

Short-Term Effects of Soil Management Strategies on the Hydro-Physical Properties of Soil and Wheat Yield in an Arid Region in Southwestern Iran

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Abstract—This study is aimed to compare the hydrophysical properties of Cambisols and wheat yield on plots under different soil management strategies. The soil (0–20 cm) consists of 21% sand, 37% silt, and 42% clay. This experiment was conducted with three tillage system types (TST) in main plots (reduced tillage using combined tillage: T1, reduced tillage comprised of chisel plough: T2 and conventional tillage: T3), three harvest residue covers (HRC) in sub-plots (no residue: C1, 40% wheat residue: C2, and 80% wheat residue: C3), and three implement forward speeds (IFS) in sub-subplots (4 km/h: S1, 7 km/h: S2, and 10 km/h: S3). Infiltration tests were performed by single-disc tensions infiltrometer with a diameter of 20 cm at successive applied matric suction (h) of 20, 14, 4, 1, and 0 cm. Mean comparison results showed that soil organic matter decreased in T3 treatment, due to soil aggregate degradation. T3, C3, and S3 treatments increased the hydraulic conductivity at matric suction (h) of 1 cm by increasing the number of macropores per unit area and their contribution to the saturated water flux. In contrast, T1 treatment increased hydraulic conductivity at h of 4, 14, and 20 cm by increasing the number of meso- and micropores. The contribution of micropores to the saturated water flux, hydraulic conductivity at $h = 20$ cm were higher in residual-cover-free plots. Hydraulic conductivity at h of 1, 4, and 14 cm increased with increasing HRC due to an increase in the number of macro- and mesopores and their contribution to the saturated water flux. Macroscopic capillary length (λ_c) under T1, T2 and S1 was more than those under T3 and high IFS. T3 treatment also reduced λ_c likely due to its destruction effects on pore continuity. The application of T2, C2, and S2 treatments led to maximum wheat yield, likely by minimizing mechanical manipulation, reducing evaporation and improving soil moisture conditions.

Keywords: tillage systems, residual cover, unsaturated hydraulic conductivity, macroscopic capillary length

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INTRODUCTION

It is well documented that management strategies of soil and water resources are critical to increasing crop productivity, environmental sustainability, and human health [12]. Soil management has become increasingly important because of the increasing global population and the consequent demands for food production [12]. Soil tillage systems, in the short and long term, affect crops yield by virtue of induced-changes in most physical, chemical, and biological properties of soil. Recent agricultural methods aim to achieve the highest production yields with minimal energy consumption in the context of environmental

protection. Improving intensive tillage-based production systems as well as replacing them with more beneficial techniques is one of the strategies to achieve this goal, which strikes a balance between yield profitability, soil quality, and environmental sustainability [75].

Conservation agriculture is gaining attention among growers in the arid and semi-arid agro-regions of the world because of the economic benefits associated with less intensive tillage operations. Conventional tillage, which presently is the preferred land preparation method in Iran as an arid and semi-arid region, has led to accelerated soil erosion by wind and water as well as degraded soil quality. The increased number of tractor and equipment passes associated

with conventional tillage practices can lead to soil compaction and yield reduction. Corsi et al. [21] defined conservation agriculture as a method for managing agro-ecosystems for sustained productivity, increased benefits, and food security. At the same time, it preserves and improves environmental resources. Conservation agriculture also includes the three basic principles of sustainable agriculture: minimum mechanical disturbance of soil, the permanent cover of organic residues, and crop diversification.

Iran is located in one of the driest areas of the world where water scarcity is recognized as the main constraint for agricultural production. In summary, for the rainfed farming suitability analysis, 125 million ha (77%) of Iran's land might be classified as poor or lower ranks [60]. In rainfed agriculture of arid and semiarid environments plants are often water-stressed due to low/erratic precipitation, high temperatures, poor irrigation efficiencies, and strong desiccating winds. Any method that can conserve moisture in the soil will help reduce the impacts of these factors and ensure crop survival against short-term droughts common in Iran. Infiltration and evaporation are the most significant processes determining soil water storage. Conservation tillage systems such as reduced tillage and no-tillage have been shown to retain more moisture in the soil than conventional tillage practices [13, 35, 84].

However, far too little attention has been paid to short-term disturbance due to tillage and crop managements on soil properties and crop yield. The information available in the literature about short-term tillage-induced effects on the soil hydraulic properties have shown that the soil loosening increases total porosity [32, 53, 62] and hydraulic conductivity [61, 65]. According to Moret and Arrue [65], although conventional and minimum tillage can reduce the largest mean macropore size, it significantly increases the number of water-transmitting pores per unit area at 0, 1, 4, and 14 cm matric suction. In the short-term, tillage operations can have transient effects on soil properties. Structural changes in soils that have recently been plowed are affected by rainfall, irrigation, wetting and drying cycles, and reaching a new equilibrium may reduce hydraulic conductivity [16, 45, 78]. Gomez-Paccard et al. [31] showed that the saturated hydraulic conductivity after 8-years-old experiment in a plowed soil was significantly (about 60%) lower than that in no-tillage. The short-term agronomic response to intensive tillage may be positive [1, 22, 49, 82] or negative [46] depending on crop category and climate [70]. However, global data have indicated that crop yields under no-tillage are frequently lower than under traditional tillage practices, especially in the short term (e.g., first 2 yr) [20, 70].

The effectiveness of conservation tillage systems on improving soil properties and conserving water also is highly dependent on the crop residue mass, which

may be limited in low residue cover [23]. Insufficient accumulation of residue cover causes the soil not to react acceptably to conservation tillage and increases soil susceptibility to compaction and erosion [67]. Residue cover on the surface protects soil from wind and water erosion, by reducing wind speed, absorbing energy from falling rain, increasing infiltration, acting as a barrier to water runoff, reducing slaking of surface aggregates, and preventing pore sealing and crust formation [51, 83]. Crop residue mass on the soil surface also moderates temperature by isolating the soil from sun heating and air temperature and preventing evaporation [56] and increases structural stability [4, 82]. Conservation tillage, along with proper residue cover, in the long run, increases farm yields due to changes in size distribution and continuity of soil pores, improved soil fauna activity, reduced soil evaporation, and increased plant-available water capacity [24, 66]. The procedure of infiltration with dye conducted by Chan and Heenan [17] revealed a much larger number of transmitting macropores in no-tillage with stubble retention (65% of all macropores) versus conventional tillage with stubble burning (1%). A short-term study conducted by Lampurlanes and Cantero-Martinez [51] found that greater surface residue cover under no-tillage helped conserve water, despite indications of lower hydraulic conductivity.

