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Effects of Crop Rotation and Tillage on Winter Wheat Growth and Yield under Cold Dryland Conditions

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Abstract: To investigate responses of two winter wheat genotypes under different crop management systems (rotation and tillage), a split–split plot experiment was conducted based on a randomized complete block design (RCBD) with three replications during 4 years in Maragheh, Iran. Three crop rotation treatments [vetch–wheat (V–W), chickpea–wheat (C–W), and safflower–wheat (S–W)] were considered in main plots, three tillage treatments (conventional-tillage (CT), minimum-tillage (MT), and no-tillage (NT)) were located in subplots, and two winter dryland wheat genotypes (Baran and Azar2) were allocated in sub-sub plots. Results indicated that soil moisture content in NT was greater than that in MT and CT. The highest relative water content (RWC), normalized difference vegetative index (NDVI), stomatal conductance (gs), and transpiration rate (E) were obtained from the Baran genotype in the V–W rotation under NT. In the last year of the experiment, rainfall productivity in NT treatment improved by 32%, compared to CT. The Baran genotype had higher rainfall productivity in both MT and NT treatments with 0.71 and 0.70 kg m^{-3}, respectively. Crop water requirement was not affected by crop rotation or tillage treatments. Maximum grain yields in V–W, C–W, and S–W rotations were recorded as 2231, 2105, and 1991 kg ha^{-1}, respectively. With increasing soil moisture storage and improving rainfall productivity under full implementation of conservation agriculture components (after 4 years), grain yield of Baran and Azar2 improved in NT compared to that of CT by about 6–9% and 6–14%, respectively. Therefore, the application of V–W rotation with NT in cold dryland areas is recommended for developing of conservation agriculture system.

Keywords: no-tillage; dryland wheat; rainfall productivity; crop water requirement

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1. Introduction

The terms 'drylands' and 'rainfed regions' are often used synonymously. The Food and Agriculture Organization (FAO) has defined drylands as areas with a length of growing period of 1–179 days [1]. The United Nations Convention to Combat Desertification (UNCCD) defines drylands based on the aridity index (Ia) computed as the ratio of mean annual precipitation (P) to mean annual potential evapotranspiration (PET). Accordingly, areas with arid (Ia = 0.05–0.20), semi-arid (Ia = 0.20–0.50), and dry subhumid (Ia = 0.50–0.65) climates are termed drylands [2]. Iran has a diverse and complex climate pattern and most of the area is arid to semi-arid. The average amount of precipitation over the country is 228 mm/year, which is less than one-third of the world average. Rainfall is extremely seasonal; about 50% of the rainfall occurs in winter, 23% in spring, 23% in autumn, and 4% in summer. About 30 percent of the precipitation is in the form of snow, and the rest is rain and other forms of precipitation. The annual evaporation rate ranges from 1500 to 2000 mm, which is about three times the global average [3]. In this situation, crop management systems that could improve crop performance in dryland conditions are critical and conservation agriculture (CA) can be a principal strategy. Conservation agriculture is particularly advantageous in drier regions, where it helps to increase soil water storage and maintain higher crop yield [4]. Some farming practices have been applied by farmers with the purpose to improve soil water storage. However, wrong farming practices can lead to soil degradation and erosion [5]. Conservation agriculture is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment [1]. The first key principle in CA is practicing minimum soil disturbance which is essential to maintain minerals within the soil, stopping erosion, and preventing water loss from the soil. The second key principle in CA is much like the first in dealing with protecting the soil. The principle of managing the topsoil to create a permanent organic soil cover can allow for the growth of organisms within the soil structure. The third principle is practicing diverse crop rotations or crop interactions. Crop rotation can be used best as a disease control against other preferred crops [6]. Crop rotation is the practice of growing a series of crops sequentially over time on the same land. Crop rotation is regarded as an environmentally friendly strategy for sustainable agriculture which adequately controls nutrients, water, weeds, pests, and diseases, as well as maintaining soil structure and fertility [7,8]. Crop rotation largely increases agricultural production without extra inputs, although its design may need to consider diverse climates, soils, crops, and management practices to maximize its agronomic and environmental benefits [9].

In dry semi-arid regions of northern China, Wang et al. [10] observed that the benefits of no-till or reduced tillage practices on soil physical conditions were more pronounced when implemented in combination with sufficient residue application. Similarly, it was reported that after 15 years of experimentation with a sorghum–cowpea rotation, minimum tillage (MT) with a sorghum residue of 6 tha^{-1} had the highest sorghum and cowpea yields, compared to no residue and lower sorghum residue [11]. O'Leary and Conner [12] reported that zero-tillage with stubble retention offered large and consistent increases in soil water storage on heavy-textured clay soils than that of sandy loam. Several long-term experiments showed that compared with conventional tillage, no-tillage treatments significantly increased soil organic matter, soil microbial abundance, and the conservation of rainwater [13,14]. Hemmat and Eskandari [15] reported that grain yields under no-till were 70 and 38% higher than yields from conventional tillage in a dry and wet year, respectively, whereas the precipitation use efficiency in a wet year increased twofold compared with the dry year.

