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Strategic tillage may sustain the benefits of long-term no-till in a Vertisol under Mediterranean climate

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ABSTRACT

Long-term no-till or reduced tillage may decline functioning ability of soils due to surface/subsurface compaction and/or stratification of plant nutrients. A long-term (ten years) field experiment was established in 2006 in the Çukurova region of Turkey to evaluate the impact of tillage on the physical properties of a soil under a Mediterranean climate. The tillage systems investigated included two conventional (CT-1 and CT-2), three reduced (RT-1, RT-2 and RT-3) and two no-till (NT and ST), including strategic/occasional tillage. Nine-year old undisturbed no-till plots were divided into two categories and half of these plots were plowed by a moldboard plow in November 2015, and this practice was defined as strategic tillage (ST), while remaining half of the plots left undisturbed. Soil samples were collected from disturbed and undisturbed plots of NT as well as plots under other tillage systems from three soil depths (i.e., 0–10, 10–20 and 20–30 cm) in November 2016. The crop rotation at the experimental areas was winter wheat (*Triticum aestivum* L.), soybean (*Glycine max.* L.) – grain maize (*Zea mays* L.) – winter wheat. Soil samples were analyzed for aggregate stability (AS), mean weight diameter (MWD), bulk density (BD), water filled pore space (WFPS), water content at field capacity (FC), permanent wilting point (PWP), available water content (PAW), micropores (MiP), macropores (MaP), total porosity (TP), and penetration resistance (PR). The ST decreased MWD of surface soil compared to NT by 7.2%, while MWD under ST was higher than NT by 78.0% and 103.6% for 10–20 and 20–30 cm depths, respectively. The NT and RT resulted higher BD and PR, and lower MaP and TP than CT and ST in all three depths, though the values were generally not limiting for crop growth. The ST significantly ($P < 0.01$) decreased BD and PR within 30 cm of soil surface. However, water content at FC, PWP and also PAW in 0–10 and 10–20 cm depths were significantly reduced with ST compared to NT. The ST significantly ($P < 0.01$) increased the MaP and TP compared to NT which favors better aeration and water movement. The mean WFPS under NT, RT-2 and RT-3 systems in 0–10 cm and with all tillage systems (except ST in 10–20 cm) in subsurface layers were higher than 60%, which is considered a threshold for nitrogen losses as N_2O fluxes. Implementation of ST into conservational practices under Mediterranean climate could be a viable management option to overcome some of the disadvantages of long-term conservation tillage and thereby to improve physical soil conditions for crop growth, air and water movement.

1. Introduction

Conservation tillage systems (no-till or zero tillage and reduced tillage) have been increasingly adopted worldwide since last several decades due to their positive impacts on soil structure, soil organic carbon concentration, erosion, nutrient cycling, productivity and biodiversity (Lal, 2015). Despite the worldwide recognition of conservation tillage practices as the best sustainable management alternative to conventional practices (Verhulst et al., 2010), conventional tillage with moldboard plough, subsequent disking and floating for seedbed preparation and weed management is commonly practiced by farmers in Turkey (Celik et al., 2012). Intensive conventional tillage practices are the main cause of soil organic matter depletion and structural degradation in Mediterranean region (Martín-Lammerding

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et al., 2013), which threaten the sustainability of agricultural production by reducing fertility and productivity.

Long-term no-till (NT) or reduced tillage (RT) minimize negative effects of intensive conventional tillage practices (Stavi et al., 2011), and increase organic matter, improve aggregate stability and enhance soil fertility (Pareja-Sánchez et al., 2017). However, due to intense machinery traffic, NT or RT systems lead to excessive compaction of surface layers in long run with undesirable impacts on air, water and solute transport and penetration of roots (Bogunovic et al., 2018; Nunes et al., 2015). Water retention of soils and water use efficiency of crops are also impaired (Hamza and Anderson, 2005), and eventually crop yield is reduced during dry years (Bogunovic et al., 2018; Lopez-Garrido et al., 2014). In addition to compaction, increasing herbicide-resistant weed populations, difficulties in controlling soil and stubble-borne diseases and accumulation of nutrients and organic matter in soil surface are the major concerns for long-term sustainability of conservative tillage systems (Dang et al., 2015).

Compacted soil layers caused by continuous implementation of conservation tillage should be removed to sustain the benefits of conservative tillage systems. Therefore, in some cases, deep tillage, known as strategic tillage (ST), one-time tillage or occasional tillage of long term NT fields has been considered a potential management option, which helps removing compaction, dispersing the nutrients accumulated near soil surface and controlling weeds (Norton et al., 2014; Stavi et al., 2011). However, the reports on the effects of ST on physical properties of soils in NT and RT systems are contradictory. The ST may have non-significant effect on aggregate stability and water content of silty loam and silty clay loam soils (Wortmann et al., 2010), negative effects on soil aggregation of coarse and fine loamy soils (Grandy and Robertson, 2006). It also exerts negative effects on resistance to water, sediment and nutrient losses after heavy rainfall (Melland et al., 2016), little and/or short-term positive effect on soil functional physical properties (Reichert et al., 2017), and positive effect on soil compaction (Kuhwald et al., 2017). Dang et al. (2018) investigated the short and long-term impacts of ST on crop productivity, soil and environmental health in a range of soil types and found contradictory results for different soil types. They reported no influence in Veritsols, though Sodosols and Dermasols were negatively affected, and became vulnerable to runoff and associated sediment and nutrient losses during intense rainfall.

The contrasting reports and mixed effects of ST on soil physical properties mostly arise due to differences in soil types, duration of NT management, equipment's used in tillage operations, frequency of occasional tillage, tillage depth, soil sampling depths, climate and other environmental factors (Blanco-Canqui et al., 2017; Crawford et al., 2015; Dang et al., 2018; Reichert et al., 2017; Zhang et al., 2017). Tillage using a chisel plow is defined subsoiling, in which compacted layer is broken-up without disturbing the soil structure. In contrast to chisel plow, moldboard plow works as deep ploughing and destroys compacted layer, while bringing subsurface soil to surface (Sun et al., 2018). Although moldboard and chisel plough are the commonly used equipment's in ST operations, the depths and frequency of tillage are not the same in different studies. For example, Stavi et al. (2011) reported the use of disk plow every 3–4 years, while Wortmann et al. (2008) used moldboard plow to 20 cm followed by tandem disk. Similarly, moldboard plow to 30 cm and disc harrowing to 15 cm was used in the studies conducted by Lopez-Garrido et al. (2011). Likewise, Kuhwald et al. (2017) used moldboard plow to 30 cm. Liu et al. (2016) performed tillage with chisel plow to 10 cm and offset disc tillage to 10 cm, whereas chisel plow to 25–30 cm and 3-disk plow to 20 cm was used by Reichert et al. (2017).

Increasing population pressure and decreasing land area per person in Turkey inevitably lead agricultural intensification in different regions of the country, especially Çukurova region. Burning of crop residues prior to conventional tillage is a very common practice in Turkey (Celik et al., 2011), and unfortunately increased with intensive crop rotation in many regions of the country (Korucu et al., 2009). Crop residues are usually burnt to enable tillage and seeding machinery to work effectively and complete the planting of next crops included in the rotation. However, no studies have been conducted yet to assess the long-term impacts of these practices on soil physical properties in the country.

Plenty of work has been done to study the effects of ST on soil physical properties of no-tilled soils around the world. However, there is no comprehensive study investigating the effects of ST on physical properties of no-tilled soil in a long-term experiment in Turkey. Therefore, we conducted this study to investigate the effects of different tillage systems on physical properties of a Vertisol.

We hypothesized that strategic tillage could eliminate deterioration of soil physical properties resulting from intensive crop production under long-term RT or NT in Vertisols. The objective of this ten-year old tillage experiment was to investigate how aggregate stability, mean weight diameter, bulk density, penetration resistance, water filled pore space, porosity and soil water content responded to long-term tillage practices, in a Vertisol. The ultimate objective was to evaluate the overall effects of ST on sustainability of long-term NT management by analyzing the alteration of functional soils physical properties.

