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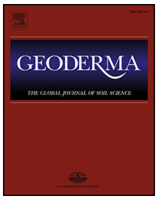

Highlights

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Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield

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- The highest soil water potential was recorded under zero tillage.
- The lowest soil temperature was registered under zero tillage.
- A significant decreasing in maize yield occurred when zero tillage is used.
- The higher maize yield was attained with the conventional tillage.
- Wireless sensors network used in this study was suitable and adequate.

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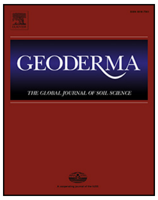

Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield

Q1 Haytham M. Salem[a,b,*], Constantino Valero[a], Miguel Ángel Muñoz[a], María Gil Rodríguez[a], Luis L. Silva[c]

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ABSTRACT

The area cultivated using conservation tillage has recently increased in central Spain. However, soil compaction and water retention with conservation tillage still remains a genuine concern for landowners in this region because of its potential effect on the crop growth and yield. The aim of this research is to determine the short-term influences of four tillage treatments on soil physical properties. In the experiment, bulk density, cone index, soil water potential, soil temperature and maize (*Zea mays* L.) productivity have been measured. A field experiment was established in spring of 2013 on a loamy soil. The experiment compared four tillage methods (zero tillage, ZT; reservoir tillage, RT; minimum tillage, MT; and conventional tillage, CT). Soil bulk density and soil cone index were measured during maize growing season and at harvesting time. Furthermore, the soil Q2 water potential was monitored by using a wireless sensors network with sensors at 20 and 40 cm depths. Also, soil temperatures were registered at depths of 5 and 12 cm. Results indicated that there were significant differences between soil bulk density and cone index of ZT method and those of RT, MT, and CT, during the growing season; although, this difference was not significant at the time of harvesting in some soil layers. Overall, in most soil layers, tillage practice affected bulk density and cone index in the order: ZT > RT > MT > CT. Regardless of the entire observation period, results exhibited that soils under ZT and RT treatments usually resulted in higher water potential and lower soil temperature than the other two treatments at both soil depths. In addition, clear differences in maize grain yield were observed between ZT and CT treatments, with a grain yield (up to 15.4%) increase with the CT treatment. On the other hand, no significant differences among (RT, MT, and CT) on maize yield were found. In conclusion, the impact of soil compaction increase and soil temperature decrease, produced by ZT treatment is a potential reason for maize yield reduction in this tillage method. We found that RT could be certainly a viable option for farmers in central Spain, particularly when switching to conservation tillage from conventional tillage. This technique showed a moderate and positive effect on soil physical properties and increased maize yields compared to ZT and MT, and provides an opportunity to stabilize maize yields compared to CT.

1. Introduction

Soil moisture is vital to plant growth and is a fundamental ecosystem resource for terrestrial vegetation, providing for plant transpiration. Irrigation management practices largely depend on accurate and timely characterization of spatial and temporal soil moisture dynamics in the root zone, especially in arid and semi-arid regions.

Adoption of in-situ soil moisture conservation systems such as conservation tillage is one of the strategies for upgrading agriculture management in these environments (Ngigi et al., 2006). Q3 Conservation tillage, which includes a variety of reduced and zero tillage techniques that leave at least 30% crop residue on the soil surface, has increasingly been adopted as the agricultural best management practice to reduce soil erosion. These tillage practices dramatically affect surface hydrologic properties, leading to increased infiltration and reduced runoff (Singh et al., 2009; Van Wie et al., 2013). Healthy plant growth and development require soil conditions that have adequate soil moisture and minimal root penetration resistance

The perceived effect of conservation tillage on soil compaction, soil moisture conditions, and soil temperature, has become a major concern among producers considering adopting this tillage system (Licht and Al-Kaisi, 2005). Soil compaction is normally evaluated by measuring soil bulk density and cone index. Soil bulk density and cone index are also used to predict the depth of soil hardpans (Afzalinia and Zabihi, 2014; Mehari et al., 2005). There are some contradictory results of research

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work conducted on the effect of conservation tillage on the soil bulk density and cone index. Results of some studies show that conservation tillage methods (reduced and zero tillage) increase the soil bulk density and cone index compared to the conventional tillage (Afzalinia and Zabihi, 2014; Taser and Metinoglu, 2005). There are also some research results showing no significant effect of conservation tillage on the soil bulk density and cone index (Afzalinia et al., 2011; Rasouli et al., 2012).

In conservation tillage, the presence of crop residues on soil surface decreases evaporation (Drury et al., 1999; Jalota et al., 2006), erosion (Rhoton et al., 2002) and soil temperature fluctuations (Alletto et al., 2011). Compared to conventional tillage, generally, soil warming under conservation tillage is slower (Alletto et al., 2011; Drury et al., 1999). On the other hand, water content in the topsoil is generally higher due to increased soil water holding capacity and decreased evaporation (Bescansa et al., 2006; Xu and Mermoud, 2001). Soil moisture and soil temperature conditions in the seedbed zone can promote or delay seed germination and plant emergence (Kaspar et al., 1990).

During the maize growing season, the effects of water stress occurring at specific stages of development, for instance, delaying in irrigation during early growth stages decreased plant dry weight (Jama and Ottman, 1993). In other cases, some authors reported that the greatest sensitivity of maize yield to water stress occurred during the period bracketing flowering (Cakir, 2004; Calvino et al., 2003). Conservation tillage was found to maintain higher soil moisture during the growing period of maize (Alletto et al., 2011; Tan et al., 2002).

Therefore, quantifying the effects of conservation tillage systems on soil moisture, soil temperature, and compaction can help to explain some of the differences in plant growth and development under different tillage systems (Licht and Al-Kaisi, 2005).

Soil water status can be obtained by determining soil water content or soil water matric potential.

Soil water matric potential is often measured using tensiometers that have a maximum range of −80 kPa limited by the vapor pressure of water which is significantly below the range where many drought tolerant plants grow and they require regular refilling and degassing after a dry period (Whalley et al., 2007; Young and Sisson, 2002). In contrast resistive soil moisture tensiometers like the Watermark® soil moisture sensors are responsive to soil potentials in excess of −200 kPa. We decided to use Watermark® sensors because of their low cost, ease-of-use, and because they are widely used by the agricultural community for scheduling irrigation. Some researchers have evaluated Watermark® sensors and found them to respond well to the wetting and drying cycles for most soil types (Allen, 2000; Eldredge et al., 1993; Shock et al., 1998, 1999; Thomson et al., 2002).

Watermark® sensors' measurement can be automated allowing them to be easily integrated into soil moisture data acquisition systems and wireless data transmission networks. These networks are composed of many autonomous, cooperating, battery-powered, small-sized motes. They can be connected through wireless links and a communication gateway with a capacity to forward data from the motes to a base station with high processing and storing capacities. This makes it possible to monitor the soil water potential with the purpose of providing accurate and up-to-date knowledge of the field. To our current knowledge, there are very few studies comparing different tillage techniques that provide daily data of soil water potential at different depths. Such studies are generally helpful in the understanding of soil water dynamics throughout the growing season.

Among the different modalities of conservation tillage, zero tillage is frequently preferred worldwide by many farmers because it saves fuel and labor costs. However, there can be some constraints which appear that zero tillage does not always produce equivalent crop yields in climates with sub-optimal soil temperatures, cold springs, and poorly drained soils (Lal, 2007; López-Garrido et al., 2014). These constraints are frequent in humid temperate regions, where wet soils and crop residues lead to difficulties in soil workability, soil compaction, cooler soil temperatures at seeding and adverse effects on plant growth and crop yield (Gajri et al., 2002).

