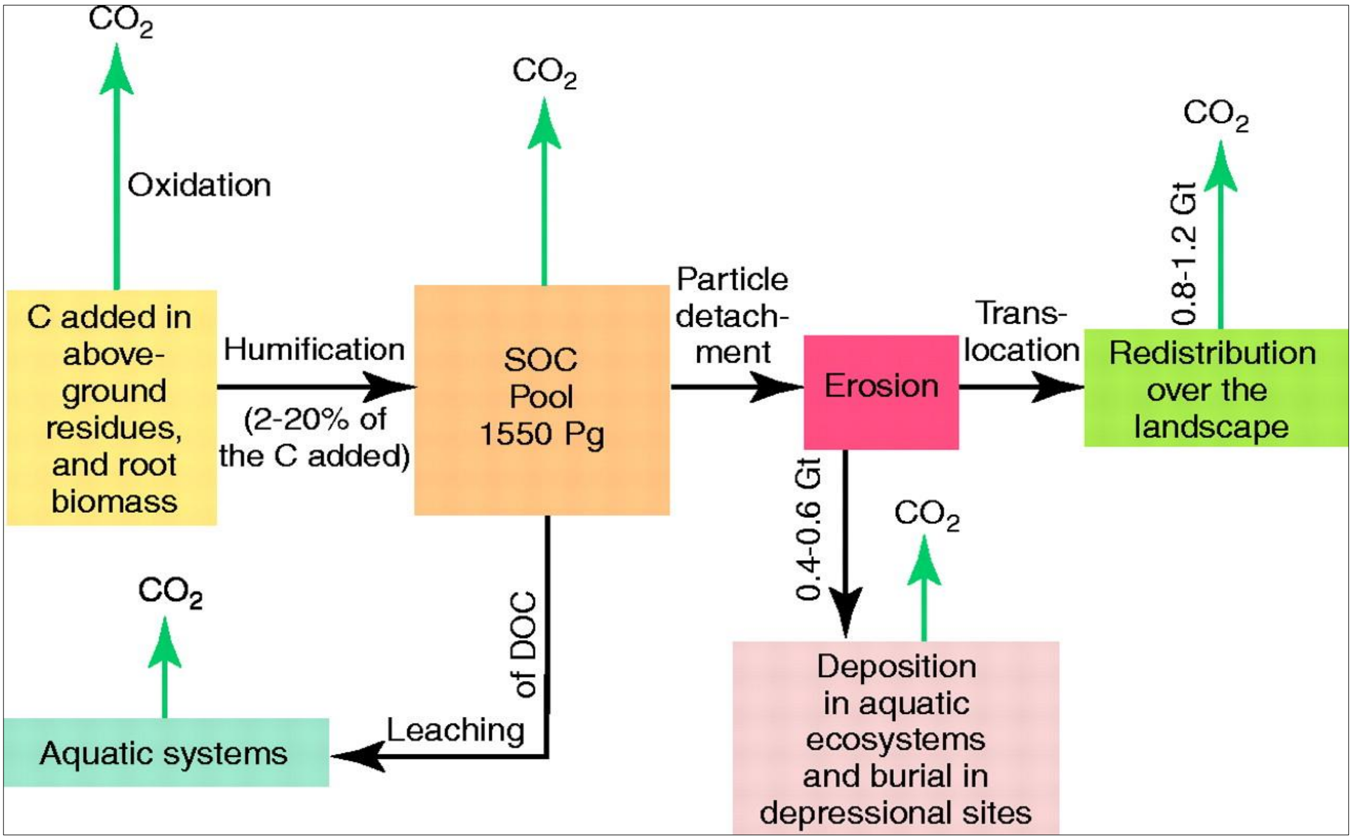



**Fig 17a:** Soil organic carbon dynamic equilibrium (Lal, 2004) [37].

Piccoli *et al*. (2016) [56] observed that at lower soil depth (15–30 cm), SOC stock was higher under conventional agriculture compared to CA. Further, Piccoli *et al*. (2016) [56] observed that SOC stock was similar up to 50 cm soil depth in both the contrasting production systems while comparing CA and non-CA systems and CA systems had no apparent edge over conventional agriculture. Only redistribution of carbon occurs in different soil layers, higher SOC stock obtained at upper surface layer followed by lower SOC stock in deeper soil layer in CA based systems over conventional system. Earlier Luo *et al*. (2010) [40] reported that improvement in net SOC stock was visible under ZT only in upper surface layer (0–10 cm), but in lower depth (20–40 cm) net depletion of SOC stock by 3.30 ± 1.61 Mg ha$^{-1}$ over conventional tillage was observed.