2. Material and methods

2.1. Study area, experimental design and tillage practices

The long-term tillage and crop rotation experiment was performed on agricultural fields of Agricultural Experimental Station, Çukurova University, Adana situated in southern Turkey (37°00′54″ N, 35°21′27″ E; 32m altitude), with slope of less than 1%. The soils had a clay texture (50% clay, 32% silt and 18% sand), formed over old terraces of Seyhan River, and classified as Haplic Vertisol in World Reference Base (IUSS Working Group, 2015) and fine, smectitic, active, mesic Typic Haploxererts in Soil Taxonomy (Soil Survey Staff, 1999). The mean pH, electrical conductivity and calcium carbonate of the experimental soil are 7.82, 0.15 dS m^{-1}, and 244 g kg^{-1}, respectively at 0–30 cm depth (Celik et al., 2011) (Table 1). The climate of the study area is Mediterranean with a mean annual temperature 19.3 °C and 642 mm precipitation, 72% of which is received during winter and spring (from November to May) and annual potential evapotranspiration is 1577 mm.

The experiment was laid out according to randomized complete block design and had 3 replications for each treatment/tillage system. The tillage practices include; two conventional (CT-1 and CT-2), three reduced (RT-1, RT-2 and RT-3) and two no-till (NT and ST) tillage systems (Table 2). The tillage plots were of 12 × 40 m (480 m^2) with a 4 m buffer zone between each plot. The experiment was initiated in summer, 2006 with six tillage treatments, excluding ST. The soils in the experimental site had been under continuous CT system, and cultivated by moldboard plow for wheat, corn and soybean production until the

Table 1
Some characteristics of Arik soil at the beginning (in 2006) of experiment.

Soil property	Soil depth (cm)		
	0–10	10–20	20–30
Sand (50–2000 μm), (g kg^{-1})	175	177	172
Silt (2–50 μm), (g kg^{-1})	333	324	324
Clay (< 2 μm), (g kg^{-1})	492	499	504
Texture	Clay	Clay	Clay
pH (H_2O, 1:2.5)	7.86	7.82	7.80
Electrical conductivity (1:5) (dS m^{-1})	0.13	0.16	0.16
$CaCO_3$ (g kg^{-1})	242	247	244
Total salt (g kg^{-1})	0.08	0.10	0.10
Total organic carbon (g kg^{-1})	8.95	8.80	8.52
Bulk density (Mg m^{-3})	1.23	1.33	1.38

Table 2
Summary of tillage methods and equipment used in the experiment.

Tillage Methods	Soil Tillage for Winter Wheat	Soil Tillage for Second Crop Maize and Soybean
Conventional tillage with stubbles (CT-1)	● Stover chopping of second crop ● Moldboard plow ● Disc harrow (2 passes) ● Float (2 passes) ● Drill	● Stubble chopping of wheat ● Heavy tandem disc harrow ● Disc harrow (2 passes) ● Float (2 passes) ● Planter
Conventional tillage with stubbles burned (CT-2)	● Stover burning of second crop ● Moldboard plow ● Disc harrow (2 passes) ● Float (2 passes) ● Drill	● Stubble burning of wheat ● Chisel plow ● Disc harrow (2 passes) ● Float (2 passes) ● Planter
Heavy disc harrow reduced tillage (RT-1)	● Stover chopping of second crop ● Heavy tandem disc harrow (2 passes) ● Float (2 passes) ● Drill	● Stubble chopping of wheat ● Rotary tiller ● Float (2 passes) ● Planter
Rototiller reduced tillage (RT-2)	● Stover chopping of second crop ● Rotary tiller ● Float (2 passes) ● Drill	● Stubble chopping of wheat ● Rotary tiller ● Float (2 passes) ● Planter
Heavy disc harrow zero soil tillage (RT-3)	● Stover chopping of second crop ● Heavy tandem disc harrow ● Float (2 passes) ● Drill	● Stubble chopping of wheat ● Herbicide treatment ● No-till planter
No-till or zero tillage (NT)	● Stover chopping of second crop ● Herbicide treatment ● No-till drill	● Stubble chopping of wheat ● Herbicide treatment ● No-till planter
Strategic tillage (ST)[a]	● Stover chopping of second crop ● Herbicide treatment ● No-till drill	● Stubble chopping of wheat ● Herbicide treatment ● No-till planter

[a] This treatment continued as NT from 2006 until November 2015. Afterwards, it was tilled with moldboard plow only once in November 2015 and then, the same operations as in NT have been implemented.

establishment of the experiment. In November 2015, half of each no-till (NT) plot (240 m^2) was plowed by moldboard plow to a depth of 30–33, which was termed as ST. The plowed NT plots were disked to break large clods and level the soil surface. In all tillage methods, the harvest residues on soil surface were chopped prior to tillage operations except CT-2.

The crop rotation, winter wheat (*Triticum aestivum* L.) – soybean (*Glycine max.* L.) or grain maize (*Zea mays* L.) – winter wheat is typical for the region, which was followed in all treatments. Corn and soybean were rotated in alternate years. The weeds were controlled by non-selective herbicide (500 g ha^{-1} Glyphosate) two weeks prior to sowing in RT-3, NT and ST treatments. Fertilizer application rate was same regardless of tillage treatments: 170–180 kg N ha^{-1} and 55–60 kg P_2O_5 ha^{-1} for wheat, 250–265 kg N ha^{-1} and 60–65 kg P_2O_5 ha^{-1} for corn and 120–130 kg N ha^{-1} and 40–45 kg P_2O_5 ha^{-1} for soybean based on soil analysis. The wheat was sown in the first week of November at seeding rate of 240 kg ha^{-1} and harvested in the first week of June. Half of N fertilizer for wheat was applied at planting and the rest was top-dressed in spring. Commercially available corn and soybean cultivars at seeding rates of 8.4 and 23.6 plants per m^2 were planted in the third week of June and harvested in the second week of October. Corn and soybean were sprinkler-irrigated every 13-day during the growing period, and no irrigation was applied to the wheat. This paper contains winter wheat and soybean yields. A plot harvester machine with a 1.35 m working distance was used to harvest the crops. For winter wheat, two 12 m long (1.35 m × 12 m = 16.2 m^2 × 2 = 32.4 m^2) lines (12 is the width of a plot) were harvested in each plot. For soybean, two middle soybean rows (40 m) from each plot were harvested. Yields of each crop have been presented as kg/ha.

2.2. Soil sampling and analyses

Composite disturbed and undisturbed soil samples were collected at three locations within each tillage plot from 0–10 cm, 10–20 cm and 20–30 cm depths after soybean harvesting in November 2016. Current wheel tracks were avoided during soil samplings. Undisturbed soil samples were taken using a 5.0 cm high and 5.1 cm internal diameter cylinder, to determine soil bulk density (BD), field capacity (FC), total porosity (TP), macroporosity (MaP), and microporosity (MiP). Permanent wilting point (PWP), aggregate stability (AS), mean weight diameter (MWD) and organic matter (OM) content were analyzed in disturbed soil samples.

For aggregate stability analysis, the disturbed soil samples were passed through 8 mm sieve and placed in plastic bags. A set of sieves (4.0, 2.0, 1.0 and 0.5 mm diameters) was used in the wet sieving method (Kemper and Rosenau, 1986). Fifty-gram soil sample was transferred to the set of sieves, fixed to an oscillation unit and gently moistened. Once the soil was moistened, the set was sieved in distilled water (30 oscillations per minute) for 10 min. The portion remaining on each sieve was dried at 105 °C for 24 h, and then sands and aggregates were separated (Gee and Bauder, 1986). The water stable aggregates (AS) were calculated as follows:

$$AS = \frac{(M_{(a+s)} - M_s)}{(M_t - M_s)} \times 100$$

where $M_{(a+s)}$ is mass of stable aggregates and sands (g); M_s is the mass of sand fraction alone (g) and M_t is total mass of the sieved soil (g).

Mean weight diameter (MWD) was calculated as follows:

$$MWD = \sum_{i=1}^{n} X_i W_i$$

where X_i is mean diameter of each size fraction (mm) and W_i is proportion of the total sample mass in the corresponding size fraction after deducting the mass of stones.

The undisturbed soil samples of 100 cm^3 cores were capillary saturated to determine the saturated weight for TP. The validity of TP was checked using dry bulk density and mean particle density (2.65 g cm^{-3}) values. Microporosity ($<$ 4.5 μm equivalent pore radius) was determined based on volumetric water content, at field capacity ($-$33 kPa) using a pressure membrane apparatus. Macroporosity ($>$ 4.5 μm equivalent pore radius) was calculated as difference between total porosity and microporosity (Danielson and Sutherland, 1986).

