Yield, water use productivity, and soil properties as influenced by conservation tillage and irrigation methods in wheat-maize cropping system

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Abstract: The objective of this study was to evaluate the interaction effect of conservation tillage and irrigation methods on the soil properties, crop yield and water use productivity in wheat-maize cropping system. A split plot experimental design with three replications was used for this study in Fars province, Iran. Surface irrigation (SI), drip tape irrigation (DTI), and sprinkler irrigation (SpI) were considered as main plots, and no-tillage (NT), reduced tillage (RT), and conventional tillage (CT) were considered as sub plots. Results showed that SI had the maximum wheat yield on average and the maximum maize yield was obtained from DTI on average; while tillage methods had no significant effect on crops yield. Results also indicated that the maximum water use productivity in wheat and maize production were obtained from DTI on average and the minimum use productivity were related to the SI on average. DTI and SpI saved water compared to the SI by 43% and 22% on average in wheat and 57% and 36% on average in maize, respectively. NT increased water content of soil compared to the CT by 51%. SI had the lowest soil infiltration rate, and NT reduced soil infiltration rate compared to the CT by 26% on average. Conservation tillage (CoT) increased organic carbon of the soil depth of 0.00 to 0.10 m by 12% compared to the CT. Therefore, DTI combined with CoT is recommended for wheat-maize cropping system in a semi-arid climate condition.

Keywords: crop residue, organic carbon, soil bulk density, water use

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1 Introduction

Conserving soil and water as two important resources of agricultural production can help the agricultural sector to produce enough food for the growing population in Iran. Wheat is the most strategic agricultural product in Iran and had the highest area of cultivation and production among all the agricultural crops in this country. Applying proper tillage systems and efficient irrigation methods in wheat cultivation is necessary for conserving soil and water. Using conservation tillage methods (CoT) (reduced tillage, RT and no-till, NT) which are rapidly growing in the world can be a potential solution for conserving soil and water in wheat production in arid and semi-arid regions of Iran.

Evaporation from the top of the soil, soil temperature, and maize yield decreases and water retention in the soil, soil bulk density, and soil penetration resistance increases

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in NT (Fabrizzi et al., 2005; De Vita et al., 2007). NT improves water conversation, winter wheat yield, water use efficiency, and economic benefit compared to the RT and conventional tillage (CT) on the Loess Plateau, China (Su et al., 2007). Results of a 15 years study on effects of CoT on soil structure and wheat productivity in the rainfed dryland farming regions of northern China shows that NT increases soil capillary porosity, water stability of macro-aggregates, soil organic matter, soil total nitrogen and potassium, earthworms, wheat yield, and water use efficiency and decreases soil bulk density compared to the CT (Li et al., 2007). NT has also the best effect on soil water conservation in fallow and crop growth period in winter wheat-spring maize rotation, so that in crop growth period, soil average water storage (depth of 0.00-2.00 m) under NT is 6.7% higher than that of deep-ploughing (Zhang et al., 2011). Zero tillage and permanent beds practices reduce irrigation water requirement and increase grain yield, biomass yield, and water use efficiency compared to the CT in the maize-wheat-mung bean cropping system (Parihar et al., 2017). Wheat straw mulch reduces runoff and soil losses in Loess Plateau of China; however, the optimum mulch rate depends on the soil type, land slope, and rainfall intensity (Rahma et al., 2019).

CoT performance may also be affected by the irrigation method used in the farm. NT has higher soil hydraulic conductivity, soil water absorption, and soil micro-organisms activity compared to the CT (McGarry et al., 2000). Flat no-till method has higher wheat productivity compared to the furrow irrigated raised bed and conventional till flat planting in maize-wheat cropping system (Jat et al., 2005). Results of a research conducted in Pakistan reveals that furrow irrigation method saves water consumption for 35.6%, and increases wheat yield and yield components compared to the flat border irrigation method (Ahmad et al., 2010). Results of evaluating the effect of irrigation on wheat root development indicates that the main root distribution zone of wheat moves upward under sprinkler and surface drip irrigations compared to the traditional border irrigation (Lv et al., 2010). Results of a study carried out in Morocco proves that DI saves water for 20% and increases crop yield and water use efficiency in wheat production compared to the SI in a semi-arid climate condition (Kharrou et al., 2011). The economic water use productivity ratio for micro-irrigation systems is about 25% of the economic water productivity ratio of basin irrigation method in winter wheat production in the North China Plain (Fang et al., 2018).

There are numerous research works in literature about effects of CoT on soil properties and wheat yield. The effects of irrigation on wheat water consumption and productivity have been also adequately evaluated in the previous research works, but the effect of interaction between CoT and irrigation (surface irrigation (SI), drip tape irrigation (DTI), and sprinkler irrigation (SpI)) on soil properties, wheat water consumption, and water productivity has not been adequately investigated so far. Therefore, our objective was to simultaneously evaluate the effect of CoT and irrigation methods on the soil properties, wheat and maize yield, wheat and maize water use productivity on semi-arid zone.

2 Materials and methods

2.1 Site specifications

The research was conducted in Marvdasht region of Fars province (Southern Iran, 30°94′E, 52°48′N, average annual rainfall of 365 mm, maximum temperature of 41°C, minimum temperature of 9°C, and 1620 m above sea level) from 2009 to 2011. Specifications of the soil (Typic Calcixerepts) in which the experiment was performed are presented in Table 1.