Identified factors by machine characteristics affecting soil compaction in agricultural and agroforestry ecosystems have included the dimensions and structural type of the tyres, the inflation pressure of the tyres, the contact area and pressure at the soil-tyre interface, the load per axle, machinery forward speed, and traffic intensity [38, 58]. Previous studies have not dealt with the possible effect of working speed of mechanical implements on soil hydro-physical characteristics and crop yield although the effect of mechanical compaction of soils under equipment used for management practices has been well studied [83]. Because of the potential benefits, such as soil and water conservation, maintenance or enhancement of organic matter in soil, improvement in soil physical properties and economic return, reduced tillage systems are becoming very popular in the arid and semiarid provinces of Iran. The objective of this work was to investigate the effect of three different tillage system types (TST)—moldboard plow and two reduced tillage—relative to levels of harvest residue cover (HRC) and implement forward speed (IFS) in the short-term (within 1 yr) on hydraulic conductivity and some hydro-physical properties associated with the movement of water to improve soil management for moisture conservation under arid conditions in southwestern Iran. In this study, we hypothesized that reduced tillage system, compared to moldboard plow, with high residual cover on the soil surface and high implement forward speed in the short-term will improve wheat yield by improving soil hydro-physical properties.

MATERIALS AND METHODS

Study area. The current study was conducted in the research station of Agriculture Sciences and Natural Resources University of Khuzestan, Ahvaz, Iran (31°35'8.22" N, 48°53'4.03" E, and altitude: 24 m). This area is located on a physiographic unit of alluvial deposit Mesopotamian plain. The average of minimum and maximum air temperatures is 14.7 and 43.5, respectively, and the average annual air temperature is 24.1°C. The average annual rainfall is 235 mm and the evaporation from a class A pan is about 3000 mm. Summers are very hot and long and winters are short and mild. Almost all the precipitation occurs in December and January, the wet season, coinciding with the lowest temperatures and the first stages of winter crop growth. The temperature and moisture regime of the studied soils are Hyperthermic and Ustic, respectively. The soil at the experimental site was classified according to the World Reference Base for Soil Resources of the IUSS Working Group [92] as Cambisols (Clayic, Drainic, Ochric). The most important properties of this soil are Ochric and Salic horizon, deep soil without gravel. The most important properties of this soil are Ochric horizon and Salic horizon, deep soil, without surface and deep gravel, 35 to 40% clay and high SAR.

Experimental design. The field layout comprised a split-split-plot experiment arranged in a randomized complete block design with three replications and a total of 81 plots (Table 1) involving three factors: I. Tillage system type including T1: reduced tillage using combined tillage (Delta 5 HSP 220, non-inverting action) up to a depth of 30 cm, T2: reduced tillage comprised of chisel plough (non-inverting action) up to a depth of 20 cm, and T3: conventional mechanized tillage consisting of moldboard plough up to a depth of 30 cm + offset disc with a maximum depth of 17 cm to prepare the seedbed for planting as the main plot; II. Harvest residue covers (wheat) including no residue (C1), 40% wheat residue cover (C2), and 80% wheat residue cover residue (C3) as the subplot, and III. Implement forward speeds including low (4 km/h, S1), normal (7 km/h, S2), and high (10 km/h, S3) as the sub-subplot. Each treatment consisted of 27 plots, the dimensions of each plot were selected 3 meters by 20 meters. The distance between the plots was 1 m and the distance between repetitions was 10 m. There were 24 culture lines in each treatment and the distance between the culture lines was 12.5 cm.

Tillage intensity increased from T1 over T2 to T3. A quantitative assessment of HRC treatment made by the line-transect method which has emerged as the preferred method for field use. This procedure involves stretching a line diagonal to the crop rows and recording whether or not residue intersects the line at specified points [47, 48]. The studied site showed homogenous soil properties since it was conventionally tilled for >30 years before the experiment setup.

Table 1. The field layout of experiment

T3C3S3	T1C2S2	T3C2S3
T3C3S1	T1C2S3	T3C2S1
T3C3S2	T1C2S1	T3C2S2
T3C1S2	T1C3S1	T3C1S2
T3C1S3	T1C3S3	T3C1S1
T3C1S1	T1C3S2	T3C1S3
T3C2S1	T1C1S3	T3C3S3
T3C2S2	T1C1S1	T3C3S2
T3C2S3	T1C1S2	T3C3S1
T2C2S3	T2C1S2	T1C3S2
T2C2S1	T2C1S3	T1C3S1
T2C2S2	T2C1S1	T1C3S3
T2C3S1	T2C2S3	T1C2S3
T2C3S2	T2C2S2	T1C2S2
T2C3S3	T2C2S1	T1C2S1
T2C1S2	T2C3S1	T1C1S1
T2C1S1	T2C3S2	T1C1S3
T2C1S3	T2C3S3	T1C1S2
T1C3S1	T3C1S2	T2C1S3
T1C3S2	T3C1S1	T2C1S1
T1C3S3	T3C1S3	T2C1S2
T1C1S2	T3C3S1	T2C2S2
T1C1S1	T3C3S2	T2C2S3
T1C1S3	T3C3S3	T2C2S1
T1C2S1	T3C2S1	T2C3S1
T1C2S3	T3C2S3	T2C3S2
T1C2S2	T3C2S2	T2C3S3

I. Tillage system type including T1: reduced tillage using combined tillage (Delta 5 HSP 220, non-inverting action) up to a depth of 30 cm, T2: reduced tillage comprised of chisel plough (non-inverting action) up to a depth of 20 cm, and T3: conventional mechanized tillage consisting of moldboard plough up to a depth of 30 cm + offset disc with a maximum depth of 17 cm to prepare the seedbed for planting as the main plot; II. Harvest residue covers including no residue (C1), 40% wheat residue (C2), and 80% wheat residue (C3) as the subplot, and III. Implement forward speeds including low (4 km/h, S1), normal (7 km/h, S2), and high (10 km/h, S3) as the sub-subplot.