The undisturbed soil samples were capillary saturated and equilibrated to FC ($-$1/3 bar) matric potentials in a pressure plate (Klute, 1986). Soil moisture at $-$15 bar matric potential (PWP) was determined using disturbed soil samples (Klute, 1986). Plant available water (PAW) content was calculated as difference between volumetric water content at FC and PWP. The BD was obtained using the core method defined by Blake and Hartge (1986). The OM content was determined using the Walkley-Black Method (Nelson and Sommers, 1996).

The water filled pore space (WFPS), an indicator used for relative potential of aerobic and anaerobic microbial activity in soil (Linn and Doran, 1984) was determined by dividing volumetric water content of soil by total soil porosity (Franzluebbers, 1999). The WFPS was calculated from the equation:

$$WFPS = (SWC \times BD)/TP$$

where, SWC is soil water content (g g^{-1}), BD is the bulk density (Mg m^{-}

^{3}), and TP is total porosity.

Penetration resistance (PR) was determined by a hand pushed electronic cone (Eijkelkamp Penetrologger 06.15.SA) following standard procedures of American Society of Agricultural Engineers (ASAE, 1994), using a cone with 1 cm^2 base area, 60° included angle and 80 cm driving shaft; readings were recorded at 10 mm intervals. We measured 18 sampling points per treatment at 0–30 cm, and the data were separated to 0–10 cm, 10–20 cm and 20–30 cm depth intervals.

2.3. Statistical analysis

The distribution of data was controlled for normality using Kolmogorov–Smirnov test. The data were log-transformed before analyses, in case of nonnormal distribution. Log-transformation was successfully normalized the nonnormal distribution of the data. Tillage systems were treated as main factor, while soil depth was taken as subfactor. The significance in the dataset was assessed by analysis of variance (ANOVA) test. Duncan's multiple range test ($P < 0.05$) was used to differentiate the means in case ANOVA denoted significant differences. The significance of changes in soil properties with depth for each of tillage system was revealed by a separate ANOVA test. The relationship among variables was investigated by Pearson correlation. The data were analyzed using IBM SPSS statistical package (Version 21.0, SPSS Inc., Chicago, IL).

3. Results and discussion

Different tillage systems and soil depths significantly ($P < 0.01$, $P < 0.05$) altered all of the soil physical properties, while tillage systems × soil depth interactions also influenced all of the soil properties except BD, PR and PWP after 10 years. A summary of these differences is provided in Figs. 1, 2, 5–10 and Table 3 and discussed in detail in the sections below.

The differences in the frequency and depth of tillage and characteristics of the crops sown in rotation might have been reported to cause differences among soil properties (Crawford et al., 2015; Dang et al., 2018; Reichert et al., 2017). Blanco-Canqui et al. (2017) investigated the effects of four different systems with moldboard plow, disc harrow, chisel and no-till on hydrological properties of soil at the University of Nebraska in 1980. Contrary to the results of current study, it was reported that none of the systems have significant effect on the bulk density, soil porosity and available water content of the fine, smectitic, mesic Typic Argiudolls soil.

Due to the difference in efficient depths and mechanical impacts, the application of moldboard plow (CT-1 and CT-2), heavy tandem disc harrow (CT-1, RT-1, RT-3), disc harrow (CT-1, CT-2), chisel plow (CT-2) and rototiller (RT-1, RT-2) have different effects on the physical structure of the soils. The moldboard plow inverts soil from 30 to 33 cm deep. On the other hand, heavy tandem disc harrow (18–20 cm) and disc harrow (13–15 cm) do not invert the soil. However, they exert more damage to soil below the efficient working depth compared to the chisel plow, which works along narrow lines at a depth of 35–38 cm without inverting the soil. The use of disc harrow increases porosity and decreases bulk density in surface horizons relative to chisel plow. The chisel plow leaves most of crop residue at soil surface and has a temporary influence on soil structure (Dahab, 2011).

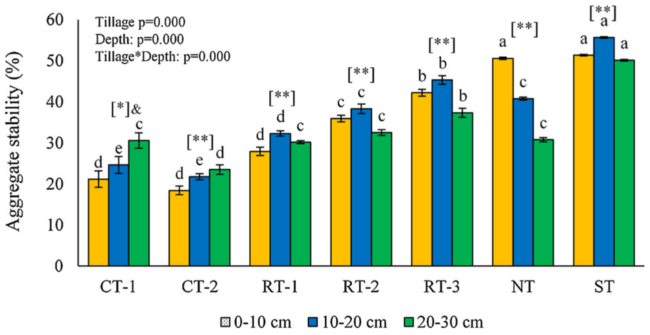

Fig. 1. Aggregate stability (%) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

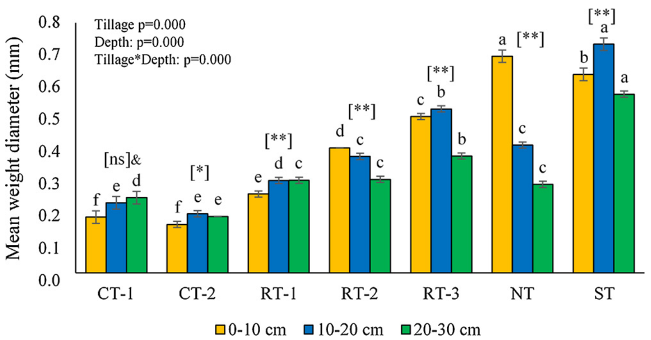

Fig. 2. Mean weight diameter (mm) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

3.1. Aggregate stability and mean weight diameter

Tillage systems, soil depth, and tillage x soil depth interaction had significant impact ($P < 0.01$) on aggregate stability (AS) (Fig. 1). The AS in 0–10 cm depth under NT, RT-3 and ST treatments (minimal soil disturbance and crop residues retained on surface) was relatively higher than rest of the tillage systems. Better aggregation in 0–10 cm depth under 10-year of NT compared to RT and CT is congruent with the findings of many other studies (Nath and Lal, 2017; Somasundaram et al., 2017). The stability of aggregates in 0–10 cm depth followed the increasing order as; CT-2 < CT-1 < RT-1 < RT-2 < RT-3 < NT < ST. Most of the existing aggregates are conserved due to lower soil disturbance and increased biomass under RT and NT compared to CT where aggregates are destroyed by frequent intensive tillage. Biotic aggregation under RT and NT systems is induced by lower disruption of habitat and addition of food by crop residues as explained by Alvarez and Steinbach (2009) and Lipiec et al. (2015). The improvement in AS under NT system is most prominent near the surface, which is linked to less physical disruption of macro aggregates, higher organic carbon accumulation and increased biological activity (Bhattacharyya et al., 2013; Kibet et al., 2016). Similar to the higher AS under RT (except RT-1) and NT systems, continuous ten-year RT and NT systems caused significant increase in OM content at 0–10 cm depth compared to CT systems (Table 3). High positive significant correlation between OM content and AS ($r = 0.71$, $P < 0.01$) favors the formation of stable aggregates in surface soils under NT system (Table 4). The lowest AS was recorded in CT-2 treatment (crop residues were burnt after each harvest) under all sampling depths. The use of moldboard plow in 26 years of corn production resulted in lower water stable aggregates, indicating higher vulnerability of soil to wind and water erosion (Karlen et al., 2013). In contrast, higher AS in surface layer under NT promotes water movement, cycling of nutrients (Hillel, 2004), which positively contribute to environmental quality by reducing soil and nutrient losses (Kibet et al., 2016).

Turning over the surface soil in NT plots by moldboard plow brought most of the organic matter and stable aggregates at surface

Table 3
Tillage effects on bulk density, penetration resistance, water filled pore space and organic matter.