The long-term effects of conservation tillage have been well documented; however less information is available regarding the short-term effects, particularly when switching to zero tillage from conventional tillage in such soil conditions; limit crop root development due to compaction and poor water infiltration is the major initial obstacles (Chen et al., 2005). The long-term benefit from conservation tillage cannot be achieved easily, unless producers see that the system works in a short term (Chen et al., 2005).

This is a very important topic from an agronomic point of view where the adoption of zero tillage has led to difficulties in soil workability, forcing farmers to switch to other systems (López-Garrido et al., 2014). In these cases it would be desirable that farmers initially opt for other modalities of conservation tillage that are different from zero tillage, such as reservoir tillage and minimum tillage. The reservoir tillage approach was developed to provide increased levels of surface storage and it offers good prospects for infiltrating and storing more water which is then available for plant uptake (Salem et al., 2014; Ventura et al., 2005). Minimum tillage practice also, conserves soil and water resources, reduces farm energy usage and increases crop production. This practice leads to positive changes in the physical and biological properties of a soil (Alvarez and Steinbach, 2009). There is limited documentation on the short-term effects of reservoir and minimum tillage practices compared to zero tillage and conventional tillage on soil conditions in central Spain. In this region farmers frequently only consider traditional tillage with soil inversion to avoid compaction and eliminate weeds. However, less aggressive tillage practices, such as reservoir tillage and minimum tillage, could solve the problem without losing the advantages of conservation agriculture.

We hypothesized that reservoir tillage and minimum tillage could be certainly viable options that can produce beneficial effects on soil physical properties and can provide an opportunity to stabilize or increase crop yields and save production costs when switching to conservation tillage from conventional tillage. Therefore, the objectives of this study were: (i) to compare the effects of four tillage practices on soil water content, soil temperature, soil compaction, yield, and some yield components of maize, and (ii) to determine soil water potential monitoring by wireless sensors network during the maize growing season affected by tillage practices.

2. Materials and Methods

2.1. Experimental Field and Different Tillage Practices Tested

The experiment was performed in spring of 2013 at the Experimental Fields of the School of Agricultural Engineers (ETSIA) belonging to the Polytechnic University of Madrid (UPM), located in (40.44695, −3.73924). Before the start of the experiment, the field was under continuous conventional tillage at a site previously cropped with rainfed barley. The experimental field used is characterized by a semi-arid continental climate. The average long-term annual precipitation for the previous 50 years was 445 mm and the average temperatures during the growing season of May, June, July, August, and September 2013 were 14.5, 21.1, 26.9, 26.1, and 21.8 °C, respectively. The soils are composed by sand, silt, and clay content of 45, 34, and 21%, respectively, the soil is a loam texture, classified as Vertic Luvisol (FAO, 1988) with a low inherent fertility, organic matter of 15 g kg^{-1}, and pH of 6.1.

The four tillage practices used in this study were:

(1) CT, conventional tillage; deep ploughing to a depth of 30 cm with the help of mouldboard followed by one pass with rototiller to a depth of 10 cm;
(2) MT, minimum tillage; chisel ploughing to a depth of 20 cm followed by one pass with rototiller to a depth of 10 cm;

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(3) RT, reservoir tillage; seedbed preparation was identical to MT treatment except that it was followed by the creation of mini-depressions or holes after planting using a hand-pushed tool with a truncated square pyramid shape;
(4) ZT, zero tillage; residues of the previously grown crop were left on the soil surface and maize seed was directly planted using a two-row pneumatic row crop planter.

The four treatments were established in a randomized block design. Three replicates per treatment were established (25 m × 4.5 m, 112.5 m^2 plots).

Maize was planted on 25 April 2013 at a rate of 70,000 plants ha^{-1} in rows 75 cm apart. Weed control was primarily made by herbicides (Glyphosate at 5 ml l^{-1}) applied at planting time. Some plots required additional hand-weeding to ensure that weeds did not affect growth and development or depress yields.

Experimental plots were irrigated using sprinkle irrigation for all treatments with the same frequencies. The total amount of water from precipitation and irrigation recorded during the growing season from 25 April to 26 September 2013 was 767.3 mm.

2.2. Measured Variables

2.2.1. Bulk Density and Cone Index

The effects of tillage techniques on soil quality were evaluated on the basis of several parameters. Soil bulk density of the 0–30 cm surface layer was progressively determined using the core method (Blake, 1965). Intact soil cores (length 5 cm, diameter 5 cm) were collected from six depths in 5 cm increments to a depth of 30 cm. The core samples were immediately weighed, and then dried at 105 °C for 24 h to a constant weight and reweighed. Volumetric water content was calculated as the product of bulk density and gravimetric water content. Soil porosity was calculated using the equation based on the relationship between the bulk density and particle density (Danielson and Sutherland, 1986). Particle density is approximately 2.65 Mg m^{-3} for minerals soils. Therefore, the 2.65 Mg m^{-3} value was used in this study because the experiment area had low organic matter. Air-filled porosity was calculated as the difference between the porosity and the volumetric water content. To characterize the degree of soil loosening among the tillage systems, soil resistance to penetration (cone index) was measured down the soil profile to 30 cm, at intervals of 5 cm, using a soil assessment cone penetrometer (Model A2451). Bulk density and cone index were performed before tillage, during the growing season, and at harvesting time, and each was replicated three times. Table 1 shows some physical properties of the soil at different soil layers before tillage operations. Bulk density of the soil prior to the experiments was high due to the high precipitation recorded during the previous year, as the soil gradually get compacted under the influence of rainfall and particle resettlement.

2.2.2. Monitoring of Soil Water Potential by Wireless Sensors Network (WSN)

Soil moisture potential data was gathered during the growing season using a Crossbow ēKo ® Pro-Series wireless sensor network (WSN). Fig. 1 shows the network consisting of a base station, two remote nodes wireless connected transmitting data every 15 min to the base each. The nodes are solar energy powered and backed up by a battery. Each node was connected to four granular matrix electrical resistance sensors (Watermark®) installed into the ground. The estimated accuracy for each sensor was ±5%. These sensors were placed at 20 and 40 cm depths in each tillage treatment, except for conventional tillage, in which the sensor was placed only at 40 cm depth. This was due to the lack of sensors and we selected this depth to cover the root zone and conventional depth of 30 cm. Sensors were implanted in the soil according to the manufacturer's recommendations: a deep hole was drilled into the root zone of the maize to be monitored. The sensors were placed and backfilled with a slurry of the soil extracted from the hole to minimize disturbance of the soil and roots. The purpose of these measurements was to monitor soil water potential under different tillage systems with the objective of interpreting plant and soil responses to different tillage treatments.

The WSN uses low power radio transmitters. The mesh networking technology enables transmission of data from one node to any other node in the network, without using high power radio transmitters. Once the wireless sensor nodes are placed in management zones and the base station is activated, the sensor network is self-formed by allocating unique addresses to each node and defining the most efficient communication path to relay data from each node to the base station. The base station which processes the data also acts as a web server. Interested parties can access the real time data by addressing a standard web browser to the URL of the web server in the base station. The graphical user interface enables the access to the real time and historical data, download required data, backup application data and set up alarms for pre-set variable values.

Table 1
Physical properties of the soil measured at different layers before tillage operations. Mean ± standard deviation.