2.2 Experimental design and treatments

The research was conducted using a strip-plot experimental design with three replications and nine treatments (Figure 1). Main plots were irrigation methods including 1) surface irrigation (SI) using gated pipe with gate space of 0.75 m as flood irrigation for both wheat (*Triticum aestivum* L.) and maize (*Zea mays L.*); 2) drip tape irrigation (DTI) with dripper space of 0.20 m and row space of 0.75 m for both wheat and maize; and 3) sprinkler irrigation (SpI) with Pirot ZK30 sprinkler, operation pressure of 300 kPa, flow rate of 0.7 litter per second, jet length of 19 m, and arrangement of 20 by 15 m for both wheat and maize. Tillage methods including no-tillage (NT), reduced tillage (RT), and conventional tillage (CT) were considered as sub plots in both crops.

Table 1 Selected properties of the soil used for the study

Soil depth (m)	O.C (%)	EC (dS m^{-1})	pH	Bulk density (g cm^{-3})	Hydraulic Conductivity (cm day^{-1})	Clay (%)	Silt (%)	Sand (%)	Soil texture
0.00-0.10	0.72	0.94	8.22	1.24	24.9	42.00	34.00	24.00	Clay
0.10-0.20	0.70	0.84	8.20	1.30	16.1	45.00	44.00	11.00	Silty-clay

Figure 1 A schematic lay-out of the experimental design.

Note: CT: Conventional tillage, RT: Reduced tillage, NT: No-tillage, R1: Replication 1, R2: Replication 2, R3: Replication 3.

Wheat standing straws were retained in the plots and residues lying flat on the soil surface were taken out of the plots. Maize was harvested as grain; therefore, all residues remained from harvesting were retained in the plots (about 10 tons ha^{-1}). Moldboard plow with working depth of 0.25 m was used for primary tillage and disk harrow and land leveler was used for secondary tillage operation in the CT, then crop seed was planted using seed planter. In the RT, seed bed was prepared using a tine and disc cultivator with working depth of 0.15 m then crop seed was planted using seed planter. Wheat and maize seed were directly planted using direct grain seeder in un-tilled soil in the NT. Seed bed was prepared in late June for maize and in late November for wheat in all treatments. Crop evapotranspiration for each crop was calculated based on FAO Penman-Monteith method (Allen et al., 1998) using climatology data and Cropwat4 software. Effective rain during growing season was deducted from the calculated

ET_c to determine irrigation water requirement for each crop (Table 2). Irrigation efficiencies of 50%, 70%, and 90% were considered for surface, sprinkler, and drip tape irrigation, respectively. Irrigation scheduling of every 10, 7, and 4 days was arranged for surface, sprinkler, and drip tape irrigation, respectively and required water was supplied to each plot using calibrated flow meters.

Table 2 Irrigation water requirement for wheat and maize

Crop	2009-2010			2010-2011		
	ETc (mm)	Effective rain (mm)	Irrigation water requirement (mm)	ET_c (mm)	Effective rain (mm)	Irrigation water requirement (mm)
Wheat	602	230	431	631	186	468
Maize	574	3	571	603	0	603

Study period started with planting wheat in November 2009 and ended with harvesting maize in November 2011 (two wheat and two maize cropping seasons). The field was fallow for one cropping season before applying the treatments; therefore, the first wheat was planted inside weed residues remained from the fallow season. Local wheat variety of Chamran with the seed rate of 250 kg ha^{-1} and row space of 0.17 m was planted in 20 by 6 m plots using Sfoggia grain drill (Montebelluna, Treviso, Italy) in late November and harvested in late June for all treatments. Maize variety of 704 single cross with the seed rate of 25 kg ha^{-1} was planted with the row space of 0.75 m using Berttini row planter (Rosario, Santa Fe, Argentina) in early July and harvested in early November for all treatments. Water applied to the main plots (irrigation treatments) was different based on irrigation method efficiency, but identical amount of water was applied to all the tillage treatments in each irrigation method. During wheat growing season, N; 184 kg ha^{-1}, P; 60 kg ha^{-1}, and K; 68 kg ha^{-1} were used as chemical fertilizers for all treatments, while fertilizers used for maize growing season were N; 276 kg ha^{-1}, P; 60 kg ha^{-1}, and K; 68 kg ha^{-1}. Weed, pest, and disease control managements were also applied to all tillage and irrigation treatments.

2.3 Parameters measurements

The soil infiltration rate was determined using the double ring method before harvesting wheat in June (one measurement for each plot). Soil bulk density was determined two times during two growing years including measurements in June 2010 and June 2011 before harvesting wheat. This parameter was measured in soil depth ranges of 0.00 to 0.10 and 0.10 to 0.20 m using core samplers (Black and Harte, 1986).