Tillage Methods	Bulk Density (g cm^{-3})	Penetration Resistance (MPa)	Water Filled Pore Space	Organic Matter (%)
0–10 cm				
CT-1	1.32$^{\#}$ ± 0.02†ab$^{\&}$ ns	1.77 ± 0.10c ns	0.57 ± 0.01 cd **	1.45 ± 0.06c ns
CT-2	1.23 ± 0.02 cd**	1.29 ± 0.11d**	0.52 ± 0.01 d**	1.34 ± 0.08c ns
RT-1	1.26 ± 0.04bc**	1.61 ± 0.12c*	0.60 ± 0.01 bc**	2.18 ± 0.04ab**
RT-2	1.29 ± 0.02abc**	1.85 ± 0.11bc**	0.62 ± 0.02 b**	2.33 ± 0.08ab**
RT-3	1.28 ± 0.03abc*	2.15 ± 0.13ab ns	0.65 ± 0.01 ab**	2.38 ± 0.06a**
NT	1.36 ± 0.02a ns	2.18 ± 0.10a**	0.68 ± 0.03 a ns	2.33 ± 0.08ab**
ST	1.17 ± 0.02d**	1.73 ± 0.10c ns	0.52 ± 0.02 d**	2.13 ± 0.09b**
ANOVA	0.001	0.000	0.000	0.000
10–20 cm				
CT-1	1.38 ± 0.04 a	1.97 ± 0.09 cd	0.74 ± 0.02 ab	1.36 ± 0.08bc
CT-2	1.35 ± 0.01 a	2.03 ± 0.15 cd	0.67 ± 0.01 c	1.29 ± 0.08bc
RT-1	1.38 ± 0.03 a	2.17 ± 0.14 bc	0.74 ± 0.01 a	1.23 ± 0.08c
RT-2	1.44 ± 0.02 a	2.43 ± 0.11 ab	0.69 ± 0.01 c	1.38 ± 0.09bc
RT-3	1.38 ± 0.03 a	2.47 ± 0.12 ab	0.71 ± 0.01 bc	1.53 ± 0.10ab
NT	1.42 ± 0.03 a	2.62 ± 0.09 a	0.70 ± 0.01 c	1.38 ± 0.06bc
ST	1.26 ± 0.03 b	1.79 ± 0.11 d	0.58 ± 0.01 d	1.95 ± 0.07a
ANOVA	0.005	0.000	0.000	0.000
20–30 cm				
CT-1	1.38 ± 0.03 ab	2.08 ± 0.14 bc	0.72 ± 0.03 b	1.31 ± 0.10b
CT-2	1.39 ± 0.03 ab	1.94 ± 0.14 c	0.68 ± 0.01 b	1.29 ± 0.08b
RT-1	1.45 ± 0.01 a	2.04 ± 0.09 bc	0.83 ± 0.02 a	1.18 ± 0.09b
RT-2	1.45 ± 0.01 a	2.37 ± 0.10 ab	0.72 ± 0.01 b	1.20 ± 0.06b
RT-3	1.39 ± 0.03 ab	2.61 ± 0.14 a	0.71 ± 0.01 b	1.30 ± 0.06b
NT	1.45 ± 0.04 a	2.64 ± 0.09 a	0.72 ± 0.02 b	1.26 ± 0.06b
ST	1.32 ± 0.04 b	1.93 ± 0.13 c	0.69 ± 0.03 b	1.65 ± 0.04a
ANOVA	0.012	0.000	0.000	0.002
Tillage	0.000	0.000	0.000	0.000
Depth	0.000	0.000	0.000	0.000
Tillage x Depth	0.686	0.357	0.000	0.000

CT: Conventional tillage, **RT:** Reduced tillage, **NT:** No-till, **ST:** Strategic tillage. ns: Not significant.

[#] Average of three plots.

[†] Standard error of the means.

[&] Different letters in a column indicate significant differences ($P < 0.05$) among different tillage systems. Changes with depth obtained in Duncan test.

** Significant at $p < 0.01$.

* $p < 0.05$.

layer to 10–20 and 20–30 cm depths while compacted subsurface soil was mixed with the surface layer in ST plots. Therefore, the highest AS and OM content for subsurface layers were observed under ST treatment (Fig. 1 and Table 3). The AS under ST was 178.7%, 155.6% and 113.5% higher than CT-2 in 0–10, 10–20 and 20–30 cm depths, respectively. The AS in the first 10 cm depth under ST was slightly higher (1.5%) than NT treatment, though the difference was not significant. However, the AS under ST was 36.5% and 62.9% higher than NT in 10–20 and 20–30 cm depth, respectively. The AS at 0–10 cm under CT-1, CT-2 and RT-1 was 30.7, 21.5 and 7.4% lower than 20–30 cm depth, whereas AS in surface layer was 10.5, 13.1, 64.4 and 2.4% higher than 20–30 cm depth under RT-2, RT-3, NT and ST (Fig. 1). The results of Kettler et al. (2000) and Quincke et al. (2007) were also in accordance with our findings.

Individual and interactive effects of tillage systems and depth significantly ($P < 0.01$) altered mean weight diameters (MWD) of the soil (Fig. 2). The MWD was significantly changed with depth in all tillage systems, except CT-1. In contrast to our results, Kibet et al. (2016) found a significant effect of tillage system on MWD at 0–10 cm, while the effect was non-significant at deeper soil layers. The MWD was generally higher under NT and ST treatments compared to CT. Cultivation resulted in significantly lower organic matter content and MWD in surface soils under CT-1 and CT-2 compared to RT and NT systems (Fig. 2 and Table 3). The finding of significant ($P < 0.01$) positive correlations between MWD and OM content ($r = 0.70$, $P < 0.01$) (Table 4) suggest that OM is acting as a binding agent to form stable aggregates. Six et al. (2000) indicated that polyvalent metal-OM complexes form bridges between negatively charged clay particles in 2:1 clay dominated soils. The MWD values ranged from 0.16 mm (CT-2) to 0.69 mm (NT) in 0–10 cm, from 0.19 mm (CT-2) to 0.73 mm (ST) in 10–20 cm and from 0.18 mm (CT-2) to 0.57 mm (ST), in 20–30 cm depths, respectively. Celik (2005) also showed that continuous conventional cultivation in Mediterranean region caused 61 and 64% decreases in MWD of forest and pasture surface soils. Similar to the decline in OM content, MWD under NT significantly reduced with depth and it was 40.6% and 59.4% lower than the MWD at 10–20 and 20–30 cm depths, respectively (Fig. 2 and Table 3).

Burning crop residues in CT-2 resulted the lowest MWD at three soil depths among seven tillage systems evaluated, while higher accumulation of biomass resulted in higher MWD of aggregates in NT and ST. Somasundaram et al. (2017) reported significantly higher MWD (0.80 mm) under stubbles retained NT compared to stubbles burnt CT (0.35 mm) which is similar to the results of current study. Verhulst et al. (2010) also reported that water stability of the aggregates in the fractions < 2 mm and < 50 μm fractions is reduced by in situ burning of crop residue. In addition to residue burning, frequent mechanical disturbance of macro-aggregates by tillage practices in CT-1 and CT-2 led to lower MWD compared to the other tillage systems. Similarly, on a silty clay loam in Nebraska, USA, NT plots in 0–10 cm depth had 1.8 times greater MWD than CT plots after 33 years (Kibet et al., 2016).

The MWD of aggregates under ST in 10–20 (0.73 mm) and 20–30 cm (0.57 mm) depths was significantly ($P < 0.01$) higher than other six tillage systems. The implementation of ST to previously NT soil decreased MWD at surface soil by 7.2% compared to NT, while the MWD at 10–20 and 20–30 cm depths was 78% and 103% higher than NT (Fig. 2). The results confirmed the well mixing of residue rich surface

Table 4
Pearson correlation among soil properties.