Yang *et al*. (2019) reported that the average annual rate of C storage in soils, as quantified by ΔC/Δt (units of Mg of C ha$^{-1}$ y$^{-1}$), was greater in the second period (13–22 years) than in the first period (1–13 years; Fig. 18a, b). These accelerating rates of soil C sequestration were apparent for both the 0–20 cm depth soil profile (Fig. 17a) and the full 0–60 cm profile (Fig. 18b). On average over all diversities, annual storage rates for the second period were 88% and 253% greater than for the first period for the 0–60 cm and the 0–20 cm profiles, respectively. In addition, across the 5 times that the top 20 cm of soil was sampled for C, the time dynamics of soil C concentration at each level of plant diversity was best fit by quadratic equations curving upward (Fig. 18c), further demonstrating that rates of C sequestration accelerated through time.

Rates of soil C sequestration were greater at higher plant diversity (Fig. 18). Annual storage rates for the first period (1–13 years) for the 0–60 cm soil depth profile were 0.08 (±0.07), 0.27 (±0.08), 0.38 (±0.09), 0.29 (±0.10), to 0.54 (±0.08) Mg-C ha$^{-1}$ y$^{-1}$ in the 1-, 2-, 4-, 8-, and 16-species treatments, respectively (Fig. 18b). For the second period (13–22 years), they increased to 0.42 (±0.10), 0.47 (±0.14), 0.60 (±0.12), 0.73 (±0.11), and 0.71 (±0.11) Mg-C ha$^{-1}$ y$^{-1}$, respectively (Fig. 18b). For the full 22-year duration of the experiment, when compared to means across all species in monocultures, higher plant biodiversity led to 60%, 115%, 115%, and 178% greater soil C storage in the 2- to 16-species plots, respectively, for the 0–60 cm profile. When initial soil C levels are considered, annual soil C proportional growth rates (dC/dt * 1/C) were 0.6%, 1.0%, 1.3%, 1.3%, and 1.6% y$^{-1}$.