Water content of soil was measured using Time Domain Reflectometry (TDR) model TRIME-PICO IPH T3/44 at the soil depth of 0.00-0.20 m (three insertions for each plot) before wheat harvesting. Soil acidity (pH), electrical conductivity (EC), and organic carbon (OC) were measured by taking mixed soil samples (mixture of three samples from each plot) from the depth of 0.00 to 0.10 and 0.10 to 0.20 m of each plot and analyzing the samples at laboratory. Soil samples were taken from the diameter of the rectangle plots. crop yield per unit area was obtained by manually harvesting 10 m^2 area of each plot (summation of 10 randomly selected points with area of one square meter each). Water use in each plot was metered and water productivity computed as the ratio of crop yield over water consumption as follow:

$$WP = \frac{Y}{W} \quad (1)$$

Where *WP* is water use productivity (kg m^{-3}), *Y* is crop yield (kg ha^{-1}), and *W* is water use (m^3 ha^{-1}).

2.4 Statistical analysis

One-way ANOVA analysis were applied to the data collected from the field experiments using SAS software and Duncan’s multiple range tests was used to compare the treatments means.

3 Results and discussion

3.1 Wheat and maize yield

Results showed that irrigation methods and tillage treatments had no significant effect on the wheat yield in the first year (Table 3). In the second year, wheat yield was significantly affected by irrigation methods and tillage treatments. Interaction between tillage and irrigation methods had no significant influence on the wheat yield in both years. Results also showed that irrigation method had significant effect on maize yield in both years. Tillage treatments and interaction between irrigation and tillage had no significant effect on maize yield in both cropping years (Table 3).

Table 3 Variance analysis of wheat and maize yield data (F values)

Variation resources	Wheat		Maize	
	2009-2010	2010-2011	2009-2010	2010-2011
Replication	3.64 ns	0.52 ns	1.51 ns	0.68 ns
Irrigation methods	0.61 ns	18.75 **	5.54*	7.57**
Tillage methods	1.01 ns	32.99 **	2.44 ns	0.32 ns
Irrigation × Tillage	1.63 ns	0.91 ns	1.59 ns	2.98 ns

Note: ns: Non-significant; *: significant at $p<0.05$; **: significant at $p<0.01$.

Means comparison of wheat yield in different irrigation methods showed that the minimum wheat yield was obtained from the treatment irrigating with SpI method in both cropping seasons (Table 4). Wheat yield in this treatment was significantly different from those of DTI and SI in 2010-2011 growing season, whereas, there was no significant difference between irrigation methods for wheat yield in 2009-2010. Wheat yield in plots irrigated with SI and DTI were almost same and there was no significant difference between them. SI increased wheat yield compared to DTI and SpI by 3.6% and 22.2%, respectively on average. Results of a study carried out in Morocco proved that DI increased wheat yield compared to the SI in semi-arid climate condition (Kharrou et al., 2011); while DI had lower wheat yield relative to the SI in our study. Results also indicated that the CT had the maximum wheat yield and the minimum wheat yield was recorded under CoT in both growing seasons; however, there was no significant difference between treatments in 2009-2010 growing season (Table 4). NT and RT reduced wheat yield compared to CT by 14.4% and 6.6%, respectively on average. Our results contradicted those of Freebairn et al. (1986), Su et al. (2007), and Li et al. (2007) who reported higher wheat yield under CoT compared with the CT under rainfed condition. Under rainfed condition, water content of soil is the most limiting factor for crop yield, and CoT improves crop yield in this condition by conserving more soil moisture compared to the CT (Pittelkow et al., 2015); whereas, in the irrigated condition sufficient water is supplied to the conservation and conventional tillage treatments. On the other hand, CoT can improve water productivity for the similar crop yield by reducing water consumption if the water is applied based on soil moisture monitoring.

Comparing wheat yield means in different irrigation methods showed that there was no significant difference between DTI and SpI methods from maize yield point of view in both growing seasons, SI had the lowest maize yield among the irrigation methods tested (Table 4). Hassanli et al. (2009) and Cetin and Bilgel (2002) also found that maize yield under pressurized irrigation methods was higher than that of SI. Maize yield showed a drastic reduction in the second year for all irrigation and tillage methods which was due to the frost phenomenon occurred at the end of 2010-2011 maize cropping season. Results showed that there was no significant difference between tillage treatments for maize yield in both growing seasons (Table 4).

3.2 Water use and water use productivity

Results of comparing water use in different irrigation methods showed that the maximum water consumption (average of 800.4 mm) occurred in the SI for wheat production and the minimum water consumption (average of 454.6 mm) was related to the DTI (Table 5). The SpI with average water consumption of 627.4 mm had the second place from the water consumption point of view among the irrigation methods tested. Results also showed that the DTI and SpI reduced water consumption in wheat production compared to the SI by 43% and 22%, respectively. Haq (1990) and Latif (1990) reported that SpI decreased water consumption compared to the SI. Results of a study conducted in Morocco also showed that DI saved water by 20% in wheat production compared to the SI in a semi-arid climate condition (Kharrou et al., 2011). The maximum water consumption in maize production was also related to the SI (1643.9 mm on average) and the DTI had the minimum water consumption (702.5 mm on average); therefore, DTI and SpI reduced water consumption compared to the SI by 57% and 36% on average, respectively (Table 5). Higher irrigation efficiency of DTI and SpI methods was the main reason of water use reduction in these irrigation systems. Since maize was a summer crop (warmer weather without precipitation in summer), water use in maize production was significantly higher than in wheat.