	AS	MWD	BD	PR	WFPS	FC	PWP	PAW	MiP	MaP	TP	OM
0–10 cm												
MWD	0.97**	1										
BD	−0.07	−0.02	1									
PR	0.50**	0.54**	0.40**	1								
WFPS	0.36*	0.36*	0.55**	0.42**	1							
FC	0.37*	0.36*	0.59**	0.46**	0.96**	1						
PWP	0.35*	0.38*	0.75**	0.52**	0.78**	0.83**	1					
PAW	0.13	0.08	−0.06	0.05	0.55**	0.55**	−0.01	1				
MiP	0.37*	0.36*	0.59**	0.46**	0.96**	1.00**	0.83**	0.55**	1			
MaP	−0.33*	−0.33*	−0.52**	−0.38*	−0.99**	−0.91**	−0.73**	−0.54**	−0.91**	1		
TP	−0.16	−0.15	−0.23	−0.12	−0.68**	−0.45**	−0.32*	−0.33*	−0.46**	0.78**	1	
OM	0.71**	0.70**	0.12	0.52**	0.50**	0.53**	0.47**	0.25	0.53**	0.46**	−0.19	1
10–20 cm												
MWD	0.96**	1										
BD	−0.19	−0.31*	1									
PR	0.09	−0.06	0.48**	1								
WFPS	−0.50**	−0.61**	0.60**	0.39*	1							
FC	−0.53**	−0.60**	0.51**	0.37*	0.72**	1						
PWP	0.16	0.00	0.68**	0.50**	0.38*	0.40**	1					
PAW	−0.62**	−0.54**	−0.20	−0.14	0.27	0.50**	−0.59**	1				
MiP	−0.53**	−0.60**	0.51**	0.37*	0.71**	1.00**	0.40**	0.50**	1			
MaP	0.48**	0.59**	−0.58**	−0.38*	−0.99**	−0.63**	−0.36*	−0.22	−0.63**	1		
TP	0.31*	0.41**	−0.45**	−0.27	−0.85**	−0.25	−0.23	0.00	−0.25	0.91**	1	
OM	0.58**	0.68**	−0.42**	−0.30	−0.62**	−0.60**	−0.23	−0.31*	−0.60**	0.60**	0.43**	1
20–30 cm												
MWD	0.96**	1										
BD	−0.31*	−0.35*	1									
PR	−0.06	−0.09	0.13	1								
WFPS	−0.12	−0.11	0.60**	−0.10	1							
FC	0.05	0.05	0.36*	−0.22	0.79**	1						
PWP	0.04	−0.02	0.59**	0.23	0.43**	0.42**	1					
PAW	0.01	0.07	−0.14	−0.41**	0.43**	0.65**	−0.42**	1				
MiP	0.05	0.05	0.36*	−0.22	0.79**	1.00**	0.42**	0.65**	1			
MaP	0.17	0.15	−0.63**	0.04	−0.98**	−0.68**	−0.42**	−0.33*	−0.68**	1		
TP	0.26	0.24	−0.58**	−0.12	−0.72**	−0.14	−0.24	0.06	−0.14	0.83**	1	
OM	0.53**	0.53**	−0.35*	−0.20	−0.22	0.04	−0.03	0.07	0.04	0.27	0.39*	1

AS: Aggregate stability, MWD: Mean weight diameter, BD: Bulk density, PR: Penetration resistance.
WFPS: Water-filled pore space, FC: Field capacity, PWP: permanent wilting point, PAW: Plant available water.
MiP: Microporosity, MaP: Macroporosity, TP: Total porosity, OM: Organic matter.

soil under NT within 30 cm of profile by moldboard plowing in ST. The MWD of aggregates under ST management was also 4.0, 3.8 and 3.2 times higher than CT-2 in 0–10, 10–20 and 20–30 cm depths, respectively.

3.2. Bulk density

Bulk density (BD) is an important indicator of soil physical quality. Tillage in wet conditions or heavy traffic may cause soil compaction (Batey and McKenzie, 2006). Tillage systems significantly affected BD at all depths ($P < 0.01$ for 0–10 and 10–20 cm, $P < 0.05$ for 20–30 cm). Similarly, soil depth had a significant ($P < 0.01$) effect on BD values (Table 3). However, tillage x depth interaction was non-significant ($P = 0.686$). The most prominent effects of tillage systems and residue management options have been observed in surface layers, while NT and CT yielded similar effects at subsurface layers (Verhulst et al., 2010). The lowest BD in 0–10 cm depth was recorded under ST (1.17 g cm^{-3}), followed by CT-2 (1.23 g cm^{-3}), RT-1 (1.26 g cm^{-3}), RT-3 (1.28 g cm^{-3}), RT-2 (1.29 g cm^{-3}), CT-1 (1.32 g cm^{-3}) and NT (1.36 g cm^{-3}). Machinery traffic for last ten years due to planting, harvesting and all other management practices resulted significantly higher soil BD in 0–10 cm depth under NT than CT-2. In addition, high clay content and swelling nature of clay minerals (montmorillonite) of the studied Vertisol (Dinç et al., 1995) increased soil compaction under NT and RT systems as indicated by Moraes et al. (2016). However, the ST treatment decreased BD at a rate of 14.0, 11.2 and 9.0% in 0–10, 10–20 and 20–30 cm depths compared with NT system (Table 3). In contrast, one-time tillage of Vertisol with either chisel plow or disc chain after 15 years under NT did not statistically impact the BD and volumetric moisture content of soils (Liu et al., 2016). Dalal et al. (2011) also reported non-significant effect of three to four tillage operations with a chisel plow each year on BD of a Vertisol compared to BD under NT treatment. The contradictory outcomes of ST are resulted from using minimal or low soil inversion implements compared to moldboard plow. Moreover, textural and structural differences of soils in experimental sites and time of BD measurement following the application of ST (Crawford et al., 2015) might have caused these differences. Because, 3 to 5 years or even longer time may be needed to stabilize the changes in BD of soils due to tillage impact (Soane et al., 2012).

Tillage systems had a significant ($P < 0.01$) effect on BD in 10–20 cm; however, the differences were only significant between ST and rest of the tillage systems. The BD (1.26 g cm^{-3}) under ST (10–20 cm) was lower than other tillage systems. The BD value at 10–20 cm depth followed the order; RT-2 < NT < RT-3 = RT-1 = CT-1 < CT-2 < ST (Table 3). The differences in BD within 0–10 and 10–20 cm under CT, RT and NT systems were small. However, moldboard plow and chisel plow treatments under CT systems have lower BD values in 20–30 cm depth compared to RT-1, RT-2 and NT systems because the tillage operations resulted in higher break up of compacted layers (Table 3). The BD at 20–30 cm depth ranged from 1.32 g cm^{-3} (ST) to 1.45 g cm^{-3} (RT-1 = RT-2 = NT). The low BD values within 0–30 cm depth in CT system may be explained by the continuous use of moldboard plow at 30–33 depth. In contrast, continuous use of disc

Fig. 3. Dense subsurface layer at a relatively shallow depth under reduced tillage.

harrow and rototiller in RT systems at the same depth led to the formation of a highly compacted subsurface layer below the tilled soil (Fig. 3).

Inconsistent results have been reported comparing the BD of soils under different tillage systems. For example, Pikul et al. (2006) found increase, decrease or no change in BD of surface soils from eight different locations in Great Plains, USA. Our results are consistent with Brunel-Saldias et al. (2016) who obtained the lowest BD value in 0–10 cm depth under CT system, though the differences under CT, RT, NT and ST were non-significant. The BD of 0–25 cm depth in 7-year CT field was smaller than reduced tillage (7-year) and uncultivated (50 year) fields (Jiang et al., 2017). In contrast, Das et al. (2014) indicated that BD was significantly lower under NT and RT compared to CT system in four-year tillage experiment, due to the higher soil organic matter accumulation (Celik et al., 2004), and lack or low density of soil disturbance.

The extent of effects caused by tillage systems on soil attributes depends on several factors, which reach to an equilibrium over the time (Moraes et al., 2016). The BD values in 0–7 cm depth of soils under 2 months of NT were lower than in soils under 3.5-year and 5-year NT system. The BD values of soils under NT system gradually increase and reach to the highest level within 3.5 to 5.0 years (Reichert et al., 2016). Reorientation of soil particles and aggregates on time and pressure applied by field equipment's, especially under inappropriate moisture conditions led to a substantial change in BD and number of pores (Horn and Dexter, 1989; Lu et al., 2004). However, researchers reported a decrease in BD values from soil under NT system for 14 years due to increase in OM content (Moraes et al., 2016). Since BD tends to decrease as OM concentration increases, negative impacts of NT on soil physical quality may decrease by time. Soil organic matter content in 0–10 cm depth under NT system was 60.7 and 73.9% higher compared to CT-1 and CT-2. Therefore, we may also expect a decrease in BD and PR values in 0–10 cm of Arık soil by accumulating higher amount of organic matter content in the future.

A significant positive correlation ($P < 0.01$) between BD and PR ($r = 0.40$), WFPS ($r = 0.55$), FC ($r = 0.59$), PWP ($r = 0.75$), MiP ($r = 0.59$), and a significant negative relationship with MaP ($P < 0.01$ $r = -0.52$) was observed at 0–10 cm depth (Table 4). In addition, BD had a strong negative correlation with TP ($P < 0.01$, $r = -0.45$ and -0.58 for 10–20 and 20–30 cm depths, respectively) at subsurface layers (Table 4). Significant positive correlations in all three depths between BD and MiP, and negative correlations with MaP and TP are consistent with the results reported by Calonego et al. (2017) who stated that soil compaction decreases MaP, increases MiP and results in lower TP.