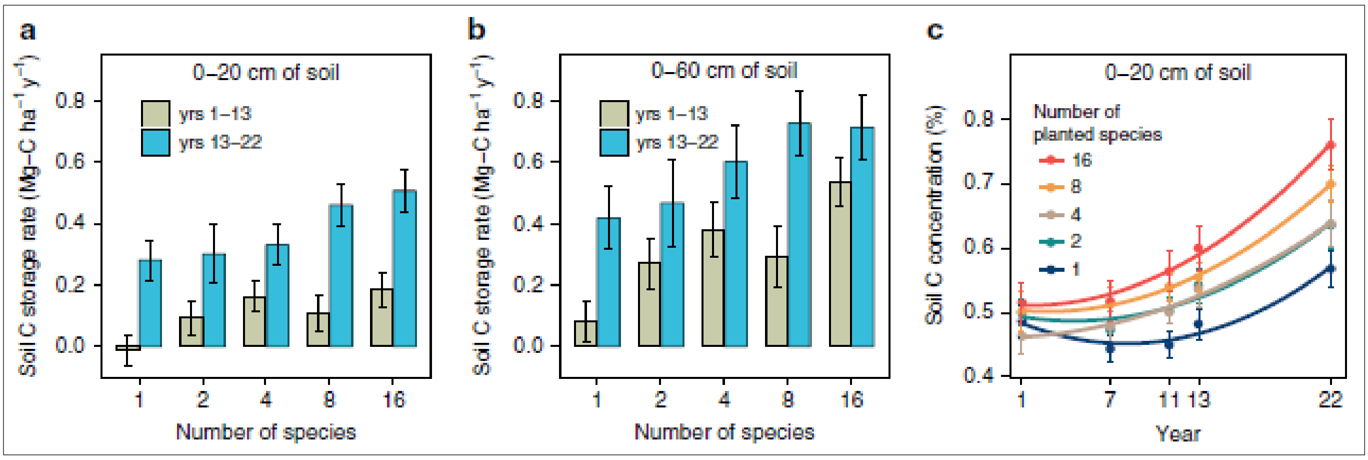
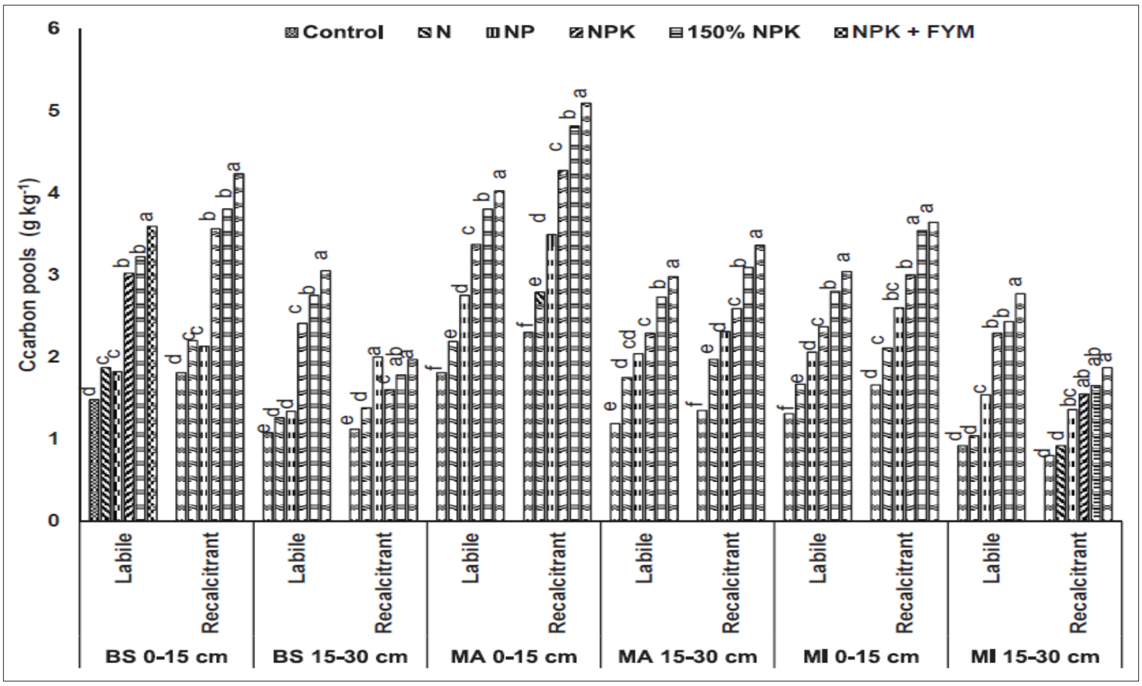