The cropping history included wheat, maize, and alfalfa. Spring bread wheat (*Triticum aestivum* L.) was sown (2014-12-08) with the simultaneous incorporation of chemical fertilizer with irrigation (6.50 m³/ha). Irrigation water has EC, pH and SAR are 2.2 dS m⁻¹, 7.2 and 4, respectively. Irrigation was done 8 times at intervals of 7 to 10 days. Harvesting operations were performed in 2015-05-07. Wheat yield was estimated based on pre-estimated test weight method [77]. Using a sampling frame, an area of 1 m² was selected

Table 2. Soil physical and chemical properties of studied farm

Texture	Sand	Silt	Clay	CaCO ₃	EC, dS m ⁻¹	pH
	kg 100 kg ⁻¹					
Clay	21 ± 2.1	37 ± 3.4	42 ± 5.2	38.93 ± 1.3	3.42 ± 1.1	7.61 ± 0.3

BD: bulk density, CaCO₃: equivalent calcium carbonate, EC: electrical conductivity. (Sample number: 20).

within each plot and the number of spikes was counted. This process was repeated 5 times to get an average of the crop per meter square area (*A*). Similarly, the number of grains was counted in 21 spikes and was took the average (*B*). The yield of the crop was then determined by using the following formula:

$$\text{Yield (ton ha}^{-1}\text{)} = \frac{A \times B \times C}{100\,000},$$

where *C* is the 1000-grain weight (g).

Sampling and laboratory soil measurements. Field measurements and soil sampling were conducted about one year after the last tillage operations (2015-12-08) in approximately 5% soil moisture content. Samples were randomly taken from a depth of 0–15 cm at four points in each plot. The soil samples were air-dried, ground to pass a 2-mm sieve and used for routine physical and chemical measurements. Particle size distribution was determined using the hydrometer method [28]. Organic matter content (OM) was determined using the wet-digestion method [89]. Calcium carbonate content (CaCO₃) was measured using the back-titration method [79]. The determination of electrical conductivity (EC) was made with a conductivity cell by measuring the electrical resistance of saturated paste extract [10]. Soil bulk density (BD) was determined using the core sampling method [11]. The aggregate mean weight diameter (MWD) was calculated from the equation:

$$\text{MWD} = \sum_{i=1}^n W_i \bar{X}_i, \quad (1)$$

where \bar{X}_i is the mean diameter of each fraction and W_i is the proportion of aggregate weight residual on each sieve to total sample weight [41]. Soil physical and chemical properties (30 cm) of the studied farm are shown in Table 2. The soil composition of 0–20 cm depth comprises 21% sand, 37% silt, 42% clay, and pH of 7.6.

Near-saturated hydraulic conductivity. In this study according to the method presented by Moosavi and Sepaskhah [63] and Kelishadi et al. [40], infiltration tests were performed by single-disc tensions infiltrometer with a diameter of 20 cm at successive applied matric suction (*h*) of 20, 14, 4, and 1 cm. A descending sequence of *h* has been recommended to prevent hysteresis [37]. First, the soil surface was removed from plant debris and leveled with minimal damage, and

then the disc was placed on a thin layer of fine sand (0.01–0.025 cm) with a thickness of ~0.3 cm. The latest was done to ensure an appropriate hydraulic contact between the nylon membrane and the soil matrix. The infiltration reservoir was filled with tap water with an electrical conductivity of approximately 0.5 dS m⁻¹. At each applied *h* value, after wetting the sand layer (20 s), the rate of water infiltration in the soil was recorded at intervals of 20 s for the initial 240 s, then 30 s for the next 180 s, and then 60 s until the steady-state conditions were met. At each applied *h* value, access to steady-state was considered when at least five consecutive readings were approximately the same. Although it takes hours to days to reach steady-state conditions, there are some who argue that the steady-state conditions are achieved in about an hour [72].

The equations describing saturated and unsaturation flow of water through soil can be solved analytically based on the infiltration data from a circular source of radius *r* with a constant *h* placed in contact with the soil surface [80]. In these relations, it is assumed that the unsaturated hydraulic conductivity varies with *h* according to Gardner exponential model [27]:

$$K(h) = K_s \exp(-h/\lambda_c), \quad (2)$$

where K_s and $K(h)$ are respectively saturated and unsaturated hydraulic conductivities ($L T^{-1}$), *h* is the applied matric suction (*L*), and λ_c [6, 34, 40, 44] is the macroscopic capillary length (*L*). The traditional method to yield the estimates of unsaturated hydraulic conductivity using the tension disc infiltration data is based on Wooding's analytical solution [91]. Wooding's solution for infiltration from a circular source may be given as:

$$Q(h) = \left[\pi r^2 K(h) \right] \left[1 + \left(\frac{4\lambda_c}{\pi r} \right) \right]. \quad (3)$$

where $Q(h)$ is the volume of water entering the soil per unit time at steady-state infiltration conditions ($L^3 T^{-1}$) and *r* is the radius of the disc (*L*). The first and second terms of the right side reflect gravitational and capillary forces, respectively [34, 44]. Therefore, Wooding's analytical solution has two unknown parameters: $K(h)$ and λ_c . To eliminate errors due to spatial variation and soil compaction, Ankeney et al. [6] proposed a method for determining unsaturated hydraulic conductivity which requires at least two steady-state fluxes obtained with a single-disc tension infiltrometer at

different h , e.g., h_i and h_{i+1} . Substituting Eq. (2) into Eq. (3) and entering h_i and h_{i+1} yield:

$$\mathcal{Q}(h_i) = \pi r^2 K_s \exp(-h_i/\lambda_c) \left[1 + \left(\frac{4\lambda_c}{\pi r} \right) \right], \quad (4)$$

$$i = 1, \dots, n-1,$$

$$\mathcal{Q}(h_{i+1}) = \pi r^2 K_s \exp(-h_{i+1}/\lambda_c) \left[1 + \left(\frac{4\lambda_c}{\pi r} \right) \right], \quad (5)$$

$$i = 1, \dots, n-1.$$

Steady-state infiltration rate measurements, $Q(h)$, for n consecutive h lead to n equations with unknown parameters K_s and λ_c . Homogeneity and isotropicity of the initial soil water content are assumptions of Wooding's analytical solution, which if ignored often leads to the production of negative values for $K(h)$ [86]. By simultaneously solving Eqs. (4) and (5), following Equations are obtained [6, 19, 63]:

$$= \frac{K(h_i)}{\mathcal{Q}(h_i)} \frac{\mathcal{Q}(h_{i+1})}{\left(1 + \frac{\mathcal{Q}(h_{i+1})}{\mathcal{Q}(h_i)} \right) / \left(1 - \frac{\mathcal{Q}(h_{i+1})}{\mathcal{Q}(h_i)} \right)}, \quad (6)$$

$$K(h_{i+1}) = \frac{\mathcal{Q}(h_{i+1}) K(h_i)}{\mathcal{Q}(h_i)}. \quad (7)$$

Determination of unsaturated hydraulic conductivity in the middle of two consecutive applied h has been described by Ankeny et al. [6], Reynolds and Elrick [73], and Jarvis and Messing [37]. According to Ankeny et al. [6], the best estimate of $K(h_i)$ is an arithmetic average of two consecutive hydraulic conductivity, i.e. $K(h_i) = [K(h_i) + K(h_{i+1})]/2$. Equations (8)–(11) show how K_{20} , K_{14} , K_4 , and K_1 are actually estimated:

$$K_1 = (K_{1(0,1)} + K_{1(1,4)})/2 \quad (8)$$

$$K_4 = (K_{4(1,4)} + K_{4(4,14)})/2 \quad (9)$$

$$K_{14} = (K_{14(4,14)} + K_{14(14,20)})/2, \quad (10)$$

$$K_{20} = K_{20(14,20)} \quad (11)$$

Number of water-transmitting pores per unit area.

We used the criteria of Clothier and White [18] and Moret and Arrue [65] for describing soil pores in this study. Therefore, soil macropores defined as those pores that discharge at h greater than 4 cm (pores with an equivalent radius greater than 0.0375 cm according to the capillary equation) and mesopores as those pores that discharge at h between 4 and 14 cm (pores with an equivalent radius between 0.0375 and 0.0107 cm). The maximum number of water-transmitting pores per unit area in infiltration region, N_h , was obtained according to the proposed procedure of Watson and Luxmoore [90], Reynolds et al. [74], and Moret and Arrue [65], using the minimum pore radius (λ_h) in

each class and applying the capillary equation in conjunction with Poiseuille's Law:

$$N_h = \frac{8\mu K_h}{\rho g \pi (\lambda_h)^4}, \quad (12)$$

where μ is the dynamic viscosity of water ($\text{g cm}^{-1} \text{s}^{-1}$), g is acceleration due to gravity (981 cm s^{-2}), and ρ is the density of water (1 g cm^{-3}). In this regard, N_h -macro and N_h -meso represent N_h for macro- and mesopores, respectively.

Relative contribution of macro- and mesopores to the total saturated flux. Assuming $dh/dz = 0$, the relative contribution of macro- and mesopores (Ψ -macro and Ψ -meso, respectively) to the total saturated flux was calculated according to expression [16, 65, 90]:

$$\Psi_i (\%) = \frac{K(h_i) - K(h_{i+1})}{K_0}, \quad i = 1, \dots, n-1, \quad (13)$$

The relative contribution of micropores at the h ranged from 14–20 cm (Ψ -micro, 14–20) was also calculated.

Macroscopic capillary length. If $n = 2$ (i.e., h of 20 and 14 cm), dividing Eq. (5) by Eq. (4) and solving for λ_c yields [6, 34, 40, 44]:

$$\lambda_c = \frac{|h_{i+1} - h_i|}{\ln \left(\frac{\mathcal{Q}(h_{i+1})}{\mathcal{Q}(h_i)} \right)} \quad i = 1, \dots, n-1. \quad (14)$$

Statistical analysis. Three-way analysis of variance (ANOVA) was applied to determine the effect of TST, HRC, and IFS on the different soil hydraulic properties. The treatment means were compared using the least significant difference (LSD) test. All statistical analyses were performed using SAS software version 9.1 (SAS Institute, Cary, NC). Plotting, fitting, and parameterization were performed using R software version 3.6.1 (<https://www.r-project.org>) using a non-linear optimization technique. In all analyses, differences were considered to be significant at $p \leq 0.05$ (p indicates the level of significance evaluated from the ANOVA test).

RESULTS

The analyses of variance for BD, OM, MWD, K_1 , K_4 , K_{14} , K_{20} , N_h -macro, N_h -meso, Ψ -micro, 14–20, and λ_c are shown in Tables 3 and 4. TST treatment had a significant ($p < 0.05$) effect on K_{14} and K_{20} . The TST \times HRC interaction also had a significant effect on K_{14} and K_{20} . The effects were not significant for K_1 and K_4 . HRC treatment had a significant ($p < 0.05$) effect on OM. There was significant effect of TST \times HRC interaction on OM. Implement forward speeds (IFS) had a significant effect ($p < 0.05$) on K_{14} . The one-year effects of TST, HRC and IFS treatments on the other considered parameters were not significant

Table 3. The F ratios determined by analyses of variance for bulk density (BD), organic matter (OM), mean weight diameter (MWD) of aggregates, and hydraulic conductivity at 1, 4, 14, and 20 cm matric suction (K_1 , K_4 , K_{14} , and K_{20} , respectively) under TST, HRC, and IFS treatments