Soil depth (cm)	ρ_b	f	$_v$	CI
0–5	1.44 ± 0.05	0.46 ± 0.02	0.13 ± 0.03	1.39 ± 0.06
5–10	1.52 ± 0.07	0.43 ± 0.03	0.17 ± 0.03	1.49 ± 0.10
10–15	1.53 ± 0.09	0.42 ± 0.03	0.15 ± 0.05	1.64 ± 0.06
15–20	1.56 ± 0.15	0.41 ± 0.06	0.19 ± 0.12	1.70 ± 0.12
20–25	1.61 ± 0.11	0.39 ± 0.04	0.19 ± 0.10	1.63 ± 0.07
25–30	1.61 ± 0.13	0.39 ± 0.05	0.18 ± 0.03	1.68 ± 0.10

Bulk density ρ_b (g cm^{-3}); total porosity f (cm^3 cm^{-3}); volumetric moisture content $_v$ (cm^3 cm^{-3}); and cone index CI (MPa).

2.2.3. Soil Temperature

Soil temperature measurements were recorded using K-type temperature thermocouple sensors connected to a data logger model HD32MT.1 manufactured by Delta Home. The estimated accuracy for each channel was ± 2%. The sensors were installed at 5 and 12 cm depths in the soil profile, in a distance of 15 cm from the plant row in each tillage treatment. Data logger was installed into a fiberglass enclosure 60 cm above the ground and powered by a sole battery of 12 V and 20 Ah. Measurements were taken every 5 s, while its mean values were stored each 15 min.

Considerable soil temperature data were collected during this study. However, only a continuous twelve days soil temperature data of May, June, and July 2013 were selected to be presented here and they represent different weather conditions during data collection.

2.2.4. Crop Yield Measurements

Maize grain yield and some yield components were determined by harvesting plants manually from 4 m^2 middle rows of each experimental plot at the end of maize growing season on 26 September 2013. Water use efficiency was computed by dividing grain yield by seasonal water including rainfall and irrigation.

2.3. Statistical Analysis

For each measurement date, measured variables at selected depths, were statistically analyzed using a completely randomized block design. Treatment effects on measured variables were tested by analysis of variance (ANOVA), and comparisons among treatment means were made using the least significant difference (LSD) multiple range test calculated at $p < 0.05$. Statistical procedures were carried out with SAS software (SAS/STAT, 1999–2001).

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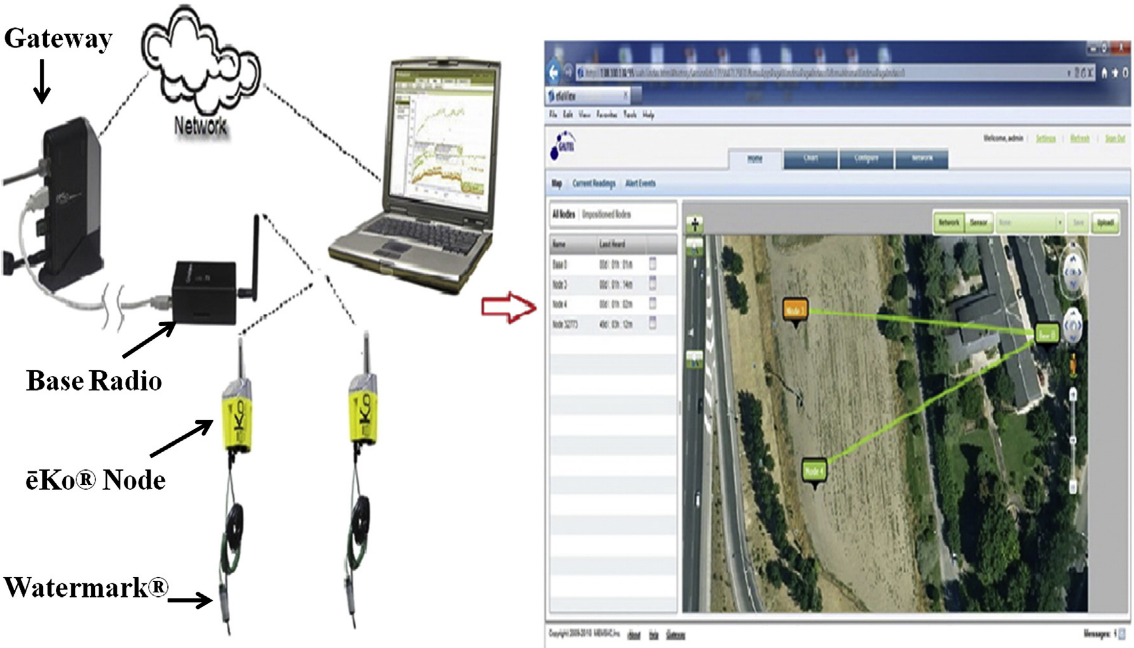

Fig. 1. Scheme for the wireless sensors network components and the nodes deployment in the experimental site.

3. Results and Discussion

The effects of tillage practices on soil physical characteristics were determined through measurements made (i) during the growing season (30 May and 4 July 2013) and (ii) at the time of harvesting (25 September 2013).

3.1. Bulk Density, Volumetric Moisture Content and Porosity

During maize growing season, for measurements taken in 30 May and 4 July, results of means comparison of soil bulk density in different tillage practices in all soil layers showed that there were some significant difference between soil bulk densities of ZT treatment and those of RT, MT, and CT in some soil depths, for example, layers 15–20, and 20–25 cm, (Table 2). Overall, in most soil layers, tillage practice affected bulk density in the order: ZT > RT > MT > CT. However, the order changed to: ZT > MT > RT > CT for measurements taken in 4 July in some soil depths, for example, layers (15–20, and 20–25 cm). In fact, comparing to the values of bulk densities for measurements taken before tillage practices (Table 1), we found that zero tillage had no clear impact on bulk density. The great effects of bulk density reduction were observed under CT due to ploughing and soil disturbance. The lower soil bulk density in conventional tillage method was also reported by Taser and Metinoglu (2005), Fabrizzi et al. (2005), and Afzalinia and Zabihi (2014).

Bulk density under RT was slightly greater than under MT in the upper soil layers, this was perhaps due to the effect of the hand-pushed tool used in the RT treatment to create depressions or mini reservoirs on the soil surface.

At the time of harvesting, there was no remarkable significant difference between tillage practices regarding soil bulk density except in some soil depths, for example, layers (5–10, and 15–20 cm). Generally,

Table 2
Tillage treatment effects on soil bulk density ρ_b (g cm^{-3}), and volumetric moisture content $_v$ (cm^3 cm^{-3}) applied in May, July, and September 2013.