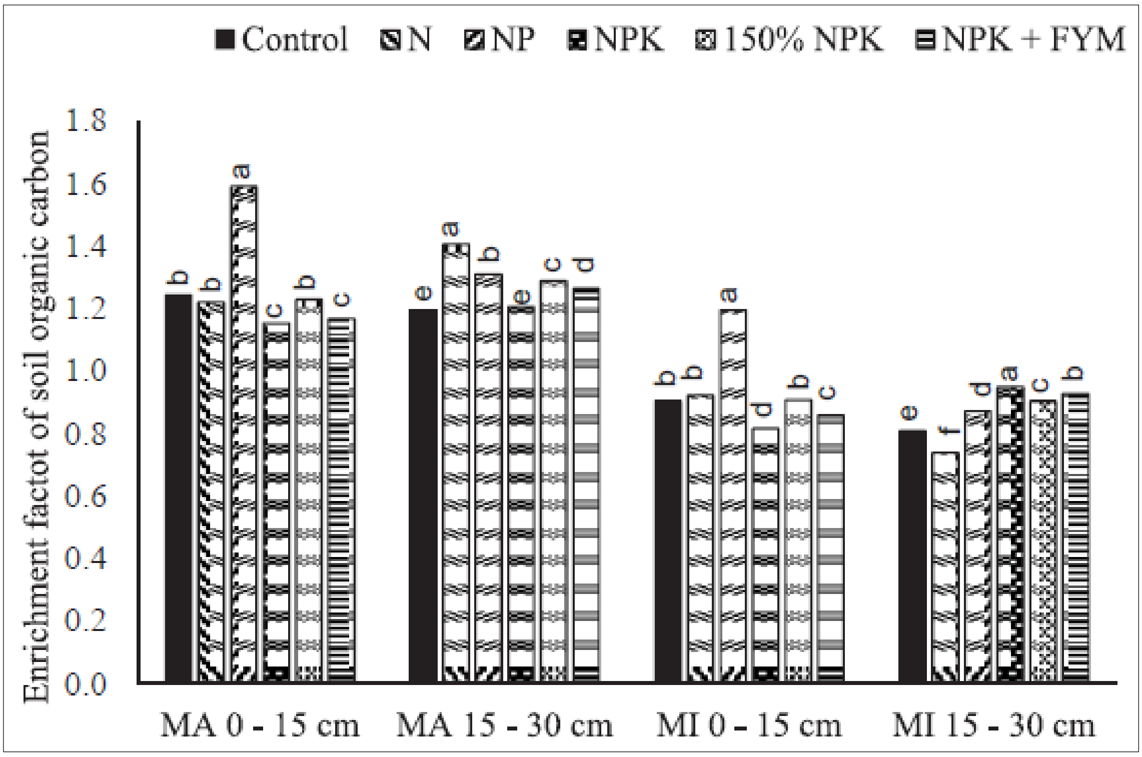

**Fig 18:** Change in root C over 24 years a) Change in root C in upper 30 cm of soil under different experimentally imposed levels of plant species diversity b) Total root C storage after 24 years of growth in upper 60 cm of soil.

Chen *et al*. (2011) reported that in C-S system, the NT treatment resulted in a distinct SOC stratification with significantly greater SOC in surface soil (0-5 cm, 19.6 g $kg^{-1}$) and lower SOC in subsurface soil (20-30 cm, 13.9 g $kg^{-1}$) relative to MP (17.0 g $kg^{-1}$ at 0-5 cm and 15.1 g $kg^{-1}$ at 20-30 cm). In C-C system, NT significantly increased SOC in surface soil (0-5 cm, 19.5 g $kg^{-1}$) by 11.5% but had the similar SOC in subsurface soil (20-30 cm, 15.4 g $kg^{-1}$) relative to MP (17.1 g $kg^{-1}$ at 0-5 cm and 15.3 g $kg^{-1}$ at 20-30 cm). The SOC stocks based on equivalent soil mass (1296 Mg $ha^{-1}$, approx. 0-10 cm depth in NT) were 3.41% and 3.40% higher in NT than in MP soil for C-S and C-C treatments, respectively. However, no significant difference in SOC stock was found when the contrast was based on the three equivalent mass of 1296, 2609 (approx. 0-20 cm depth in NT), and 3932 Mg $ha^{-1}$. On equivalent soil depth basis, the SOC stock showed a significant SOC enrichment of 7.70% under NT compared with MP in 0-10 cm in C-S system, while there was no significant difference between NT and MP in 0-20 and 0-30 cm depths in two rotation systems. Accordingly, the annual fall mould-board plow, spring disking and field cultivation resulted in the uniform SOC distribution in the top 20 cm of MP. Soil organic carbon contents were similar at 0-5 cm under NT in C-C and C-S systems, but the former was consistently higher than the latter at 5-30 cm by 2.8-10.6% under NT and at 0-30 cm by 0.8-1.6% under MP, respectively. This was likely due to significant larger residue remained on the soil surface each year in C-C than in C-S system. Ghosh *et al*. (2018) [27] observed that in soil surface, plots with NPK+FYM had significantly higher labile C within macro-aggregates compared with NPK and control plots (Fig.19a). However, labile C concentrations within macro-aggregates of 150% NPK and NPK+FYM were similar. Labile: recalcitrant C in macro-aggregates of NPK+FYM was 1.38:1. There was a gradual decrease in labile C within macro-aggregates in NP, N and control plots. Similarly, recalcitrant C closely followed the trend of labile C within macro-aggregates, except under NP plots, which had significantly less labile C within macro-aggregates than all other plots. However, macro-aggregates of NPK+FYM had 19% and 46% higher recalcitrant C than NPK and NP plots. Like labile C within macro-aggregates, 150% NPK and NPK+FYM plots had similar recalcitrant C pools. Similar trend of C concentration was observed within micro-aggregates, as was observed within macro-aggregates. Moreover, labile: recalcitrant C ratios within macro-aggregates were similar for all treatments. When expressed on a total soil basis, macro-aggregates accounted larger part of total SOC in surface and subsurface soil layers. Interestingly, macro-aggregates of NP plots in soil surface had 1.36 and 1.38 times greater SOC enrichment than NPK+FYM and NPK treated plots. Whereas, macro-aggregates from N plots had 1.12 and 1.18 times greater C enrichment than NPK+FYM and NPK plots, respectively, in sub-surface soil. Carbon enrichment factor of soil micro-aggregates from all plots were<1, indicating net C depletion (Fig. 19b). Low labile: recalcitrant C ratios in surface than subsurface soil were due to higher C accumulation in surface soil. Abrupt decrease in labile: recalcitrant C ratios in bulk soils under NP indicated C occlusion within aggregates.