Wheat (*Triticum aestivum* L.) is the third most-grown crop globally and feeds about 30% of the world's population. Winter wheat is one of the main food crops in the arid area of Iran, accounting for 65% of the total cultivated dryland area in Iran, and plays an important role in food security [16]. Crop cultivars are generally compatible with specific environments and management practices. To select cultivars for a specific cropping system, the growers need the best available genetic materials, ideally bred locally for these conditions. Improved crop cultivars grown in the right environment using optimized management practices will offer the highest value to the farmer [17]. In this research, the relationship between soil moisture changes in different tillage and rotation methods with the physiological characteristics and grain yield of two winter wheat genotypes and the productivity of rainfed in cold dryland conditions was investigated.

2. Materials and Methods

2.1. Experimental Site Details

The experiment was conducted for 4 consecutive years, from September to July each year 2016–2020 at a Dryland Agriculture Research Institute (DARI). The experimental field (378,120 N; 468,200 E; 1730 m a.s.l.) is located 25 km from Maragheh, Iran. The region is characterized by a temperate continental climate with warm summers. The soil (fine mixed, mesic, vertic, calcixerepts, USDA system; calcisols, FAO system) is classified as clay loam in the 0–15 cm surface layer and clay in the 15–80 cm depth. The mean annual precipitation for the most recent 10 years was 357 mm. The total precipitation and average temperature per month of the experimental site are shown in Table 1.

Table 1. Monthly rainfall distribution and mean temperature all over the year during 2016–2020.

Month	2016–2017		2017–2018		2018–2019		2019–2020	
	P (mm)	D (°C)	P (mm)	D (°C)	P (mm)	D (°C)	P (mm)	D (°C)
October	0	11.92	0.2	11.43	9.7	13.76	22	13.47
November	27	6.62	36	8.55	47	5.57	4	4.44
December	61	−2.94	48	−0.83	91	2.39	28	1.02
January	19	−7.14	29	1.4	41	−2.51	68	−3.24
February	21	−6.76	85	−0.99	86	−1.26	25	−6.19
March	22	−1.34	80	4.34	56	0.27	59	2.74
April	75	6.05	55	8.66	116	5.22	80	5.08
May	35	13.12	67	10.41	43	9.62	42	11.40
June	2	17.80	23	16.78	4.2	18.14	0	18.35
July	1	23.67	0	24.62	0	22.70	13	21.63
August	0	24.70	0	24.83	0.5	23.66	2	22.53
September	0	21.84	1.8	20.04	0	19.23	3	19.95
Year	263	8.96	425	10.77	494.4	9.73	346	9.26

P = precipitation (total), D = average degrees (average).

2.2. Experimental Design and Treatments Management

For the present study, in order to investigate the effect of different crop management methods on two winter dryland wheat genotypes' performance, a split–split experiment was set up in a randomized complete block design (RCBD) and replicated three times. The treatments consisting of three crop rotation treatments [chickpea–wheat (C–W), safflower–wheat (S–W), and vetch–wheat (V–W)] were considered in main plots, three tillage treatments [conventional (CT), minimum (MT), and no-tillage (NT)] were located in subplots, and two dryland winter wheat genotypes (Baran and Azar2) were allocated in sub-sub plots.

For tillage treatments, a 3-bottom general purposed mouldboard plow equipped with share points and operated at 5 km h^{-1} was used in the CT system. MT included only one tillage operation using a sweep plow equipped with 43 cm sweeps and operated at 6 km h^{-1}. Primary tillage operations (mouldboard and sweep plow) were performed around 30 September. The depth of plowing in treatments CT and MT were 20 and 10 cm, respectively. All plots under CT were subsequently smoothed to a depth of 8–10 cm with a tandem disk harrow with seven disks in each gang and operated at 6.3 km h^{-1}. The diameter of each disk was 53 cm and the disk spacing was 23 cm. The only soil disturbance in NT occurred during the seeding operation.