Parameter	df	F ratio						
		BD	OM	MWD	K_1	K_4	K_{14}	K_{20}
Repeat (rep)	2	0.77	0.15	0.01	2.57	15.07	34.06	27.94
TST	2	0.65	1.14	1.58	0.50	0.86	3.68*	3.65*
TST × rep	4	1.18	0.27	0.08	1.46	0.14	1.89	0.83
HRC	2	1.18	3.30*	1.56	1.34	0.14	2.98	0.32
TST × HRC	4	1.23	3.96**	0.82	0.54	1.24	4.15**	3.02*
HRC × rep	12	0.86	1.52	1.21	1.48	0.82	1.08	0.30
IFS	2	1.45	0.17	2.39	0.75	0.15	3.94*	3.11
TST × IFS	4	0.69	0.71	0.89	1.17	0.74	1.33	0.88
HRC × IFS	4	0.70	0.36	0.99	1.56	1.28	1.15	0.32
TST × HRC × IFS	8	1.06	1.68	0.53	1.51	0.93	1.40	0.95

* and ** Significant at 0.05 and 0.01 levels of probability, respectively.

Table 4. The F ratios determined by analyses of variance for number of effective water-transmitting macro- and meso-pores per unit area (N_h -macro and N_h -meso, respectively), relative fraction of macropores (Ψ -macro) and mesopores (Ψ -meso) to the total saturated water flux, and macroscopic capillary length (λ_c) under TST, HRC, and IFS treatments

Parameter	df	F-ratio						Wheat yield
		N_h -macro	N_h -meso	Ψ -macro	Ψ -meso	Ψ -micro, 14–20	λ_c	
Repeat (rep)	2	4.00	2.13	3.99	3.08	4.18	3.85	1.23
TST	2	1.56	0.08	0.94	1.22	0.77	1.03	3.76*
TST × rep	4	2.95*	0.69	0.80	1.47	0.70	0.63	2.22
HRC	2	0.90	0.95	0.35	0.89	0.58	0.04	4.33**
TST × HRC	4	1.49	1.32	0.86	1.84	1.11	1.36	1.78
HRC × rep	12	1.75	0.70	0.74	1.06	0.67	0.73	1.15
IFS	2	1.77	0.22	1.25	1.90	1.16	0.57	4.07**
TST × IFS	4	1.22	1.29	0.46	1.02	0.44	0.17	0.98
HRC × IFS	4	1.26	1.30	0.71	1.26	0.69	0.66	0.99
TST × HRC × IFS	8	1.00	1.70	0.97	0.79	1.04	1.15	0.77

* and ** Significant at 0.05 and 0.01 levels of probability, respectively.

at the $p = 0.05$ level. Considering the dynamic variability of the soil properties [88] and to understand resulting changes after one crop year experiment of different management strategies, the differences and patterns were explained based on the mean comparisons (Table 5).

Physical Properties

Bulk density (BD). The effects of TST, HRC, and IFS treatments on the obtained BD values were not significant ($p < 0.05$) (Table 3). According to the data shown in Table 5, intensive tillage in T3 plot decreased BD by 2% compared with T1. Also, S3, likely by

affecting the duration of compressive stress and magnitude degree of strike of implements with bulk soil, decreased BD by 1.3% compared with S1. From the Table 5 we can see that crop residue mulch maintained on the soil surface mitigates increasing pattern in soil BD. Among the different levels of HRC, the lowest amount of BD obtained at the C3 level (1.3% less than C1).

Organic matter (OM). Soil OM contents were significantly affected by HRC treatment and HRC × TST interaction. The OM in the C3 treatment was 4.6% more than C1. Also, T3 and T2 treatments had OM content about 3% more than T1. There was no significant difference between different levels of IFS

Table 5. Mean comparisons of bulk density (BD), organic matter (OM), mean weight of diameter (MWD) of aggregates, hydraulic conductivity at 1, 4, 14, and 20 cm matric suction (K_1 , K_4 , K_{14} , and K_{20} , respectively), number of effective water-transmitting macro- and meso-pores per unit area (N_h -macro and N_h -meso, respectively), contribution of macro-, meso-, and micropores (Ψ -macro, Ψ -meso, and Ψ -micro14–20, respectively) to the total saturated water flux, macroscopic capillary length (λ_c), and wheat yield between different TST, HRC, and IFS treatment^a

Parameter	TST			HRC			IFS		
	T1	T2	T3	C1	C2	C3	S1	S2	S3
BD, g cm ⁻³	1.51 ^b	1.53 ^{ab}	1.54 ^a	1.54 ^a	1.51 ^b	1.52 ^b	1.53 ^b	1.54 ^a	1.51 ^c
OM, kg 100 kg ⁻¹	1.35 ^a	1.32 ^b	1.31 ^b	1.31 ^b	1.31 ^b	1.37 ^a	1.33 ^a	1.32 ^a	1.34 ^a
MWD, mm	1.33 ^a	1.30 ^b	1.28 ^c	1.24 ^b	1.33 ^a	1.35 ^a	1.26 ^b	1.33 ^a	1.33 ^a
K_1 , mm h ⁻¹	33.30 ^b	34.62 ^{ab}	39.54 ^a	29.58 ^b	38.52 ^a	39.360 ^a	31.62 ^b	36.06 ^{ab}	39.72 ^a
K_4 , mm h ⁻¹	16.50 ^a	13.86 ^b	14.22 ^b	14.64 ^a	14.40 ^a	15.54 ^a	14.22 ^a	15.06 ^a	15.36 ^a
K_{14} , mm h ⁻¹	7.32 ^a	6.18 ^b	5.82 ^b	5.82 ^b	6.24 ^b	7.26 ^a	7.20 ^a	6.54 ^b	5.52 ^c
K_{20} , mm h ⁻¹	6.42 ^a	4.86 ^c	5.52 ^b	5.82 ^a	5.52 ^b	5.40 ^b	6.30 ^a	5.64 ^b	4.86 ^c
N_h -macro, pores m ⁻²	50.64 ^b	82.55 ^{ab}	115.22 ^a	56.96 ^b	85.82 ^{ab}	105.63 ^a	48.81 ^c	82.02 ^b	117.58 ^a
N_h -meso, × 10 ² pores m ⁻²	33.93 ^a	31.79 ^a	31.49 ^a	37.32 ^a	31.58 ^b	28.31 ^b	34.91 ^a	31.59 ^a	30.71 ^a
Ψ -macro, %	43.82 ^b	49.32 ^a	53.50 ^a	45.98 ^b	48.76 ^{ab}	51.90 ^a	42.96 ^b	49.63 ^a	54.05 ^a
Ψ -meso, %	34.83 ^a	31.51 ^b	30.35 ^b	30.77 ^b	31.42 ^b	34.50 ^a	35.53 ^a	31.14 ^b	30.02 ^b
Ψ -micro, 14–20, %	8.08 ^a	7.12 ^b	6.28 ^b	7.77 ^a	7.74 ^a	6.27 ^b	8.22 ^a	7.24 ^a	6.01 ^b
λ_c , mm	93.71 ^a	91.43 ^a	71.58 ^b	87.11 ^a	86.92 ^a	82.65 ^a	94.91 ^a	84.88 ^{ab}	76.90 ^b
Wheat yield, ton ha ⁻¹	7.33 ^a	6.74 ^b	5.95 ^c	6.66 ^b	7.48 ^a	5.98 ^c	6.52 ^b	6.99 ^a	6.36 ^c