A

**Fig 19 a:** Labile and recalcitrant carbon pools in bulk soils and aggregates as affected by long-term fertilization in the 0–15 and 15–30 cm soil layers under a wheat based cropping system in an Inceptisol




B

**Fig 19b:** Enrichment factor of soil organic C (SOC) in aggregates as affected by 44 years of fertilization under wheat based cropping system in an Inceptisol. MA: Macro-aggregates, MI: Micro-aggregates, MA 0–15 cm: Macro-aggregates of 0–15 cm soil depth, and so on.

Memon *et al*. (2018) [44] reported that the average SOM content in 2016–2017 significantly increased by 3.08% to 17.07% under all residue-incorporated treatments. Plots without straw incorporation showed a decreased SOM content (1.69–3.97%) compared with pre-treatment values under reduced and conventional tillage methods. However, the SOM content was higher (25.12, 24.06, 23.83, 23.80, 22.41, and 22.12 g/kg) in the $RTsi_{60}$, $RTsi_{100}$, $CTsi_{100}$, $CTsi_{60}$, $RTsi_{30}$, and $CTsi_{30}$ treatments, respectively, compared to RTns (21.10 g/kg) and CTns (20.61 g/kg) [Fig.20]. The SOM difference between $CTsi_{60}$ and $CTsi_{100}$ was non- significant in the 0–30 cm soil profile depth. Moreover, SOM in the topsoil (0–10 cm) was higher in $RTsi_{60}$ (26.31 g/kg) and CTsi60 (24.51 g/kg) under RT and CT, respectively. Compared with the no straw incorporation treatment level in RTns, the SCS with the $RTsi_{60}$, $RTsi_{100}$, and $RTsi_{30}$ treatments increased by 14.20%, 8.82%, and 4.60%, respectively, under RT tillage methods. In the case of CT practice treatments, the SCS under $CTsi_{60}$, $CTsi_{100}$, and $CTsi_{30}$ were 9.81%, 8.99% and 4.51%, respectively, compared with the CTns treatment associated to no residue incorporation.