Table 4 Wheat and maize yield in different irrigation and tillage methods

Irrigation methods	Wheat yield (kg ha^{-1})			Maize yield (kg ha^{-1})		
	2009-2010	2010-2011	Average	2009-2010	2010-2011	Average
Drip tape	5883a	4816a	5350	10049a	6208a	8129
Surface	5728a	5354a	5541	6934b	3371b	5153
Sprinkler	5548a	3521b	4535	8409ab	7343a	7876
Tillage methods	-	-	-	-	-	-
Conventional tillage	5926a	5132a	5529	9469a	5157a	7313
Reduced tillage	5474a	4856a	5165	7837a	5847a	7292
No-tillage	5759a	3703b	4731	8086a	5917a	7002

Note: a, b: Averages with different letters in each column are statistically different at $p<0.01$.

Table 5 Wheat and maize water use in different irrigation methods

Irrigation methods	Water use in wheat (mm)			Water use in maize (mm)		
	2009-2010	2010-2011	Average	2009-2010	2010-2011	Average
Drip tape	471.3b	437.8c	454.6	609.0c	796.0c	702.5
Surface	708.3a	892.4a	800.4	1415.1a	1872.7a	1643.9
Sprinkler	637.0a	617.7b	627.4	1078.1b	1037.1b	1057.6

Note: a, b: Averages with different letters in each column are statistically different at $p<0.01$.

Variance analysis of water productivity data revealed that irrigation methods had significant effect ($p<0.01$) on water use productivity in wheat production in both years, while tillage methods had significant effect ($p<0.05$) on the wheat water use productivity only in 2010-2011 cropping season (Table 6). Results also showed that interaction between irrigation and tillage methods had no remarkable influence on wheat water use productivity. Since water consumptions and wheat yield in various irrigation methods were significantly different, significant effect of irrigation methods on water use productivity was expected. On the other hand, however same amount of water was supplied to the tillage methods in this study, water use productivity was affected by tillage methods in 2010-2011 growth season due to statistically different wheat yields of tillage methods. Irrigation method had also significant effect ($p<0.01$) on maize water use productivity, whereas maize water use productivity was not significantly affected by tillage treatments (Table 6). Interaction effect of irrigation and tillage methods on maize water use productivity was significant ($p<0.05$) only in 2010-2011cropping season.

Means comparison of wheat water use productivity in irrigation methods showed that DTI had the maximum water use productivity (1.18 kg m^{-3} on average) and the minimum water use productivity (0.71 kg m^{-3} on average) was related to SI (Table 7). The difference between water use productivity of DTI and those of SI and SpI was significant, whereas the difference between water use productivity of SI and SpI was not significant. Therefore, in spite of having lower water consumption, the SpI had water productivity close to that of SI in both years because of the lower crop yield compared to the SI. Kharrou et al. (2011) also reported that DI improved water use efficiency compared to the SI in wheat production. Results also showed that there was no significant difference between tillage methods for wheat water use productivity in 2009-2010; while the difference between tillage methods was significant in 2010-2011 (Table 7). CT had the maximum water use productivity (0.93 kg m^{-3} on average) and the minimum water use productivity (0.81 kg m^{-3} on average) was related to the NT. Our results contradicted those of Freebairn et al. (1986) and Li et al. (2007) who reported the higher wheat water use productivity for CoT compared to the CT under rainfed condition which has different circumstances with respect to the irrigated cropping system.

Table 6 Variance analysis of water use productivity data (F values)

Variation resources	Wheat		Maize	
	2009-2010	2010-2011	2009-2010	2010-2011
Replication	4.49^{ns}	0.57^{ns}	1.82^{ns}	0.9^{ns}
Irrigation methods	69.1**	41.92**	113.54**	22.38**
Tillage methods	1.68^{ns}	9.6*	2.94^{ns}	0.08^{ns}
Irrigation × Tillage	1.88^{ns}	0.35^{ns}	1.36^{ns}	3.64*

Note: ^{ns}: Non-significant; *: significant at p<0.05; **: significant at p<0.01.

Table 7 Wheat and maize water use productivity in different irrigation and tillage methods

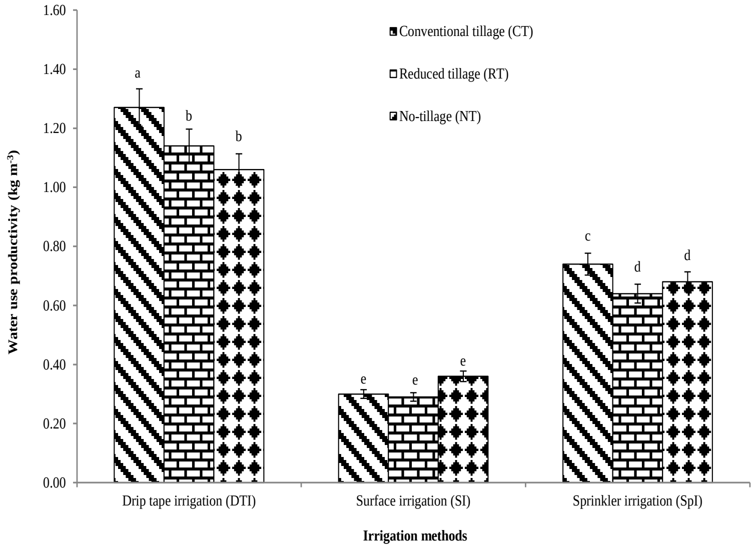
Irrigation methods	Wheat water use productivity (kg m^{-3})			Maize water use productivity (kg m^{-3})		
	2009-2010	2010-2011	Average	2009-2010	2010-2011	Average
Drip tape	1.25 a	1.10 a	1.18	1.65a	0.78a	1.22
Surface	0.81 b	0.60 b	0.71	0.49c	0.18b	0.34
Sprinkler	0.87 b	0.57 b	0.72	0.78b	0.71a	0.75
Tillage methods	-	-	-	-	-	-
Conventional tillage	1.01a	0.84a	0.93	1.08a	0.54a	0.81
Reduced tillage	0.92a	0.81a	0.87	0.90a	0.58a	0.74
No-tillage	0.99a	0.63b	0.81	0.94a	0.55a	0.75