^a Figures followed by similar letters in each row and for each management systems (tillage method, residual cover, and forward speed) are not significantly different at $p < 0.05$ (LSD). Tillage system types (TST); reduced tillage using combined tillage: T1, reduced tillage comprised of chisel plough: T2 and conventional tillage: T3, three harvest residue covers (HRC); No residue: C1, 40% wheat residue: C2, and 80% wheat residue: C3, and three implement forward speeds (IFS); 4 km/h: S1, 7 km/h: S2, and 10 km/h: S3.

treatment. Our results indicated that reduced tillage when combined with retention of harvest residue can be more effective, even in short-term, to improve soil OM content.

Aggregate stability. As can be seen from the Table 3, neither TST nor HRC and IFS treatments significantly affected MWD. As shown in Table 5, the average of MWD in T3 plot was 3.9% lower than T1. The average of MWD also increased with increasing HRC from 1.24 mm in C1 to 1.35 mm in C3. In terms of IFS effects, the average of MWD was in order S3 = S2 > S1, with values of 1.33 mm for both S3 and S2 and 1.26 mm for S1.

Hydraulic Properties

Near-saturated hydraulic conductivity. As Table 3 shows, there were no significant differences in K_1 due to tillage, residue cover, and forward speed managements. Overall, TST affected K_1 in the order T3 > T1 = T2 (Table 4 based on LSD test at $p < 0.05$). A similar pattern emerged from N_h -macro and Ψ -macro, indicating that the macropores contribution for the flow increased after moldboard plowing. The N_h -macro

under T3 was higher than those for T2 and T1 by 40 and 128%, respectively.

Considering HRC, mean values of K_1 , N_h -macro, and Ψ -macro all followed the order C3 = C2 > C1. Compared with C1, C3 increased N_h -macro and Ψ -macro by 85 and 13%, respectively. IFS effects on K_1 were in the order of S3 > S1 = S2. Understandably, the values of N_h -macro affected by IFS were in the order of S3 > S2 > S1, with relative magnitude being 1.43 : 1.68 : 1.00.

As can be seen from the Table 3, neither TST nor HRC and IFS treatments significantly affected K_4 . In terms of TST effects, the mean K_4 values were in the order T1 > T2 = T3, with values of 16.50, 13.86, and 14.22 mm h⁻¹, respectively. The aforementioned pattern was also observed in Ψ -meso. According to the mean comparison results, HRC and IFS treatments had no notable effect on K_4 . There were significant effects of TST and TST × HRC interaction on K_{14} and K_{20} . In addition, induced changes in K_{20} in different levels of IFS were significant. Trends in the mean of K_{14} and K_{20} in terms of tillage effects were T1 > T2 = T3 and T1 > T3 > T2, respectively. Also, HRC affected K_{14} and K_{20} in the order C3 > C2 = C1

and $C1 > C2 = C3$, respectively. The mean K_{14} and K_{20} values in the IFS treatments were in the order: $S1 > S2 > S3$ and $S1 = S2 > S3$, respectively. The maximum values of Ψ -micro-14–20 also were observed in T1, C1, and S1. At $h = 4$ cm, due to the higher tortuosity of micropores, water-transmitting mesopores, with radius between 0.0375 and 0.0107 cm, have a dominant effect on water flow. At higher h (drier conditions) where mesopores are drained, micropores with a maximum radius of 0.0107 cm are responsible for the transmission of water.

From these facts we can conclude that surface soil loosening caused by moldboard ploughing in the short-term increased K_1 probably as a result of an increase in the N_h -macro and Ψ -macro. In the short-term, reduced tillage operations increased K_4 , K_{14} , and K_{20} , which were likely a result of an increase in N_h -meso, Ψ -meso, and Ψ -micro-14–20. Besides, crop residue mulch maintained on the soil surface increased N_h -macro and N_h -meso likely due to its role in both protecting the soil from the impact of rainfall and preventing the macropores filling and surface crust formation. In contrast, macropores can be destroyed and filled in crop-residues-free plots leads to an increase in the contribution of micropores to the water flux and subsequently K_{20} . In addition, IFS treatment in the short-term plays an important role in the configuration of water-transmitting pores likely by affecting the duration of compressive stress and magnitude degree of strike of implements with bulk soil. In general, the higher the macroporosity, the higher is the IFS and vice versa.