Tillage	0–5 cm*		5–10 cm		10–15 cm		15–20 cm		20–25 cm		25–30 cm	
	ρ_b	v	ρ_b	v	ρ_b	v	ρ_b	v	ρ_b	v	ρ_b	v
30 May												
CT	1.19^b	0.25	1.20^b	0.29	1.28^b	0.30	1.27^b	0.28	1.33^b	0.30	1.36^b	0.26
ZT	1.40^a	0.32	1.49^a	0.34	1.46^a	0.32	1.53^a	0.31	1.55^a	0.35	1.58^a	0.38
MT	1.23^{ab}	0.20	1.27^b	0.19	1.27^b	0.20	1.29^b	0.25	1.36^b	0.26	1.37^b	0.29
RT	1.29^{ab}	0.27	1.31^{ab}	0.31	1.31^{ab}	0.32	1.29^b	0.33	1.38^b	0.34	1.39^{ab}	0.31
LSD	0.205	0.148	0.188	0.227	0.187	0.234	0.160	0.225	0.201	0.169	0.208	0.158
4 July												
CT	1.25^b	0.18	1.26^b	0.20	1.25^b	0.22^{ab}	1.30^b	0.25	1.32	0.28	1.34^b	0.28^a
ZT	1.44^a	0.28	1.47^a	0.29	1.47^a	0.30^a	1.54^a	0.34	1.51	0.31	1.56^a	0.29^a
MT	1.29^{ab}	0.15	1.30^{ab}	0.17	1.33^{ab}	0.16^b	1.39^{ab}	0.18	1.40	0.18	1.44^{ab}	0.18^b
RT	1.33^{ab}	0.24	1.35^{ab}	0.23	1.35^{ab}	0.25^{ab}	1.34^b	0.26	1.36	0.24	1.44^{ab}	0.25^a
LSD	0.186	0.137	0.179	0.253	0.205	0.135	0.180	0.236	0.227	0.167	0.217	0.070
25 September												
CT	1.30	0.15	1.34^b	0.17	1.42^{ab}	0.18	1.36^b	0.16	1.34	0.21	1.39	0.20
ZT	1.49	0.18	1.56^a	0.21	1.60^a	0.21	1.58^a	0.24	1.58	0.26	1.62	0.24
MT	1.38	0.13	1.39^b	0.15	1.43^{ab}	0.19	1.47^{ab}	0.22	1.50	0.20	1.52	0.23
RT	1.38	0.18	1.38^b	0.19	1.37^b	0.24	1.34^b	0.23	1.38	0.19	1.50	0.24
LSD	0.236	0.151	0.129	0.271	0.218	0.173	0.147	0.260	0.283	0.188	0.229	0.141

* Soil depth. CT: conventional tillage; ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage. Different letters in the same column indicate significant differences ($p < 0.05$).

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means comparison of soil bulk density at different soil layers revealed that soil bulk density increased when increasing soil depth and when time passed after tillage. Our results in some soil layers agree with previous studies indicated that soil disturbance effect on the soil bulk density during maize growing season and after that there is no significant difference between CT with high soil disturbance and ZT with zero soil disturbance (Afzalinia and Zabihi, 2014; Afzalinia et al., 2012).

Results of soil volumetric moisture content indicated that there were no significant differences among tillage practices in all soil layers for measurements taken during the growing season and at the time of harvesting, except in some soil depths for measurements taken in 4 July, for example, layers (10–15, and 25–30 cm). However, in most soil layers ZT had the greater soil volumetric moisture content compared to the MT, and CT (Table 2).

Table 3, presents the mean values of total porosity and air-filled porosity at different soil depths under different tillage practices. During maize growing season, measurements taken in 30 May and 4 July, results indicated that there were some significant difference between total porosity of ZT treatment and those of RT, MT, and CT. In general, ZT had the lower total soil porosity compared to the other tillage practices. On the other hand, no significant differences between RT, MT, and CT were found in most soil layers. At the time of harvesting, there was no significant difference between ZT and the others tillage practices regarding total soil porosity except in some soil depths, for example, layers (10–15, and 15–20 cm).

During the growing season, for measurements taken in 30 May and 4 July, results indicated that there were some significant difference between air-filled porosity of ZT treatment and those of RT, MT, and CT, except, in soil layers (5–10, and 15–20 cm). Overall, in most soil layers, tillage practice affected air-filled porosity in the order: MT > CT > RT > ZT. Otherwise, at the time of harvesting, there were no significant differences between tillage treatments regarding air-filled porosity in all soil layers; however, air-filled porosity was notably lower under ZT compared to the other tillage practices (Table 3).

3.2. Penetration Resistance

Penetration resistance is an indirect measure of soil shear strength (Osunbitan et al., 2005). Soil penetration resistance was measured by cone index at the same time of measuring bulk density and soil moisture content, because those factors significantly affect penetration resistance (Unger and Jones, 1998). Cone index at different depths in response to tillage treatments is shown in Fig. 2 (a, b, and c). Results of treatments' mean comparison for soil cone index showed that there was a significant difference between ZT treatment and other tillage treatments (RT, MT, and CT), except in the deep layers from the measurements taken at the time of harvesting. On the other hand, the difference among RT, MT and CT was not significant in the layers of 0–10 cm from the measurements taken during growing season, also, in the layers of 20–30 cm.

ZT had the highest soil cone index and CT had the lowest soil cone index in all the measurement stages because of intact soil in ZT compared to the tilled soil in CT treatment. Increasing soil cone index in ZT treatment compared to the CT has been already reported in the literature (Afzalinia and Zabihi, 2014; Taser and Metinoglu, 2005). Also, our results agree with previous studies that indicated that with little increase in bulk density, a significant increase in soil penetration resistance occurred when the soil have the same moisture content (Osunbitan et al., 2005; Zhang et al., 2001). As we mentioned, there were no significant differences among tillage practices regarding soil volumetric moisture content. Compared to soils with lower bulk density, Soils with higher density will generally have higher proportion of small diameter pores and therefore greater shear strength and higher suction when they both have the same moisture content (Zhang et al., 2001).

Although ZT treatment had the maximum amount of soil cone index, the cone index obtained from this tillage method was lower than the critical soil cone index for agricultural crops (about 2 MPa). Soil cone index in RT showed intermediate values between these groups of treatments and at the time of harvesting, the plot showing the soil cone index variation trend in the RT treatment is close to variation trend in the MT treatment rather than CT cone index plot because of similar soil disturbance in the RT and MT operation.

3.3. Soil Water Potential

Fig. 3 (a, b, c, and d) presents daily mean soil water potential in May, June, July, and August 2013, respectively, at a soil depth of 20 cm under ZT, MT, and RT treatments. There was no measurement taken at this depth under CT treatment. During the study period, soil water potential of the different tillage treatments ranged from −67.2 ± 7.4 to −0.86 ± 0.07 under ZT, from −121.9 ± 11.8 to −2.4 ± 0.13 under MT, and from −83.1 ± 7.2 to −2.1 ± 0.09 under RT.

Soil water potential under all tillage practices changed during the entire observation periods in response to irrigation and climate conditions. From 1 May to 15 June 2013, the plots exhibited the highest soil

Table 3

Tillage treatment effects on total porosity f ($cm^3\ cm^{-3}$) and air-filled porosity f_a ($cm^3\ cm^{-3}$) applied in May, July, and September 2013.

Tillage	0–5 cm*		5–10 cm		10–15 cm		15–20 cm		20–25 cm		25–30 cm	
	f	f_a	f	f_a	f	f_a	f	f_a	f	f_a	f	f_a
30 May												
CT	0.55^a	0.30^a	0.55^a	0.26	0.52^a	0.22	0.52^a	0.24	0.50^a	0.20^{ab}	0.49^a	0.23^a
ZT	0.47^b	0.15^b	0.44^b	0.10	0.45^b	0.12	0.42^b	0.12	0.42^b	0.06^b	0.41^b	0.03^b
MT	0.53^{ab}	0.33^a	0.52^a	0.32	0.52^a	0.32	0.52^a	0.27	0.49^a	0.22^a	0.48^a	0.19^a
RT	0.51^{ab}	0.24^{ab}	0.51^a	0.19	0.50^{ab}	0.19	0.51^a	0.18	0.49^a	0.15^{ab}	0.48^{ab}	0.17^a
LSD	0.079	0.144	0.070	0.230	0.068	0.257	0.061	0.225	0.077	0.146	0.077	0.111
4 July												
CT	0.53^a	0.34^a	0.53^a	0.33	0.53^a	0.31^{ab}	0.51^a	0.26	0.50	0.22^{ab}	0.49^a	0.21^b
ZT	0.46^b	0.18^b	0.45^b	0.16	0.44^b	0.14^b	0.42^b	0.08	0.43	0.13^b	0.41^b	0.12^c
MT	0.51^{ab}	0.35^a	0.51^{ab}	0.34	0.50^{ab}	0.33^a	0.47^{ab}	0.30	0.47	0.29^a	0.47^{ab}	0.28^a
RT	0.50^{ab}	0.26^{ab}	0.49^{ab}	0.26	0.49^{ab}	0.24^{ab}	0.49^a	0.24	0.49	0.24^{ab}	0.45^{ab}	0.20^b
LSD	0.069	0.130	0.070	0.228	0.081	0.179	0.070	0.236	0.090	0.145	0.079	0.069
25 September												
CT	0.51	0.36	0.49^a	0.33	0.47^{ab}	0.28	0.49^a	0.32	0.49	0.28	0.47	0.27
ZT	0.44	0.25	0.41^b	0.20	0.40^b	0.19	0.40^b	0.16	0.40	0.15	0.39	0.15
MT	0.48	0.35	0.48^a	0.32	0.46^{ab}	0.27	0.44^{ab}	0.22	0.43	0.23	0.43	0.19
RT	0.48	0.30	0.48^a	0.30	0.48^a	0.25	0.49^a	0.26	0.48	0.29	0.43	0.20
LSD	0.091	0.172	0.048	0.254	0.079	0.164	0.058	0.262	0.109	0.187	0.090	0.175