3.3. Penetration resistance

The differences in tillage equipment's, which changes the level of soil disturbance and the frequency of tillage operations resulted in significantly different PR values ($P < 0.01$) among seven tillage systems (Table 3). After 10 years of crop production, NT system increased PR in all three layers compared to the CT systems. The increase in PR under NT compared to CT-1 and CT-2 systems was 23.2 and 69.0%, 35.5 and 29.1%, and 26.9 and 36.1% in 0–10, 10–20 and 20–30 cm depths, respectively. Similarly, NT system increased PR of soils by 0.3–1.6 MPa in nine out of 13 major land resource areas in eastern USA (Blanco-Canqui and Lal, 2007). Compacted surface and subsurface layers in NT, and partially in RT systems are mainly associated with the absence of soil disturbance and cumulative effects of pressure exerted by agricultural machinery traffic. In agreement with our study, Martínez et al. (2016) and Moraes et al. (2016) reported higher PR and BD values at surface layers for NT compared to moldboard plowing. However, in contrast to our findings both have reported higher PR and BD values in subsurface layers for CT compared to NT.

Surface layers in RT plots have been mechanically mixed with heavy tandem disc harrow, rototiller, etc. since the beginning of the experiment in 2006, but subsurface layers have not been disturbed which increased the compaction in subsurface layers. The PR values in 10–20 cm depth followed the increasing order; ST (1.79 MPa) < CT-1 (1.97 MPa) < CT-2 (2.03 MPa) < RT-1 (2.17 MPa) < RT-2 (2.43 MPa) < RT-3 (2.47 MPa) < NT (2.62 MPa), and in 20–30 cm depth; ST (1.93 MPa) < CT-2 (1.94 MPa) < RT-1 (2.04 MPa) < CT-1 (2.08 MPa) < RT-2 (2.37 MPa) < RT-3 (2.61 MPa) < NT (2.64 MPa) (Table 3). The difference in the intensity of soil loosening resulted in obtaining different PR values among RT systems. Similarly, PR value for RT system in upper 30 cm depth was reported as at least 1.0 MPa higher than CT, and at some points reached to 4.8 and 4.3 MPa (Kuhwald et al., 2017). In contrast to increased PR in deeper soil layers observed in the current study, Soracco et al. (2012) and Moraes et al. (2016) indicated that higher macro porosity for NT due to roots and faunal activities in non-disturbed conditions contributes to the improvement of physical quality in subsurface layers. Indeed, we observed common earthworm activities (biopores) within subsurface layers of NT and RT plots (Fig. 4), though this activity was not reflected into the structural

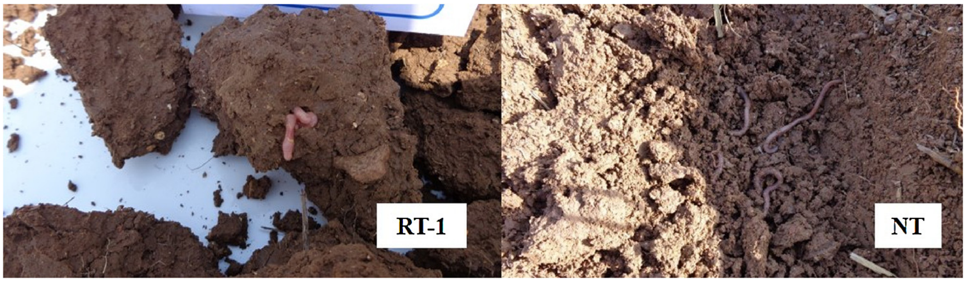

Fig. 4. Biopores and earthworm activities in compacted layers under reduced and no-tillage systems.

improvement.

The measurements of PR in ST plots (< 2 MPa) indicated the successful removal of the compacted layer developed under nine-year of NT in all three soil depths (Table 3). The PR in 0–30 cm depth was always lower in ST treatment compared to RT and NT treatments. Twelve months after the use of moldboard plowing, the reduction of PR in ST relative to NT was 20.6, 31.6 and 26.9% in 0–10, 10–20 and 20–30 cm depths, respectively, showing at the similar order of magnitude as in the CT-1 and CT-2. Similar results have been reported by Kuhwald et al. (2017), indicating significantly ($P < 0.05$) lower PR in surface soils and removal of compaction zone between 10 and 20 cm depths of 18-year RT plots after plowing by moldboard plow to a depth of 30 cm.

The PR > 2 MPa is assumed to be critical limit for root penetration in the absence of permanent root canals and cracks (Bengough et al., 2005). However, Sa et al. (2014) reported that critical limit of 2 MPa for root development may not be applied for different tillage systems. The 2 MPa can still be valid for high clayey soil under CT, though the critical limit should be raised to 3 MPa for chisel plowing under RT and to 3.5 MPa under NT system (Sa et al., 2014). According to the given criteria, soils under CT do not have any compaction problem, but the PR values are close to the critical threshold of 2 MPa. The PR values in RT systems were mostly above the critical threshold of 2 MPa, but lower than the 3 MPa set for the chisel plowing (Table 3). Thus, the increase in soil compaction under RT compared to CT is relatively small and may not be expected to adversely impact crop yield. Indeed, slight soil compaction may be beneficial for high clayey soils by reducing preferential flow and promoting saturated and unsaturated water flow through soil matrix (Blanco-Canqui and Lal, 2007). Significantly higher wheat yields under RT treatments compared to CT, NT and ST systems support the above discussion (Table 5). Most of the PR values under NT were reported above the critical value by Sa et al. (2014). The increase in PR should be monitored and if needed, necessary preventive steps should be taken to avoid further destruction of soil structure, chemical and biological properties of soils. Positive correlation between PR and micropores ($r = 0.46$, $P < 0.01$) and negative correlation with macropores ($r = -0.38$, $P < 0.05$) in 0–10 cm depth indicated that the rate of macropores to micropores in soil matrix reduced by compaction (Table 4).

3.4. Water filled pore space (WFPS)

The use of water-filled pore space (WFPS), which provides additional information related to water and aeration limiting conditions affecting microbial activity, is preferred over volumetric water content. Since it normalizes the moisture content, WFPS removes complexity caused by texture differences at different sites (Dobbie and Smith, 2001). The WFPS of soils significantly differed ($P < 0.01$) among different tillage systems (Table 3). The WFPS values ranged from 0.52 (CT-2 and ST) to 0.68 (NT) in 0–10 cm, from 0.58 (ST) to 0.74 (CT-1 and RT-1) in 10–20 cm and from 0.68 (CT-2) to 0.83 (RT-1) in 20–30 cm depths (Table 3). Higher WFPS values under NT and RT systems are the results of higher soil water contents and bulk densities compared to CT and ST. Similar to our findings, Plaza-Bonilla et al. (2014) reported significant effects of long-term tillage practices on WFPS under Mediterranean climate with NT resulting in the highest WFPS.

Table 5
Tillage effects on wheat and soybean yields.

Tillage Methods	Wheat ($kg\ ha^{-1}$)	Soybean ($kg\ ha^{-1}$)
CT-1	4246.1[#] ± 15.5[†] c[&]	4336.9 ± 64.6 a
CT-2	4290.1 ± 14.9 c	4228.6 ± 63.5 a
RT-1	5351.9 ± 7.0 a	4210.7 ± 97.2 a
RT-2	5370.2 ± 18.3 a	4240.5 ± 71.1 a
RT-3	5401.4 ± 25.1 a	4283.3 ± 87.4 a
NT	5170.0 ± 15.2 b	4319.1 ± 77.6 a
ST	4291.4 ± 19.3 c	4294.1 ± 60.6 a
ANOVA	0.000	0.868

CT: Conventional tillage, **RT:** Reduced tillage, **NT:** No-till, **ST:** Strategic tillage.

[#] Average of three plots.

[†] Standard error of the means.

[&] Different letters in a column indicate significant differences ($P < 0.05$) among different tillage systems.

The incubation studies revealed that aerobic microbial activity is impaired in higher than 60% WFPS at which aeration is significantly reduced, while below this level water may limit the microbial activity (Linn and Doran, 1984; Torbert and Wood, 1992). Forte et al. (2017) indicated that WFPS threshold value for the activities of denitrifying bacteria in fine textured soils under Mediterranean climate might be lower than 42%. The mean WFPS values in 0-10 cm under NT, RT-3 and RT-2 systems and in subsurface layers under all tillage systems (except ST in 10–20 cm) were higher than 60%, indicating that these soils may be at significant risk of losses of N via denitrification. The results obtained are consistent with Linn and Doran (1984) who found that WFPS in 0–7.5 cm depth under NT management was significantly higher (62%) than CT (44%). The increased WFPS under NT resulted in 3.4 and 9.4 times higher CO_2 and N_2O fluxes from surface layer under NT over a 24-h period than plowed soils (Linn and Doran, 1984). The ST significantly decreased WFPS in NT plots from 0.68 to 0.52 in 0–10 cm, from 0.70 to 0.58 in 10–20 cm and from 0.72 to 0.69 in 20–30 cm depths.