Macroscopic capillary length (λ_c). As can be seen from the Table 4, neither TST nor HRC and IFS treatments significantly affected λ_c . The mean values of λ_c for different levels of TST were as follows: $T1 = T2 > T3$. The λ_c is related to soil's internal pore geometry, as is the case with K . HRC did not significantly change the λ_c . The mean values of λ_c for different levels of IFS treatment were as follows: $S1 > S3 = S2$. Low IFS (S1) and less intense tillage (T1 and T2) with increasing N_h -meso and N_h -micro, 14–20 increases the relative contribution of capillary forces vs. gravitational forces to fluid flow.

Wheat yield. As can be seen in Table 5, different levels of TST ($p < 0.05$), HRC, and IFS ($p < 0.01$) treatments had a significant effect on wheat yield after one crop year. In terms of TST, the average of wheat yield was in the order $T1 > T2 > T3$ with the magnitude of 7.33, 6.74, and 5.95 ton ha^{-1} , respectively. Trends in the magnitude of wheat yield in terms of HRC and IFS effects respectively were $C2 > C1 > C3$ and $S2 > S1 > S3$. The wheat yield in the T1 treatment was 8% more than T2 and 19% more than T3. In addition, wheat yield in the C2 treatment was 11 and 20% more than C1 and C3, respectively. It is somewhat surprising that this study found a significant increase in

wheat yield between different management systems after just one crop year. In arid and semi-arid areas, such as most parts of Iran, water availability is most important limiting factor in agriculture under rain-fed conditions. With attention to the climatological conditions of the study area, a possible explanation for this is that T1 and C2 with decreasing evaporation from the soil surface, increasing soil water content in the topsoil, and improving soil temperature has the potential to create a better soil environment for seedling survival and crop development even in the short time, leading to higher yield.

DISCUSSION

Physical properties. In the conventional tillage treatment, the average BD increased 1.02 times compared to the combined tillage treatment. Conversely, application of 80% of crop residues reduced BD by 1.013 times compared to no residue treatment. High IFS (10 km/h) compared to normal (7 km/h) and low (4 km/h) treatments reduced BD by 1.019 and 1.013%, respectively. Therefore, conservational tillage, crop residues and high IFS in the short-term have also reduced the amount of BD. The average amount of BD (1.54 g cm^{-3}) in conventionally tilled plots in this study, after one year, indicated that the effective rainfall was insufficient to completely reconsolidate the soil. This result is in agreement with the findings of other researchers [2, 9, 87]. They indicated that the reconsolidation after tillage occurs due to raindrop impact, alternate wetting and drying cycles, and dragging effect of soil particles results from the dynamic forces of water movement through the pores.

On average, the amount of soil OM in the combined tillage system increased by 4.58% compared to the conventional tillage. Also, the application of 80% of crop residues increased 4.58% of soil OM compared to the other two treatments (40% residue and no residue). Therefore, conservational tillage (combined tillage) and crop residues (80%) have increased soil organic matter in the short-term. These findings are consistent with You et al. [93] showing that short-term (2-yr) reduced tillage (rotary-till and no-till) and crop residue increased organic matter in the surface layer (0–10 cm) of the soil compared with plow-till practice. Tillage treatments can increase the contact between residue and soil microbes, which promotes the decomposition process [93]. Disturbance and macro-aggregates degradation in conventional tillage also accelerates the decomposition rate of organic matter and the mineralization of carbon and nitrogen [5, 95].

Aggregate stability decreased by 1.56 and 3.90% on average in conventional tillage compared to chisel plow and combined tillage, respectively. Conversely, application of 80% of crop residues increased aggregate stability by 1.5 and 8.87% compared to 40% residue and no residue treatments, respectively. Increasing IFS to more than 10 km/h increased the aggregate

stability by 5.55%. Thus, conservational tillage, crop residues, and high IFS in the short term have also increased aggregate stability. In conventional tilled soils, the intensive physical stress caused by plough leads to a disruption and collapse of aggregates especially macro-aggregates and exposes organic fraction to microbial decomposition [29, 36, 39, 82, 95]. In general, the difference in aggregate stability is high when no-tillage is compared with moldboard plow but, is intermediate when it is compared with minimum-tillage systems such as chisel plough [4, 43, 94]. Leaving crop residues protects the soil from raindrops and thus prevents the destruction of aggregates and the formation of surface crusts [13, 30, 31, 81, 82, 84, 85]. A similar conclusion was reached by Khakural et al. [42] for a short-term (3-yr) conservation tillage experiment (no-till) in Eastern South Dakota and Madison soils.

Hydraulic properties. On average in the conventional tillage, the amount of K_1 (18.73%) has increased compared to the combined tillage, and on the contrary, the amount of K_4 (13.81%), K_{14} (20.49%) and K_{20} (14.01%) has decreased. Application of 80% of crop residues compared to non-application has increased K_1 (33.06%) and K_{14} (24.74%) and decreased K_{20} (7.21%). Also, high IFS (10 km/h) compared to low IFS (4 km/h), increased K_1 (25.61%) and decreased K_{14} (23.33%) and K_{20} (22.85%). On average, in conventional tillage and high IFS (10 km/h), the N_h -macro (pores m^{-2}) were 127.52 and 140.89%, respectively, compared to conservational tillage (combined tillage) and low IFS (4 km/h) increased. Also, application of 80% of crop residues compared to non-application, increased N_h -macro (pores m^{-2}) (85.39%) and decreased N_h -meso ($\times 100$ pores m^{-2}) (24.14%) has been. On average in the Conventional tillage, the amount of Ψ -macro (22.09%) has increased compared to conservation tillage (combined tillage) and vice versa, the amount of Ψ -meso (12.86%) and Ψ -micro (22.27%) decreased. Application of 80% of crop residues compared to non-application increased the amount of Ψ -macro (12.87%), and Ψ -meso (12.12%) and decreased Ψ -micro (19.30%). Also, high IFS (10 km/h) compared to low IFS (4 km/h), increased Ψ -macro (25.81%) and decreased Ψ -meso (15.50%) and Ψ -micro (26.88%). Therefore, in the short term, Conventional tillage, application of plant residues at 80% and high IFS (10 km/h), increases macropores (increases low suction) and reduces micropores (reduces higher suction).