* Soil depth. CT: conventional tillage; ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage. Different letters in the same column indicate significant differences ($p < 0.05$).

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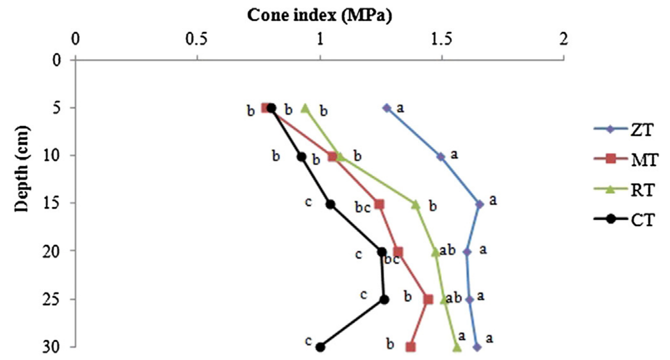
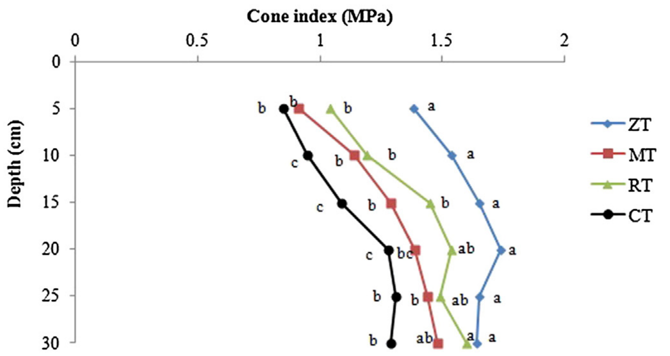
(a) 30 May 2013



(b) 4 July 2013



(c) 25 September 2013

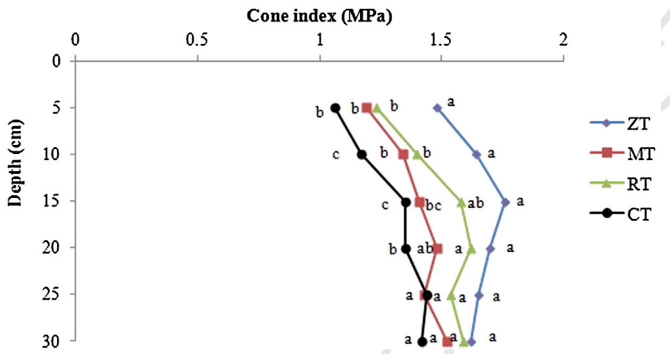


Fig. 2. (a, b, and c). Effects of tillage treatments on cone index during (a) growing season (30 May), (b) growing season (4 July), and (c) at the time of harvesting (25 September). CT: conventional tillage; ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage. Values within the same depth followed by different letters indicate significant differences ($p < 0.05$).

water potentials under all tillage practices due to the previous irrigation at the beginning of maize emergence. Thereafter and due to the increasing in temperature, soil water potential began to decrease till the end of July. Following, a slighter increase in soil water potential occurred till the end of August.

From 1 to 16 of May, the highest soil water potential was observed under ZT treatment but decreased thereafter and closely paralleled the trends of MT and RT treatments. And from 16 May to 17 June, no clear differences in soil water potential had been observed among tillage treatments.

From 17 June to the end of July, soil water potential decreased rapidly under all tillage treatments except in ZT soils. The plots of ZT exhibited the higher soil water potential, while plots of MT exhibited the lowest soil water potentials, and plots of RT showed intermediate values between these groups of treatments.

In August, soil water potentials in RT treatment began decreasing more than in MT; on the other hand ZT treatment was still considerably wetter than in all other treatments.

Fig. 4 (a, b, c, and d) presents daily mean soil water potential in May, June, July, and August 2013, respectively, at soil depth of 40 cm under ZT, MT, RT, and CT treatments. During the study period, soil water potential of the different tillage treatments ranged from −50.3.2 ± 8.9 to −1.3 ± 0.12 under ZT, from −145.5 ± 12.1 to −2.2 ± 0.16 under MT, from −90.1 ± 8.7 to −0.25 ± 0.06 under RT, and from −133 ± 11.9 to −0.76 ± 0.11 under CT. From 1 May to 16 June 2013, the plots of all tillage treatments exhibited the highest soil water potential during the entire observation period and no clear differences had been observed among tillage treatments and soil water potential throughout this period ranging from −0.25 to −5.18 kPa, the higher values of soil water potential in response to the sequent irrigation at the beginning of maize emergence. After 16 June, soil water potentials in all tillage treatments decreased rapidly except that values in ZT treatment showed less decrease and in July and August the plots of ZT and MT exhibited the highest and lowest soil water potentials, respectively, and soil water potentials in RT was the second highest among the four treatments. Soil water potentials in plots of MT and CT treatments were closely paralleled and similar to each other and lower than the other two treatments throughout the period.

Irrespective of the entire observation period, soils under ZT and RT treatments usually had higher water potential than the other two treatments at both depths (20 and 40 cm); this can be explained by the fact that the presence of crop residues on the soil surface could conserve soil water by decreasing evaporation and increasing infiltration. Also, the large infiltration surface area created by the depressions to collect and hold water during irrigation in the case of using RT could not only encourage infiltration but also promote fast evaporation, especially for periods that had a high temperature. The difference in soil water potential among tillage treatments could also be related to the difference of plant water uptake. This role of plant water uptake was consistent with the effect of compaction on soil water potential and maize roots in the ZT treatment, and the higher soil water potential in ZT treatment at 40 cm could be due to less plant water uptake as root growth was inhibited by compaction. In addition, compaction will have decreased mean pore sizes and may change soil pores from being water-transmitting to water-retaining.

3.4. Soil Temperature

Fig. 5 (a, b, and c) presents mean soil temperatures at 5 cm depth measured continuously in all tillage treatments for selected 36 days from 10 to 21 May, from 1 to 12 June, and from 1 to 12 July 2013. During the study period, soil temperatures (average of three measurements, in (°C), the average mean values of soil temperatures ± standard deviations) of the different tillage treatments were 16.3 ± 1.2, 17.6 ± 0.9, and 21.2 ± 1.1 under ZT, 17.6 ± 0.8, 18.8 ± 0.7, 22.5 ± 1.2 under MT, 17.4 ± 1.1, 18.8 ± 0.9, 22.8 ± 0.9 under RT, and 18.2 ± 1.4, 20 ± 1.6, 23.7 ± 1.1 under CT, for measurements taken in May, June, and July, respectively.