3.5. Porosity

The amount and structure of soil pores have significant influence on water retention, movement, root development, gas diffusion and biodiversity (Pires et al., 2017). The results confirmed a considerable influence of different tillage practices on TP in 10–20 ($P < 0.01$) and 20–30 cm ($P < 0.05$) depths, while there was no significant difference in TP among tillage systems at first 10 cm (Fig. 5). However, contrasting tillage effects have been reported from several studies conducted under various environmental conditions. For example, Blanco-Canqui et al. (2017) found that 35-year of different tillage treatments including NT, disc, chisel plow and moldboard plow had non-significant effect on bulk density and soil porosity at any depths between 0 to 30 cm of soil profile. The TP in 0–10 cm depth followed the increasing order; RT-3 = NT (0.58 $cm^3\ cm^{-3}$) < RT-2 (0.59 $cm^3\ cm^{-3}$) < CT-1 = RT-1 (0.60 $cm^3\ cm^{-3}$) < CT-2 (0.61 $cm^3\ cm^{-3}$) < ST (0.62 $cm^3\ cm^{-3}$). Calonego et al. (2017) also stated that soil disturbance under CT system favors disaggregation of microaggregates in surface soils. In contrast to our results, Kay and VandenBygaart (2002) reported higher TP in

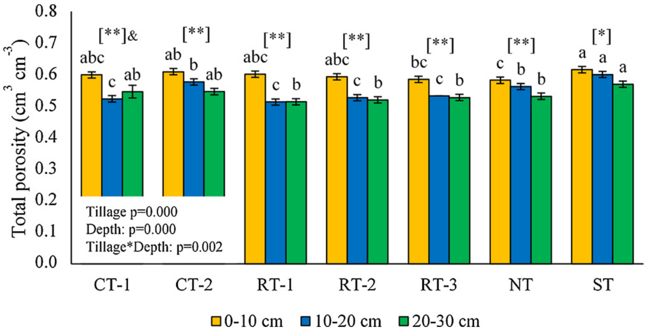

Fig. 5. Total porosity ($cm^{-3}\ cm^{-3}$) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

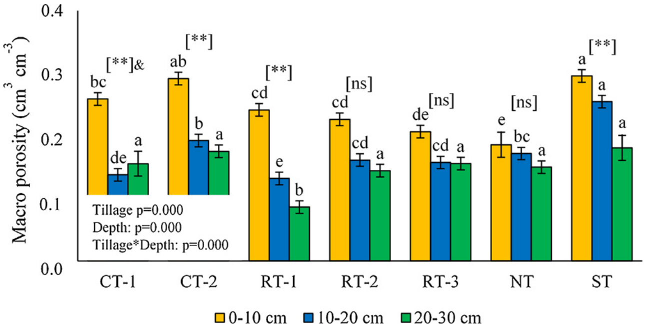

Fig. 6. Macroporosity (cm^{-3} cm^{-3}) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

surface soils under RT and NT system due to higher soil organic matter content.

The processes such as infiltration, soil aeration, drainage and water retention are regulated by the sizes of pores rather than the total porosity (Kay and VandenBygaart, 2002). The soil structure is disturbed under CT and natural soil aggregates are broken resulting in higher MaP (Kay and VandenBygaart, 2002). Tillage systems had significant effect ($P < 0.01$) on MaP at all three depths (Fig. 6). The MaP under all tillage treatments except NT has been significantly ($P < 0.01$) changed with depth. The ANOVA indicated significant ($P < 0.01$) effects of tillage x depth interaction on MaP of soils. The highest MaP at 0–10 cm and 10–20 cm depths was obtained under ST (0.30 and 0.25 cm^3 cm^{-3}), followed by CT-2 (0.29 and 0.19 cm^3 cm^{-3}). Soil tillage converts pores > 250 μm into 54–250 μm (Dal Ferro et al. 2014). The lowest MaP (0.19 cm^3 cm^{-3}) in 0–10 cm depth was obtained in soils under NT, while in subsurface layers, soils under RT-1 had lower MaP (0.13 and 0.09 cm^3 cm^{-3}) than rest of the tillage systems. The MaP in RT-1 was 166.7% higher at 0–10 cm (0.24 cm^3 cm^{-3}) than at 20–30 cm depth (0.09 cm^3 cm^{-3}), whereas this difference was only 26.7% in NT and 31.2% in RT-3. Continuity of macro pores as in NT and RT-3 provides healthy flow of air, water and heat, thus supports plant growth (Strudley et al., 2008). The MaP difference in ST (67%) between 0–10 and 20–30 cm is higher relative to NT and very close to CT-1 and CT-2. Thus, ST disrupted the continuity of pores within tillage depth of NT. Similarly, Moraes et al. (2016) and Dal Ferro et al. (2014) also found large differences in pore size between surface and subsurface layers under CT system.

Soil MaP in the upper 20 cm of soil surface under all tillage systems was higher than the critical value (0.10 cm^3 cm^{-3}) for optimal plant growth (Richards, 1983), though MaP in 20–30 cm depth under RT-1 was lower than 0.10 cm^3 cm^{-3} (Fig. 6). Low level of MaP at 20–30 cm in RT-1 may constraint oxygen availability, which induces production of ethylene that impairs the plant growth (Gardner et al., 1999), and inhibits water movement, consequently decreasing crop yield. Similar trend for decreasing MaP and TP under RT or NT treatments relative to CT was reported from other studies (Reichert et al., 2016; Glab and Kulig, 2008). After 14 years of NT, Reichert et al. (2016) found reduced MaP and TP, and increased MiP due to the structural changes induced by machinery traffic. Similarly, Glab and Kulig (2008) also reported higher MaP (14.79%) for soils with CT compared to soils under RT systems (6.55%). In contrast to our results, Moraes et al. (2016) indicated that continuous use of CT significantly increased the BD and reduced the MaP at layers below 10 cm depth to critical levels for crop growth.

The MiP of soils was significantly ($P < 0.01$) influenced by different tillage systems at all three depths (Fig. 7). In contrast to MaP, the highest MiP within 20 cm soil depth was obtained with NT system (0.40 and 0.39 cm^3 cm^{-3}), while the MiP in 0–20 cm depth under ST (0.32 and 0.35 cm^3 cm^{-3}) that was being used as NT for the last nine years was significantly lower than the NT system. The ANOVA test revealed that the MiP values did not significantly change with depth under RT-2, RT-3 and NT systems (Fig. 7). Non-significant change of MiP among soil depths shows more continuous micro pore distribution in soil profile under RT and NT systems.

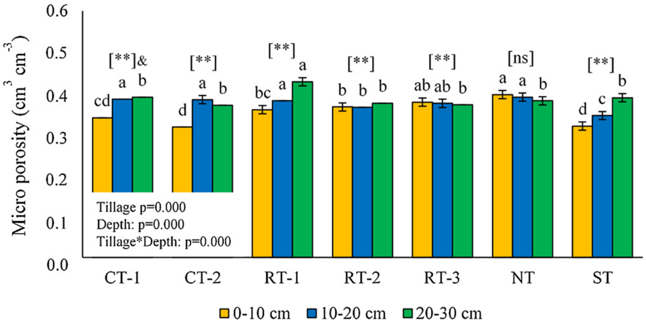

Fig. 7. Microporosity (cm^{-3} cm^{-3}) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

The ST resulted the highest values of MaP and TP in 0–10 and 10–20 cm depths compared to NT, whereas opposite was observed for MiP (Fig. 7). Similar to our findings, moldboard plowing in long term NT increased MiP at surface layer of sandy loam soil (Reichert et al., 2017). Despite significant effects of tillage systems on TP, the differences between ST and NT were numerically small (0.04 cm^3 cm^{-3} for all soil depths). Although NT has resulted in lower TP and MaP in comparison with ST, the values were not limiting for crop growth. However, increased level of MaP under ST favors water movement and infiltration, diffusion of oxygen and better environment for root growth (Gardner et al., 1999) relative to NT. It is important to keep in mind that total porosity as in all other physical soil attributes in this study were determined about one year after the deep tillage (ST) operation. As stated by Strudley et al. (2008) and Blanco-Canqui et al. (2017) hydraulic attributes of soils among tillage systems can vary with time after tillage. Surface pressure during crop production will cause collapsing and natural reconsolidation of loose tilled soil in time (Strudley et al., 2008; Reichert et al., 2016), thus sustainability of ST effect recorded after one year of deep tillage needs to be monitored on temporal basis.