Size, distribution, and continuity of soil pores are most important factors that impress soil hydraulic properties and water flow. These factors determine how soil particles are connected, and their changes in time and space follow changes in tillage practices [57]. However, some researchers have evaluated tillage-induced effects on the soil hydraulic conductivity with respect to changes in BD and total porosity [50, 55],

more accurate interpretations will be obtained by considering the pore size distribution [64, 65]. It is widely supposed that water and solute transport properties is mainly regulated by macroporosity even though they occupied a small fraction of total soil porosity [16, 61]. Watson and Luxmore [90] showed that where infiltration rate is low, transport in meso- and micropores accounted for 76% of the total water flux, while the contribution of these pores at the highest infiltration rate was only 8%. In their 8–10 years trial in Central Aragon, Moret and Arrue [65] indicated that although a bigger macropore size was observed under no-tillage, the soil hydraulic conductivities at h of 14, 4, 1, and 0 cm under this treatment were significantly lower than those measured for conventional and reduced systems due to a lower N_h -macro. After 12 years of trial, Evett et al. [25] also observed higher values of K_s under tilled treatments in comparison with non-tilled plots. As reported by previous works, a mulch layer formed by crop residues at the soil surface often results in an increase of soil macroporosity and infiltration rates because it can protect the soil surface from the impacts of rain drops, thereby leaving surface-connected macropores undisturbed, and preventing surface crust formation [31, 82]. One also should not overlook the fact that soil properties in freshly tilled soils change dynamically with time until a new, more stable state is reached [32, 45]. The speed and degree of temporal changes largely depends on weather conditions such as frequency, intensity and cumulative amount of rainfall as well as dynamic variations in soil temperature and moisture [8, 65, 69, 76]. Kool et al. [45] showed that K_s decreased dynamically with time following tillage. Chan and Heenan [17], McGarry et al. [59], Logsdon et al. [54], Arshad et al. [7], and Gomez-Paccard et al. [31] observed higher values of K_s in soils under long-term no-tillage practices. In comparison with conventional tillage, Pagliai et al. [68] in a 10-years-old experiment reported that reduced tillage improved the soil pore size distribution by increasing storage pores (0.0005–0.05 cm in diameter) and elongated transmission pores (0.5–0.05 cm in diameter). They added that the increase of storage pores in soils under reduced tillage is important for improvement of the available water storage capacity.

On average, combined tillage and high IFS (10 km/h) increased λ_c by 30.91 and 23.42, respectively, compared to conventional tillage and low IFS (4 km/h). According to Huang et al. [33], clayey soils with poorly-developed structure and microporosity have λ_c approximately to 100 cm while this value for well-structured soil and sandy soils reaches to 3 cm. Keli-shadi et al. [40] stated that land use significantly affects λ_c . They measured greater λ_c in follow and pasture land uses with higher degree of compactness when compared with dryland farming.

Wheat yield. Wheat yield in conservational tillage (combined tillage and chisel plow) increased by 23.19 and 25.08%, respectively, compared to conventional tillage. However, the application of 40% of crop residues led to a maximum wheat yield (12.31% more than no residue). But with the increase of crop residues up to 80%, the yield decreased by 11.37% compared to no residue. Also, at normal IFS (7 km/h), maximum wheat yield was obtained, but with increasing high IFS (10 km/h), wheat yield decreased by 9.9% compared to low IFS (4 km/h). Probably, the optimum speed for seeding operations could be achieved at 7 km/h, and lower and higher operational speeds result in poor seed establishment. Harvest residual cover on the soil surface can create a microenvironment with more suitable temperature and moisture, which in turn creates favorable conditions for the activity of microorganisms. It should be noted that high crop residues on the soil surface (C3) can impede seed establishment, create unfavorable conditions for tillering, and reduce yields [52, 71]. To improve soil water storage and water use efficiency, most researchers have suggested replacement of conventional tillage with conservational tillage [15]. In a 34-year-old experiment, Nouri et al. [67] reported that the soil moisture content in vetch cover crop and no-tillage was approximately 29 and 36% more than those of no cover crop and conventional tillage, respectively. Using the stable isotope technique, Busari et al. [14] reported that soil stable water isotopes ($\delta^{18}\text{O}$ and δD) were more enriched near the soil surface under conventional tillage compared with no-tillage, with the result that more evaporation can occur in intensively tilled soils. In addition, Alvarez and Alvarez, [3] found higher active microbial biomass and carbon-mineralization during the first crop after the introduction of conservation tillage (no-till) to agricultural soil.

Fernandez-Ugalde et al. [26] also reported that higher moisture content is more evident in conservational tillage compared to conventional tillage at lower water potentials (drier conditions). Some experiments have shown that higher yields can be obtained in tilled soils in wet years, but this difference may be reversed in dry years with better results in conservational tillage [4].

CONCLUSIONS

After one crop year experiment of different management strategies, the high values of wheat yield were found in the minimally tilled soils with moderately residue cover and normal forward speed likely due to decreased disturbance and aggregate degradation, thereby decreasing evaporation from the soil surface, leading to increasing soil water content in the topsoil, and improving soil temperature. Short-term agricultural management strategies modified the configuration of the water-transmitting pores within the soil matrix. Intense tillage increased hydraulic conductivity

at $h = 1$ cm by increasing the number of macropores. The highest meso- and micropores and consequently hydraulic conductivity at h of 4, 14, and 20 cm achieved when less intense tillage was applied. The mulch layer formed by crop residues on the soil surface increased the number of water-transmitting macro- and mesopores likely due to its role in both protecting the soil from the impact of rainfall and preventing the macropores filling and surface crust formation. The absence of residue cover on the soil surface increased the relative contribution of micropores to the saturated water flux. This study has shown that forward speed of agricultural implements in the short time exerts an influence on the soil pore size distribution. The low forward speed produced less macropores and more micropores than higher ones. Results also showed that soil organic matter decreased in conventionally tilled plots, due to soil aggregate degradation leading to accelerate the decomposition rate of organic matter.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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