The plots of ZT and CT exhibited the lowest and highest soil temperature during the entire observation period. The maximum soil temperatures under ZT treatment were 28, 34, 35.7 °C, while under CT treatment were 31.2, 35.2, and 37.7 °C, on the other hand, the minimum soil temperatures under ZT treatment were 7.2, 7.1, and 12.2 °C while under CT treatment were 8.4, 5.8, and 13.1 °C, for measurements taken in May, June, and July, respectively.

The differences in soil temperature between ZT and CT systems were due to differences in residue accumulation on the soil surface. The high solar reflectivity and low thermal conductivity of the crop residues prevent an increase of temperature under ZT (Fabrizzi et al., 2005; Schinners et al., 1994). Also, the ZT soils had a lower soil temperature because of the greater water content especially in the upper layers.

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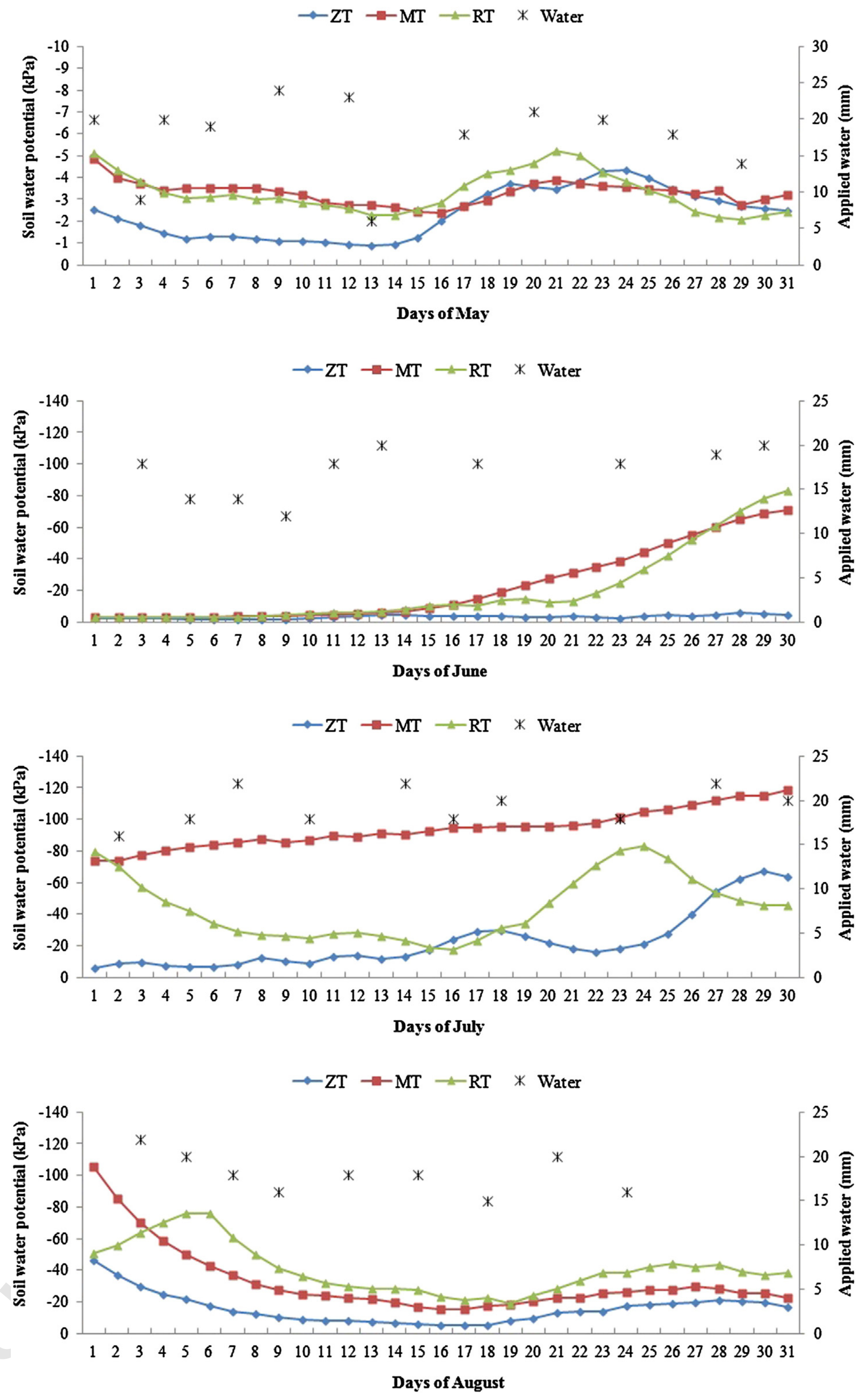

Fig. 3. (a, b, c, and d). Daily mean soil water potential (average of three measurements, in (−kPa), mean value of each day based on observations numbers ranged from 79 to 95 ± standard deviations) in May, June, July, and August 2013, respectively, at soil depth of 20 cm. ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage. Applied water (precipitation and irrigation, mm).

Fig. 6 (a, b, and c) presents mean soil temperatures at 12 cm depth recorded three times continuously in all tillage treatments for the same days as depth of 5 cm.

Soil temperature trends at 12 cm followed the same pattern of temperature recorded at 5 cm depth, and generally, soil temperatures at 12 cm were lower than 5 cm by 1–1.2 °C. Also, the plots of ZT and CT indicated the lowest and highest soil temperature during the entire observation period, otherwise, the differences between the two treatments were slightly higher than those at 5 cm depth. The mean values of soil temperatures under ZT treatment were 14.9 ± 1.3, 16.7 ± 0.9, and