Note: a, b: Averages with different letters in each column are statistically different at p<0.01.

The maximum water use productivity in maize production (1.22 kg m^{-3} on average) was related to the DTI because of high crop yield and low water consumption in this irrigation method (Table 7). On the other hand, SI had the lowest maize water use productivity (0.34 kg m^{-3} on average) in both years due to its low crop yield and water use efficiency. There was no significant difference between tillage treatments from maize water use productivity, because maize yield was not significantly different in various tillage treatments (Table 4) and the same water amount was supplied to the tillage treatments (Table 7). Interaction effect of irrigation and tillage methods on maize water use productivity indicated that CT irrigated with DTI had the maximum water use productivity and RT irrigated with SI had the lowest water use productivity (Figure 2).

3.3 Soil water content

Variance analysis of soil water content showed that irrigation method and interaction between irrigation and tillage methods had no significant effect on water content of soil in March 2010, but water content of soil was affected by irrigation systems (p<0.01) and interaction between irrigation and tillage methods (p<0.05) in March 2011 (Table 8). Tillage methods had significant effect (p<0.01) on water content of soil in both growing seasons. Since crop residue management and intensity of soil disturbance was different in tillage methods evaluated in this research, moisture retention in the soil was influenced by the tillage methods.



Note: a, b, c, d, e: Averages with different letters in each column are statistically different at p<0.01.

Figure 2 Interaction effects of tillage and irrigation methods on average maize water use productivity.

Plots irrigated with different irrigation systems had statistically same water content of soil in March 2010 (Table 9). Plots irrigated with DTI system had the maximum water content of soil in March 2011 and the plots irrigated with SpI had the lowest water content of soil in this measurement. Interaction effect of irrigation type and crop residue retention on soil surface (more crop residues were retained on soil surface in 2010-2011 compared to 2009-2010) probably was the reason for significant effect of irrigation methods on the soil moisture retention in March 2011.

Table 8 Variance analysis of soil water content data (F values)

Variation resources	March 2010	March 2011
Replication	0.09^{ns}	0.2^{ns}
Irrigation methods	0.67^{ns}	7.9^{**}
Tillage methods	12.35^{**}	19.9^{**}
Irrigation × Tillage	2.27^{ns}	4.2^{*}

Note: ^{ns}: Non-significant; *: significant at p<0.05; **: significant at p<0.01.

Results showed that NT had the maximum soil moisture retention and the CT had the minimum one in both years (Table 9). There was no significant difference between moisture retained in CT and RT in March 2010, while moisture retained in CT and RT in March 2011 was significantly different. Meanwhile, NT increased water content of soil compared to the CT by 21.4% in March 2010, whereas soil moisture increment in NT with respect to the CT was 80.2% in March 2011. The difference between amounts of crop residue retained on the soil surface in two cropping years made difference in effect of tillage methods on soil water content in two years. Increasing soil moisture retention in CoT compared to the CT has been also reported in the previous research works (Fabrizzi et al., 2005; De Vita et al., 2007; Zhang et al., 2011). Results also indicated that NT had the maximum soil moisture retention in all irrigation systems and the highest moisture retention was related to the NT irrigated with DTI (Figure 3).

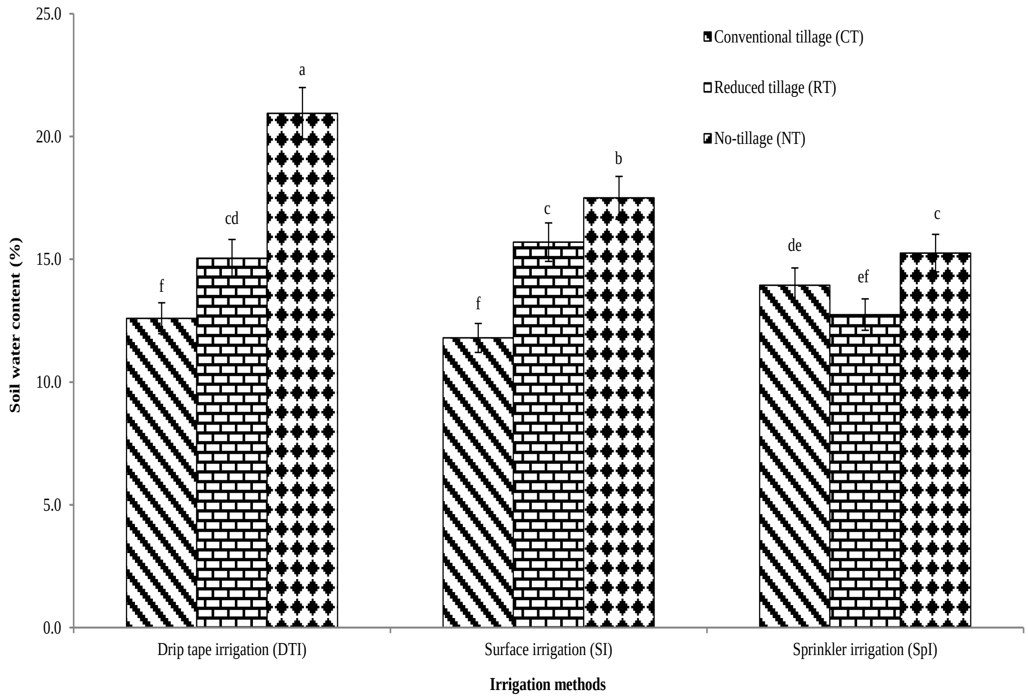
Table 9 Soil water content (%) in different irrigation and tillage methods