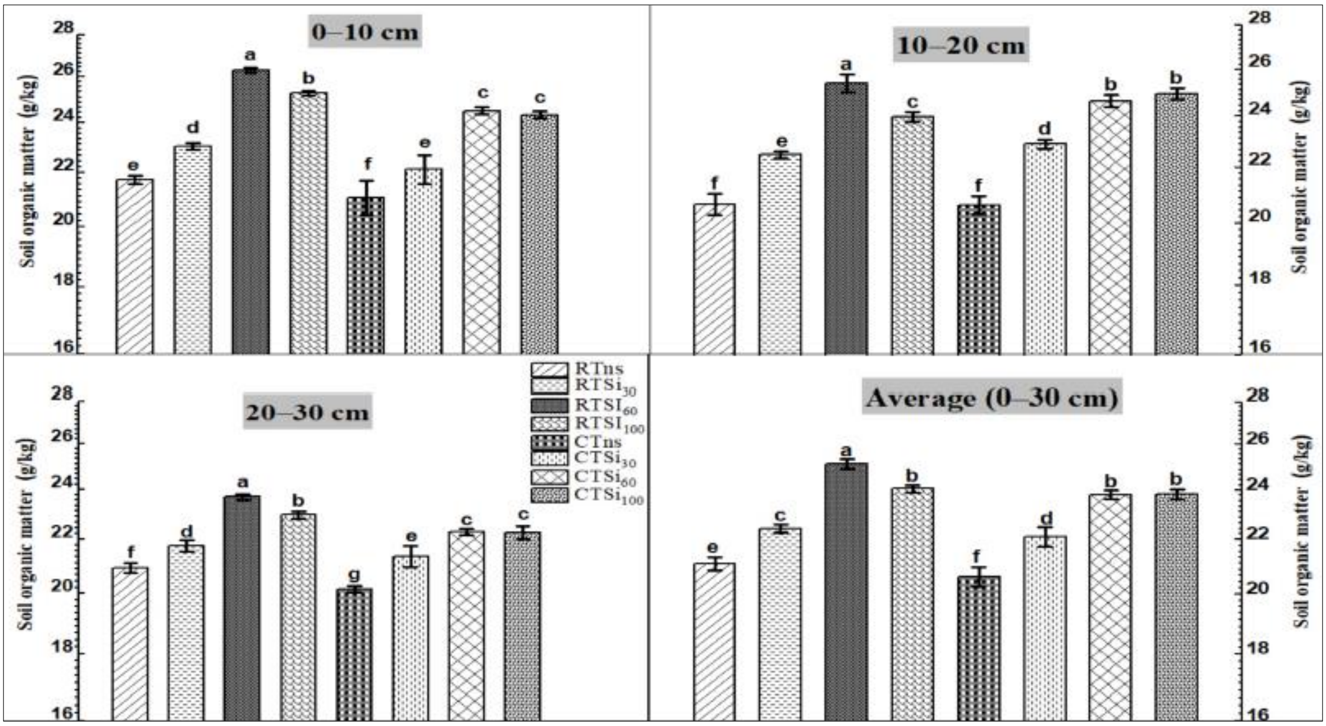



**Fig 20:** Depth-wise distribution of mean soil organic matter (SOM) under each treatment. Note: RTns: RT without straw incorporation, RTsi30: RT with straw incorporation (SI) at 30%, RTsi60: RT with SI at 60%, RTsi100: RT with SI at 100%, CTns: CT without straw incorporation, CTsi30: CT with SI at 30%, CTsi60: CT with SI at 60%, and CTsi100: CT with SI at 100%.

## Conclusions

In any crop production system, optimum soil physical health is very important for efficient utilization of nutrients. Water present in soil profile is needed by plant roots and also provides physical support to plants. In conventional tillage system, continuous use of farm machineries over the year develops a sub-surface hardpan, which hampers water movement and root penetration, resulting in decline in crop performance. Moreover, continuous use of machineries also pulverizes the upper surface making the soil more prone to erosion. In conservation agriculture, successive addition of crop residues over the years increases soil organic matter. In the beginning, the increase in organic matter is confined to the upper soil layer, but over time, it extends to deeper soil layers also. It plays an important role in improving various soil–water characteristics, and stabilizing the soil temperature.

The weight of agricultural vehicles has increased tremendously since the last sixty years. Wheel loads of combine harvesters have increased from about 1.5 Mg in 1960 to 9 Mg today, and wheel loads of tractors have increased from approximately 1 Mg in 1955 to more than 4 Mg today. The effect of the increase in weight of agricultural vehicles on soil stress and soil bulk density, and estimated the consequences of the increase in compaction levels for root growth and soil hydraulic properties. The increase in machinery weight has resulted in an increase in subsoil compaction levels. This suggests that soil compaction is one of the causes of the yield stagnation observed for major crops. Furthermore, we show that the increase in compaction levels has decreased saturated hydraulic conductivity and the water storage capacity in arable sub-soils.

Tillage had almost uniform effect on SWC and SPR due to the continuous conservation thoughtfulness under peculiar weather conditions. The surplus water remaining from the former season will be more important in the future and the studies should focus their attention to apply water conservation solutions. SC and CA, considering the soil surface exposure to the weather factors, were affected by tillage treatments. The total impact of CA system on soil physical health varies location-to-location and is dependent on soil inherent properties, site limitations, period of time under CA system, per cent soil disturbance, nature of the crop, intensity of the crop rotation, type of cover crops, per cent of total surface area covered by crop residues, soil moisture regime, soil temperature, and other prevailing climatic factors of a particular region. Hence, CA is a site-specific technology and all three components of CA, *viz*. minimum or no-tillage, crop residue and crop rotation significantly impact soil physical health. Thus, systematic conservation agriculture is a panacea to cure the soil of its many physical health disorders on a long term basis.

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