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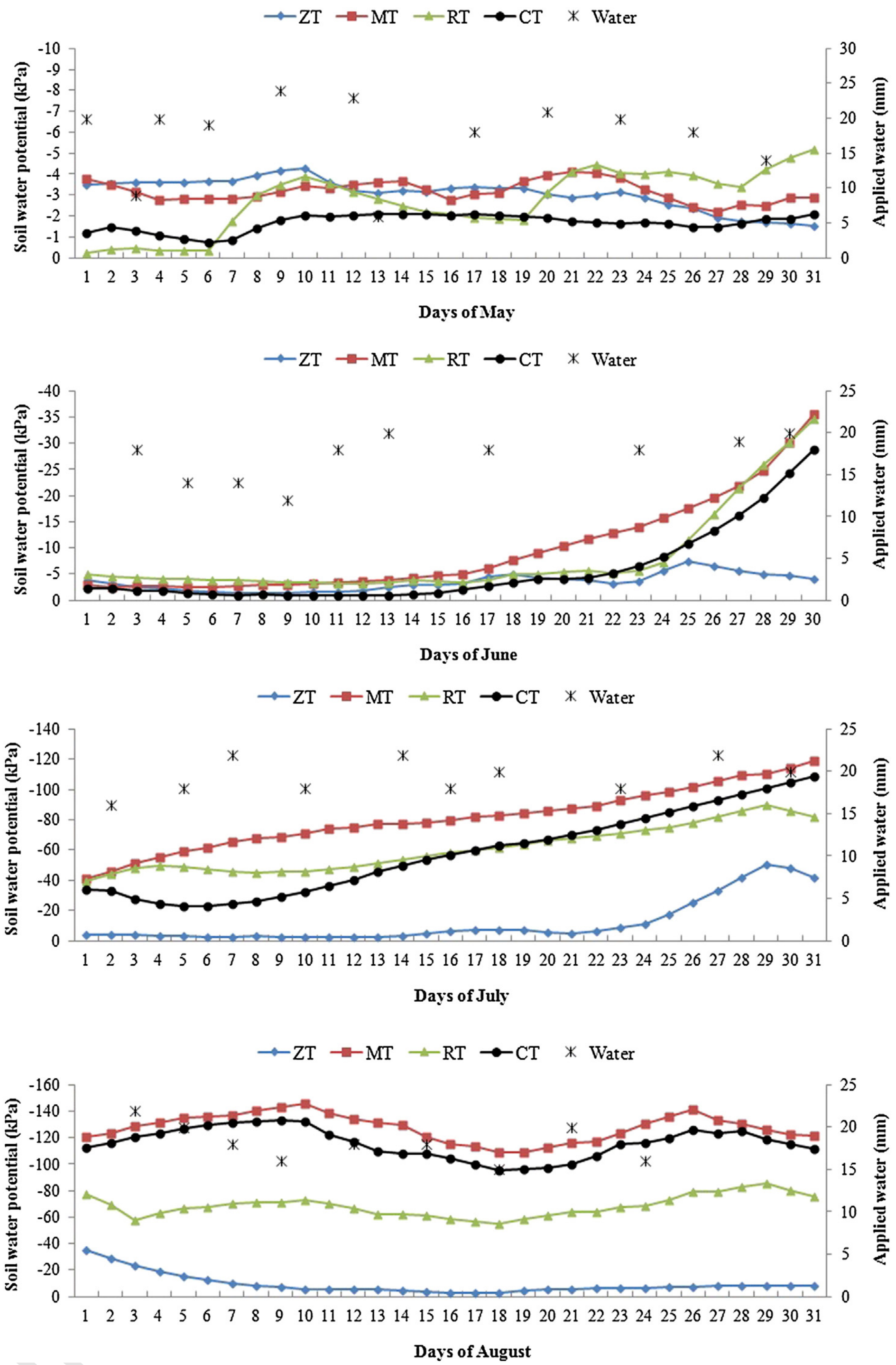

Fig. 4. (a, b, c, and d). Daily mean soil water potential (average of three measurements, in (−kPa), mean value of each day ± standard deviations) in May, June, July, and August 2013, respectively, at soil depth of 40 cm. CT: conventional tillage; ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage. Applied water (precipitation and irrigation, mm).

20 ± 1.2 °C, while under CT treatment were 17.2 ± 1.1, 19.1 ± 1.2, and 22.6 ± 1.4 °C, for measurements taken in May, June, and July, respectively.

Soil temperatures in the RT were the second lowest among the four treatments, and no clear differences were noticed between RT and MT at 5 and 12 cm depths.

Overall, at both soil depths, tillage practice affected soil temperatures in the order: CT > MT > RT > ZT. These differences in soil temperature were due to the higher soil water potentials (higher moisture content) recorded under ZT and RT, also, due to soil disturbance and are highly related to changes in soil heat flux. Heat flux in the soil depends on the thermal conductivity and heat capacity of soils changed by tillage, which affects water content, soil structure, and bulk density (Hillel, 1998), because soil particles have a greater heat conductivity and lower heat capacity than water, therefore, dry soils potentially cool and warm faster than wet soils (Licht and Al-Kaisi, 2005). This difference in temperature and water content behavior, already described in the literature, is due to the presence of residues under conservation tillage that limit the penetration of solar radiation and consequent soil heating, and reduce evaporation from its surface. It was found that changing soil temperature even by 1 °C could affect maize growth and yield (Schneider and Gupta, 1985).

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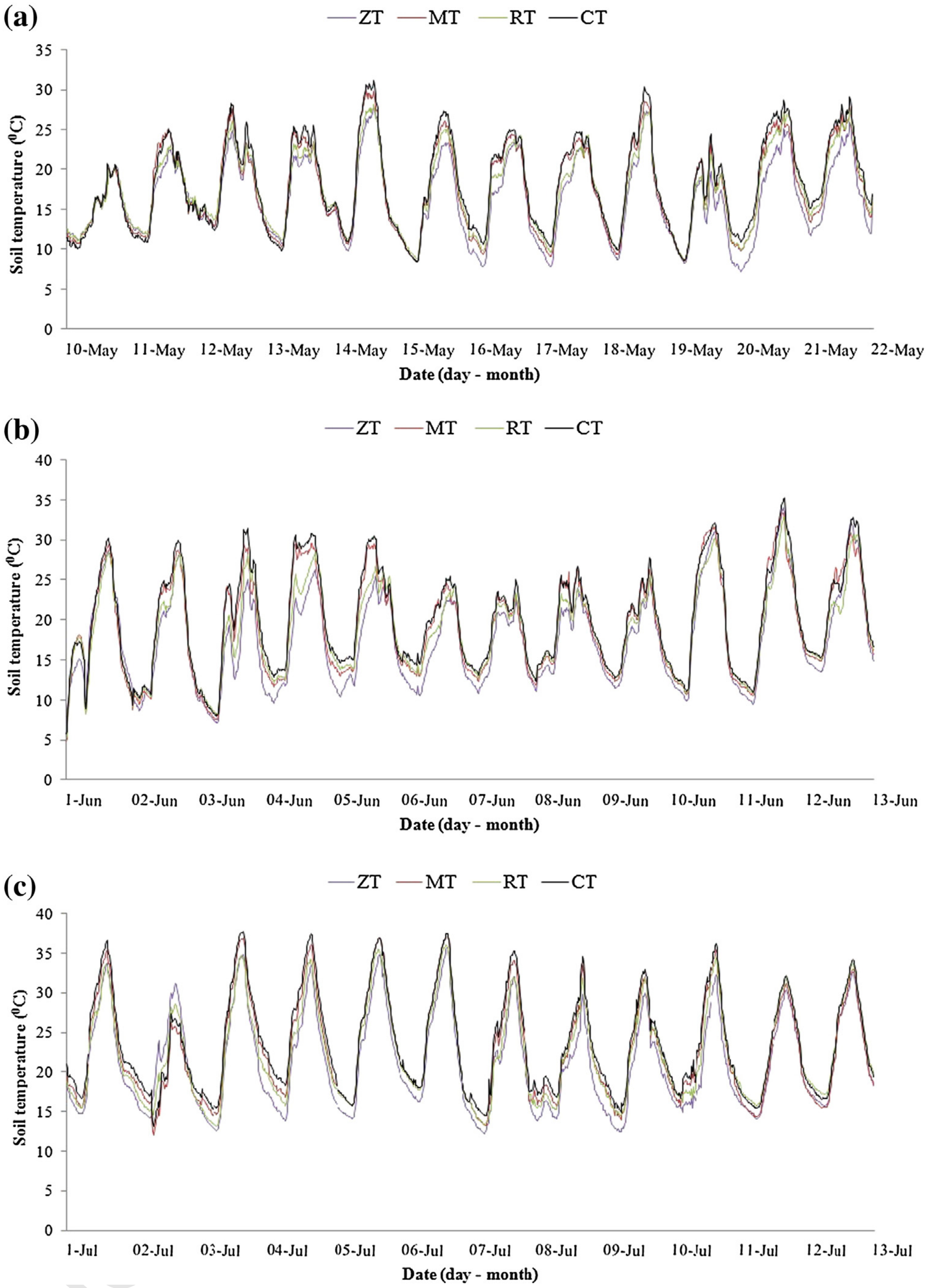

Fig. 5. (a, b, and c). Mean soil temperature at 5 cm depth recorded during (a) 10–21 May, (b) 1–12 June, and (c) 1–12 July 2013. CT: conventional tillage; ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage.