Irrigation methods	March 2010	March 2011	Average
Drip tape	16.1 a	16.3 a	16.2
Surface	15.6 a	14.4 b	15.0
Sprinkler	16.3 a	11.7 c	14.0
Tillage methods	-	-	
Conventional tillage	14.5 b	11.1 c	12.8
Reduced tillage	15.8 b	13.2 b	14.5
No-tillage	17.6 a	18.2 a	17.9

Note: a, b: Averages with different letters in each column are statistically different at p<0.05.

3.4 Soil bulk density

Variance analysis of soil bulk density data showed that bulk density was not affected by irrigation systems, tillage methods, and interaction between irrigation and tillage methods in both measurements and soil depths (Table 10). Tillage methods showed no significant effect on soil bulk density because of measuring this parameter at the end of growing season; while, CoT usually have the higher soil bulk density compared to the CT from the beginning to the middle of growing season (Afzalinia and Zabihi, 2014).



a, b, c, d, e, f: Averages with different letters in each column are statistically different at $p<0.01$.

Figure 3 Interaction effects of tillage and irrigation methods on average soil water content.

Table 10 Variance analysis of soil bulk density data (F values)

Variation resources	June 2010		June 2011	
	0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m
Replication	0.80^{ns}	0.36^{ns}	1.64^{ns}	2.64^{ns}
Irrigation methods	3.65^{ns}	0.11^{ns}	2.02^{ns}	1.41^{ns}
Tillage methods	0.47^{ns}	0.51^{ns}	1.43^{ns}	3.81^{ns}
Irrigation × Tillage	1.14^{ns}	0.84^{ns}	0.88^{ns}	0.34^{ns}

Note: ^{ns}: Non-significant; *: significant at $p<0.05$; **: significant at $p<0.01$.

Comparing soil bulk density in different irrigation methods showed that there was no significant difference between irrigation systems for soil bulk density; however, SI and SpI had the higher soil bulk density compared to the DTI especially at the soil depth of 0.00 to 0.10 m (Table 11). The higher soil bulk density in SI was probably because of drops impacts on the soil surface. In SI, clay leaching due to the high amount of water consumption was the potential reason for the higher soil bulk density in this irrigation method compared to the DTI.

Results also showed that tillage methods had no significant effect on the soil bulk density (Table 11). Since soil disturbance was lower in the CoT compared to the CT, the higher soil bulk density was expected in the CoT with respect to the CT, but this did not happen for two potential reasons. The first reason was the time-consuming nature of tillage effects on the soil properties. Tillage effects on soil bulk density were evaluated for two years in this study, while more time was needed to observe the tillage effects on soil bulk density. The second reason was the measuring soil bulk density at the end of growth season in this study. The difference between soil bulk densities in CoT and CT was significant from the beginning up to the middle of growth season, whereas there was no significant difference between bulk densities from the middle up to the end of crop growth season (Afzalinia and Zabihi, 2014). These results showed that CoT did not compact the soil at least in the short time. Results of some previous research works show the higher soil bulk density in the CoT compared to the CT (Liu et al., 2005; Taser and Metinoglu, 2005; Sayed et al., 2020); however, there are also some research results showing no significant effect of CoT on the soil bulk density (Logsdon and Karlen, 2004).

Table 11 Soil bulk density (Mg m^{-3}) in different irrigation and tillage methods

Irrigation methods	June 2010		June 2011	
	0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m
Drip tape	1.21a	1.31a	1.27a	1.29a
Surface	1.28a	1.29a	1.31a	1.31a
Sprinkler	1.25a	1.30a	1.31a	1.32a
Tillage methods	-	-	-	-
Conventional tillage	1.24a	1.28a	1.30a	1.33a
Reduced tillage	1.26a	1.29a	1.25a	1.29a
No-tillage	1.24a	1.32a	1.34a	1.32a

Note: a, b: Averages with different letters in each column are statistically different at $p<0.05$.

3.5 Soil infiltration rate

Variance analysis of soil infiltration rate data showed that irrigation methods, tillage systems, and interaction between irrigation and tillage methods had significant influence ($p<0.01$) on the soil infiltration rate in all measurements (Table 12). Since soil disturbance and crop residue decomposition were different in various irrigation and tillage methods, significant effect of irrigation and tillage methods on the soil infiltration rate was expected.