3.6. *Water retention*

Similar to the most of physical properties, tillage systems significantly affected the water content at field capacity (FC), permanent wilting point (PWP) and plant available water (PAW) content of soils (Figs. 8–10). At the first 20 cm depth, water contents at FC and PWP were significantly higher under NT than the other six tillage systems (Figs. 8 and 9). Significant tillage effect on soil water retention is consistent with the findings of Stone and Schlegel (2010) who reported significantly higher water content at -1.5 MPa matric potential (PWP) under native prairie compared to NT, RT and CT. However, water content under NT was greater than RT and CT, but RT and CT were similar to each other. Water retention at PWP is primarily associated with the specific surface area of solid phase (Stone and Schlegel, 2010), thus higher water content at PWP under NT compared to other six tillage treatment is resulted from increased organic matter in surface soils under NT (Table 3). In contrast with our findings, Blanco-Canqui et al. (2017) reported that 35 years of NT, chisel plow, disc and moldboard plow management on a silty clay loam soil had non-significant effect on

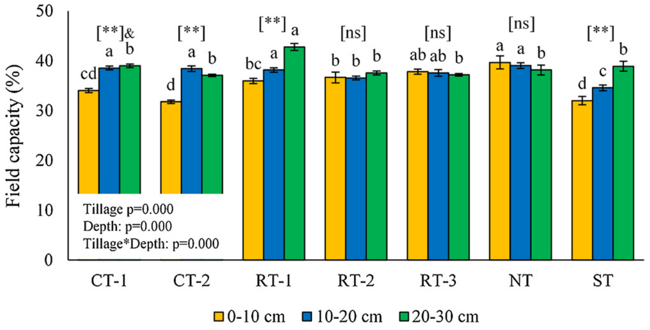

Fig. 8. Field capacity (%) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

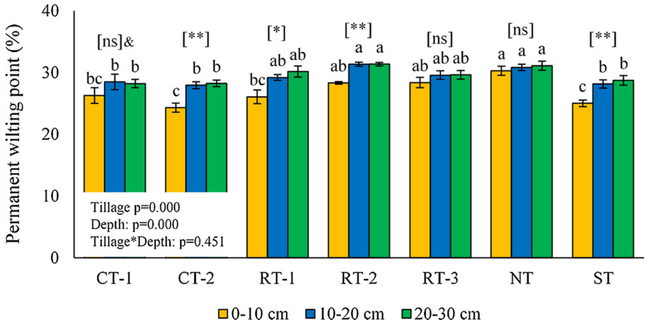

Fig. 9. Permanent wilting point (%) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

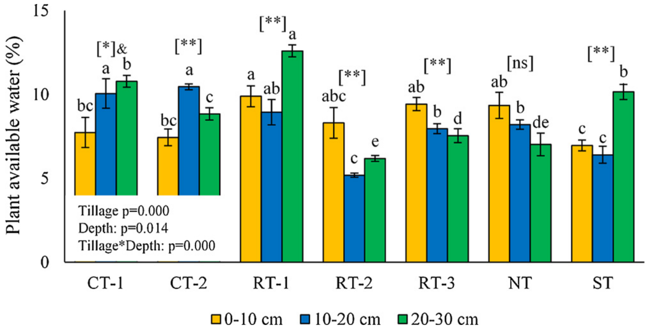

Fig. 10. Plant available water (%) under different soil tillage treatments. Lower case letters indicate significant differences ($P < 0.05$). Error bars indicate standard error. CT: Conventional tillage, RT: Reduced tillage, NT: No-till, ST: Strategic tillage. &: Changes with depth obtained in ANOVA test conducted for each tillage system separately **: Significant at $p < 0.01$, *: $p < 0.05$; ns: Not significant.

total porosity, saturated hydraulic conductivity and water retention. Similarly, Reichert et al. (2017) have also obtained non-significant difference in water retained at PWP among soil tillage systems.

Significant positive correlations were obtained between water contents at FC ($r = 0.46$, $P < 0.01$ and $r = 0.37$, $P < 0.05$ for 0–10 and 10–20 cm, respectively) and PWP ($r = 0.52$, $P < 0.01$ and $r = 0.50$, $P < 0.01$ for 0–10 and 10–20 cm, respectively) and PR of soils (Table 4). Similar relationships for FC and PWP were obtained with BD for all three soil depths (Table 4). The results revealed that water content at FC and PWP increased with increasing compaction as indicated by highly positive correlation with BD and PR. Higher PR and BD values obtained in 30 cm of soil profile under NT are compatible with the higher water content at FC and PWP under NT management. Higher water content under relatively compacted NT is related to decrease in MaP and increase in MiP, which result in higher water retention between saturation and −10 kPa matric potential (Reichert et al., 2017). Higher water retention under RT and NT systems caused to significantly higher wheat yield compared to CT-1, CT-2 and ST systems (Table 5). Since wheat is not irrigated in the region, water stored in soil profile is used by plants during growing season. However, soybean yield was not significantly different among tillage systems due to the irrigation of soybean every 13-day during the growing period. The water content at FC, PWP and PAW within 30 cm depth had homogeneous distribution under NT.

The variation of FC with depth under CT-1, CT-2, RT-1 and ST was significantly different at $P < 0.01$ level, PWP was different under CT-2, RT-2 and ST ($P < 0.01$) and RT-1 ($P < 0.05$), and PAW was different under CT-2, RT-1, RT-2, RT-3 and ST treatments ($P < 0.01$) and CT-1 ($P < 0.05$). The decrease in BD due to ST increased TP, which in turn increases soil water retention of soil layers. However, ST significantly reduced water content at FC, PWP and PAW in 0–10 and 10–20 cm depths compared to NT (Figs. 8–10). Lower PAW content in 0–20 cm depth under ST also resulted in lower wheat yield compared to that of NT systems (Table 5). The PAW, however at 20–30 cm under ST was significantly higher than NT. Since wheat has relatively shallow rooting system, higher PAW in 20–30 cm depth did not help to improve wheat yield under ST. The destructive impact of tillage alters structure related soil properties such as porosity, saturated hydraulic conductivity, infiltration etc. in a very short period (Blanco-Canqui et al., 2017). Variation in soil water at FC by application of ST is expected, because water content at FC is retained primarily due to meso and micro porosity (Reichert et al., 2017). However, changes in water content at PWP is not expected by the deep tillage, if there is no significant reduction in organic matter content of soil occurs. In this study, water content at PWP in all three layers under ST management was different from NT. The changes of water content at PWP in soil layers though ST may be attributed to the redistribution of organic matter within tillage depth. The ST slightly reduced the organic matter content in surface soil under NT, whereas organic matter content under ST was slightly higher at 10–20 and 20–30 cm depths (Table 3), respectively compared to NT management. The changes in organic matter content even at non-significant level may significantly increase the water absorbance of soils at PWP (Stone and Schlegel, 2010).

4. Conclusions

The results of current study revealed that negative outcomes of long-term conservational tillage especially under NT can be alleviated by application of ST. The functional physical properties of soils, bulk density, aggregate stability, penetration resistance, etc. have been improved by the implementation of ST into NT system. The bulk density and penetration resistance of soils under ST system have been significantly decreased to the similar levels in conventionally managed soils, and positive effects of long-term NT system still remained similar after one-time moldboard plowing of NT soils. Therefore, ST should be adopted as a promising strategy to improve the main constraints facing conservative tillage practices. Contradictory to our hypothesis, decreases in bulk density and increase in total porosity by ST did not lead to increase in soil water storage capacity of 0–20 cm soil layer. Therefore, despite the improved physical quality, yield of rain-fed winter wheat under ST was lower due to lower plant available water in 0–20 cm depth.

The results reported in this study belong to the soil samplings only for 12 months, which is a relatively short period after ST application. Therefore, impacts of ST tillage on functional soil physical properties and crop yield should be monitored in time to determine the frequency of ST application under local agroclimatic conditions.

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