3.5. Maize Yield and Water Use Efficiency

Maize grain yield, some yield components, and water use efficiency in response to tillage treatments are shown in (Table 4), results of treatments' mean comparison for cob length, number of rows per cob, grain yield, and water use efficiency showed that there was a significant difference between ZT treatment and other tillage treatments (RT, MT, and CT).

Results of maize thousand kernel weight exhibited that there were no significant differences among tillage treatments. Also, all treatments' mean comparison indicated that no significant differences were found between RT, MT, and CT. Treatments' mean comparison indicated that ZT treatment decreased cob length, number of rows per cob, and grain yield, compared to the CT method for 18.8, 15.8, and 15.4%, respectively. Water use efficiency followed the same trend as in grain yield.

Results of this study showed that the increasing of soil compaction and decreasing of soil temperature in the ZT method is a potential reason for maize yield and yield components reduction in this tillage method. Similarly, Afzalinia and Zabihi (2014) found that zero tillage in a short-term investigation decreased maize grain yield and yield component compared to conventional tillage for 18.2 and 11.1%, respectively. They reported that the reason for that decrease in maize yield is the higher soil compaction under zero tillage.

4. Conclusions

The short-term effects of four different tillage practices on soil compaction indicators, soil water potential, soil temperature, and maize yield were evaluated.

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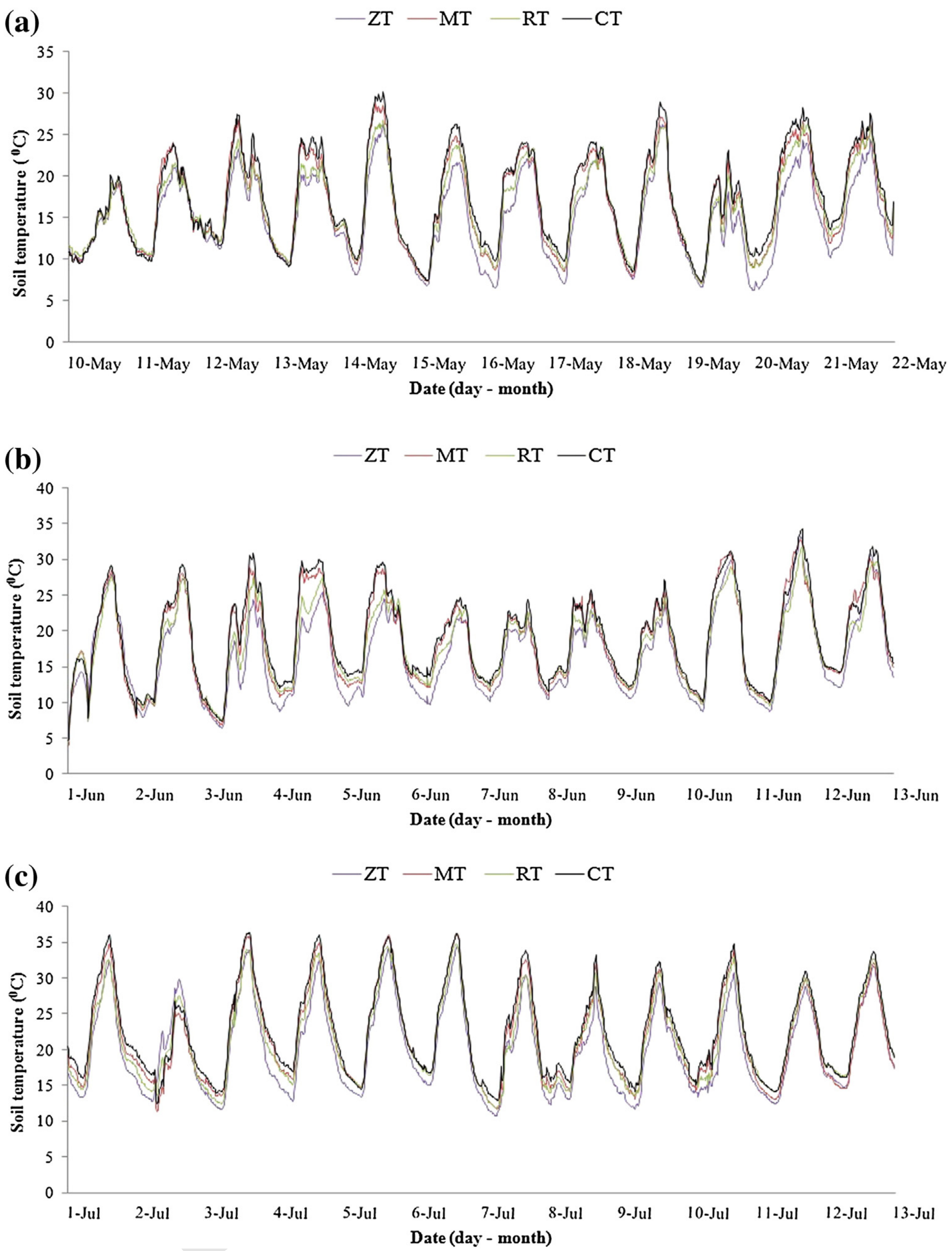

Fig. 6. (a, b, and c). Mean soil temperature at 12 cm depth recorded during (a) 10–21 May, (b) 1–12 June, and (c) 1–12 July 2013. CT: conventional tillage; ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage.

Results of this research showed that soil compaction decreased when conventional tillage is used compared to the other tillage practices, the topsoil is loosened by aggressive ploughing with conventional tillage, such that it reduces bulk density compared to zero tillage. Reservoir tillage and minimum tillage showed a moderate effect on soil compaction indicators. Furthermore, among tillage methods tested, soil temperature under zero tillage was generally lower than under the other tillage practices at emergence and this difference continued during the stages of plant development. In our case study, water resources for irrigation were not limited, and the combination of lower temperature and higher soil compaction was the most important factor that affected maize yield. Among tillage methods tested, a significant

Table 4
Means comparison of maize yield and some yield components in different tillage methods.

Tillage methods	Cob length (cm)	N. of rows per cob	Weight of 1000 kernels (g)	Grain yield (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
CT	22.3^a	19^a	292.3	9508^a	12.39^a
ZT	18.1^c	16^b	273	8041^b	10.48^b
MT	20.8^b	18^a	281.3	9183^a	11.97^a
RT	21^{ab}	18^a	285.2	9228^a	12.03^a
LSD	1.47	2.24	21.47	600	0.78

CT: conventional tillage; ZT: zero tillage; MT: minimum tillage; RT: reservoir tillage. Different letters in the same column indicate significant differences ($p < 0.05$).

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decreasing in maize yield occurred when zero tillage is used. On the other hand, there were no significant differences among conventional tillage, reservoir tillage, and minimum tillage on maize yield. The higher maize yield was attained with the conventional tillage followed by the reservoir tillage and the minimum tillage. The methodology implemented for the evaluation of the soil water potential using the wireless sensors network in this study was suitable and adequate, and can be considered as a helpful tool in the understanding of soil water dynamics throughout the growing season.

We found that reservoir tillage is certainly a viable option that has moderate and positive effects on soil physical properties and increased crop yields compared to zero tillage and minimum tillage, and provided an opportunity to stabilize crop yields compared to conventional tillage. Furthermore, it could retain soil organic carbon, reduce erosion, and save fuel and production costs due to the less aggressive tillage performance. It is therefore desirable to encourage farmers to initially opt for this technique when switching from conventional tillage to conservation tillage. Nevertheless, continued research is needed to determine the longer term effects of these tillage practices on soil properties and crop yield.

Q10 Q9

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