Table 12 Variance analysis of soil infiltration rate data (F values)

Variation resources	June 2010	June 2011
Replication	42.7^{**}	1.2^{ns}
Irrigation methods	38.2^{**}	197.2^{**}
Tillage methods	13.5^{**}	46.1^{**}
Irrigation × Tillage	15.6^{**}	7.7^{**}

Note: ^{ns}: Non-significant; *: significant at $p<0.05$; **: significant at $p<0.01$.

DTI had the maximum soil infiltration rate in measurement June 2010 and with a slight difference (no significant difference) with SpI, had the second highest infiltration rate in measurement June 2011 (Table 12). Although the SpI had the higher soil infiltration rate compared to the DTI in June 2011 measurement, the difference between these two treatments was not significant. SI had the minimum soil infiltration rate in both measurements. Water reaches the soil gradually in DTI and clay leaching in this irrigation method is low; therefore, soil has more porous structure and higher infiltration rate in this irrigation system (DTI has the lower soil bulk density compared to the SI as shown in Table 11). In contrast, more clay leaching in SI slows down the water movement in the soil in this irrigation system. Results also showed that soil infiltration rate increased from the beginning to the end of research period in all treatments because of increasing soil organic matter due to crop residue retention in the soil.

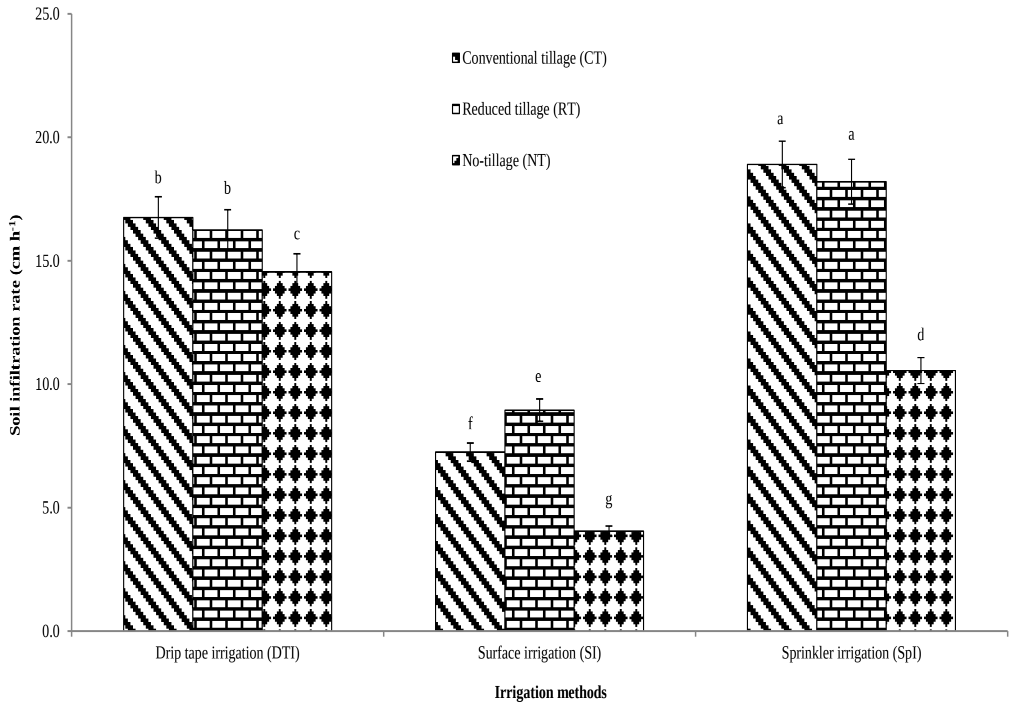
Table 13 Soil infiltration rate (cm h^{-1}) in different irrigation and tillage methods

Irrigation methods	June 2010	June 2011	Average
Drip tape	6.5 a	25.2 a	15.9
Surface	4.0 b	9.4 b	6.7
Sprinkler	4.6 b	27.2 a	15.9
Tillage methods	-	-	
Conventional tillage	5.1 b	23.6 a	14.4
Reduced tillage	5.8 a	23.1 a	14.5
No-tillage	4.3 c	15.2 b	9.8

Note: a, b, c: Averages with different letters in each column are statistically different at $p<0.05$.

Results of soil infiltration rate means comparison in different tillage methods revealed that CT had the highest soil infiltration rate compared to the CoT in both measurements; however, the difference between CT and RT was not significant in June 2011 (Table 13). The minimum soil infiltration rate in both measurements was related to the NT. NT reduced soil infiltration rate compared to the CT by 16% and 36% in June 2010 and

June 2011, respectively. The higher soil infiltration rate in the CT compared to the NT was probably because of more soil disturbance in this tillage method. Means comparison of soil infiltration rates affected by interaction between irrigation and tillage methods showed that CT irrigated by sprinkler irrigation had the maximum soil infiltration rate and the NT method irrigated by SI had the minimum soil infiltration rate (Figure 4).



a, b, c, d, e, f, g: Averages with different letters in each column are statistically different at $p<0.01$.

Figure 4 Interaction effects of tillage and irrigation methods on average soil infiltration rate.

3.6 Soil pH, EC, and OC

Variance analysis of soil pH, EC, and OC data revealed that soil pH was affected by irrigation methods at the soil depth of 0.00 to 0.10 m, while irrigation method had no significant effect on this parameter at the soil depth of 0.10-0.20 m (Table 14). Since amount of water leaching was different in various irrigation methods, soil pH was affected by irrigation methods at the soil depth of 0.00 to 0.10 m. Tillage methods and interaction between irrigation and tillage methods had also no significant effect on soil pH. Soil EC was influenced by irrigation methods at both soil depths, but tillage methods and interaction between irrigation and tillage methods had no significant effect on soil EC. Organic carbon (OC) was only affected by tillage methods at the soil depth of 0.00 to 0.10 m; whereas, irrigation systems and interaction between irrigation systems and tillage methods had no significant effect on soil OC. Since residual management and soil disturbance was varied in different tillage methods, effect of tillage systems on soil OC was significant.

SpI had the maximum soil pH at the soil depth of 0.00 to 0.10 m which was not statistically different from that of the plots irrigated by SI (Table 15). The minimum soil pH was recorded under DTI. DTI had the highest soil EC at both soil depths, while SpI had the lowest soil EC which was not statistically different from that of SI. DTI concentrated soil and water salts on the soil surface; whereas, SI leached the soil and water salts and moved the salt to deeper soil. Therefore, soil EC in DTI was higher than that of SpI and SI. There was no significant difference between irrigation methods from the soil OC point of view.

Means comparison of tillage treatments for soil pH, EC, and OC revealed that only OC at the soil depth of 0.00 to 0.10 m was affected by tillage treatments and tillage methods were categorized in one group from soil pH (both soil depths), EC (both soil depths), and OC at the soil depth of 0.10 to 0.20 m (Table 15). RT had the maximum soil OC and the minimum OC was observed under CT. Since crop residue was kept on the soil surface or mixed with top soil layer in the CoT and minimum soil disturbance was accrued in these methods, soil OC at the soil depth of 0.00 to 0.10 m increased in the CoT compared to the CT. Increasing soil OC in CoT systems compared to the CT has been also shown in previous research works (Li et al., 2007; Madejón et al., 2009; Garcia-Orenes et al., 2009; Houshyar and Esmailpour, 2020).

Table 14 Variance analysis of soil pH, EC, and OC data (F values)

Variation resources	pH		EC		OC	
	0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m
Replication	0.83 ^{ns}	1.32 ^{ns}	0.45 ^{ns}	0.32 ^{ns}	1.21 ^{ns}	0.27 ^{ns}
Irrigation methods	14.27**	0.68 ^{ns}	8.71**	15.18**	0.90 ^{ns}	0.60 ^{ns}
Tillage methods	0.50 ^{ns}	1.95 ^{ns}	0.25 ^{ns}	0.32 ^{ns}	2.97*	1.0 ^{ns}
Irrigation × Tillage	2.94 ^{ns}	1.0 ^{ns}	0.53 ^{ns}	2.31 ^{ns}	0.54 ^{ns}	1.44 ^{ns}

Note: ^{ns}: Non-significant; *: significant at *p*<0.05; **: significant at *p*<0.01. pH: Acidity, EC: Electrical conductivity, and OC: Organic carbon.

Table 15 Soil pH, EC, and OC in different irrigation and tillage methods

Irrigation methods	pH		EC (dS m^{-1})		OC (g kg^{-1})	
	0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m
Drip tape	8.2 b	8.5 a	3.7 a	1.5 a	7.2 a	7.3 a
Surface	8.4 a	8.4 a	1.7 b	0.8 b	6.8 a	7.3 a
Sprinkler	8.7 a	8.4 a	0.9 b	0.8 b	6.6 a	7.0 a
Tillage methods	-	-	-	-	-	-
Conventional tillage	8.4 a	8.4 a	2.4 a	1.1 a	6.4 b	7.0 a
Reduced tillage	8.4 a	8.5 a	1.9 a	1.0 a	7.6 a	7.4 a
No-tillage	8.4 a	8.4 a	2.0 a	1.0 a	6.7 ab	7.1 a

Note: a, b: Averages with different letters in each column are statistically different at *p*<0.05. pH: Acidity, EC: Electrical conductivity, and OC: Organic carbon.

4 Conclusions

Interaction effects of irrigation and tillage methods on soil properties, crop yield, and water use productivity in wheat-maize cropping system were studied. Results showed that water content of soil and soil infiltration rate were affected by interaction between tillage and irrigation methods. Since both irrigation and tillage methods influence water use in wheat-maize cropping system, we expected to observe positive effect of interaction between irrigation and tillage on water use productivity, but this was not observed because of supplying same water quantity to the tillage treatments. Therefore, in order to detect the positive effect of interaction between tillage and irrigation on water use productivity, water should be applied to the tillage treatments based on soil moisture content. CoT did not significantly reduce maize yield showing that, CT can be replaced by CoT in maize production. Despite having advantages such as increasing soil water retention and organic carbon, NT reduced wheat yield compared to the CT showing that soil needed more time to get adapted to the new conditions provided by NT. On the other hand, DTI and SpI had lower water use and higher water productivity compared to the SI in both crops; therefore, these irrigation systems are preferred in wheat-maize cropping system.

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