A soil auger was used to collect the soil samples at 10 points of experimental sites from 0 to 30 cm depth. After air-drying, the soil samples were dried in an oven under 105 °C for 24 h. The soil was then crushed and sieved through a 2 mm sieve and used for physical and chemical analyses (Table 2). Wheat genotypes (Bran and Azar2), vetch (Vicia pannonica), safflower (Faraman), and chickpea (Saral) with the rate of 380, 250, 50, and 30 seeds per m^2, respectively, were sown by an Aske model 2200 seeder (13 planting rows with 17.5 cm distance between rows) in 3–5 cm depth of soil. Each plot for wheat consisted of 13 rows, spaced 17.5 cm apart, and for crop rotation plants consisted of 7 rows, spaced 35 cm, 20 m in length. Fertilizers including 90 kg ha^{-1} N (urea), 30 kg ha^{-1} P (triple superphosphate) used for wheat and safflower, and 45 kg ha^{-1} N (urea), 30 kg ha^{-1} P (triple superphosphate) used for vetch and chickpea. Weeds were controlled by the application of Granstar® herbicide in the wheat site and Gallant™ Super herbicide in crop rotation sites.

Table 2. Physical and chemical properties of the soils (from the field before the experiment).

Soil Depth (cm)	Soil Texture (%)			pH	K	P	TN	OC	$CaCO_3$	SP
	Sand	Silt	Clay		(Mg kg^{-1})			(%)		
0–30	40	43	17	7.8	661	9.1	0.14	0.72	7.4	52

K: potassium; P: phosphorus; TN: total nitrogen; OC: organic carbon; $CaCO_3$: calcium carbonate; SP: saturation percentage.

2.3. Soil Moisture Content

Soil moisture content was measured only in the last year of the experiment 2019–2020 at a depth of up to 60 cm in the flowering stage of wheat. The soil sample was taken, its weight was measured, and then it was dried in an oven in the laboratory for 16 h at 105 °C [18]. Afterward, it was weighed again. The difference between the two measurements corresponds to the amount of moisture content in the soil.

2.4. Physiological Traits

Normalized difference vegetation index (NDVI), stomatal conductance (gs), and transpiration rate (E) from three plants in each plot were recorded at the flowering stage of wheat by GreenSiker (Trimber), and AP4 leaf porometer (ADC, UK), respectively.

Relative water content was determined by flag leaf sampling of three plants at the flowering stage as follows:

$$\text{Relative water content (\%)} = \frac{(\text{Fresh weight} - \text{Dry weight})}{(\text{Saturated Weight} - \text{Dry wieght})} \times 100$$

2.5. Crop Water Requirement and Rainfall Productivity

Crop water requirement was determined using CROPWAT software. The information of three parts related to soil, plant, and climate are included in this software, and crop water requirement was estimated. Rainfall productivity was calculated as the ratio of crop grain yield to rainfall during the crop growth period.

2.6. Grain and Biological Yield

Five samples of 3 square meters (35% of the plot) were taken from each plot when grain in spike had around 14–15% moisture. After being harvested, each plot's worth of grain was packed and threshed. Then, grains of the whole plot were weighted and the yield for 15 m^2 was determined. According to that, the grain yield (GY) was calculated in Kg per hectare. For measuring 1000 seed weight used an automatic seed counter with eight repetitions.

Before threshing, plants were collected from a designated area within each plot, and their total weight was recorded as the biological yield (BY), expressed as Kg per hectare.

2.7. Data Analysis

All the data were analyzed on the basis of experimental design, using SAS v. 9.1 software. The mean value of each trait was compared according to the Duncan multiple range test at $p \leq 0.05$.

3. Results and Discussion

3.1. Soil Moisture Content

Crop rotation, tillage, and the interactions of rotation × genotype and tillage × genotype were significant on soil moisture percentage (Table 3).

Table 3. Analysis of variance of soil moisture (%) in the last year of the experiment.

SOV	df	Soil Moisture %
Replication	2	0.081
Rotation	2	1.386 *
E1	4	0.151
Tillage	2	29.90 **
Rotation × Tillage	4	0.058 ns
E2	12	0.324
Genotype (G)	1	0.274 ns
Rotation × Genotype	2	1.707 *
Tillage × Genotype	2	0.117 ns
Rotation × Tillage × Genotype	4	0.127 ns
E3	18	0.301

*, **, and ns: significant at $p \leq 5\%$, at $p \leq 1\%$ probability level, and non-significant.

Soil moisture of S–W rotation was 18.12%; however, there were no significant differences with V–W treatment (Figure 1a). Soil moisture percentage in NT was recorded as 19.16%, and it was 8% and 15% higher than that of MT and CT conditions, respectively (Figure 1b). It seems that due to the root structure of safflower plants (deep root system), it has been able to increase the penetration of moisture to the deep layer of the soil. Biological methods such as deep-rooted cover crops can be another potential solution to ameliorate the negative effects of soil compaction, particularly in no-tillage farming production [19]. Cover crops such as safflower with vigorous taproots can reduce soil compaction by penetrating and loosening the compacted layer. Eventually, these roots decompose over time and form root channels and large voids that enable air, water, nutrient, and roots of subsequent crops to move more deeply through the soil profile, thus enhancing soil macropores and physical quality [20].

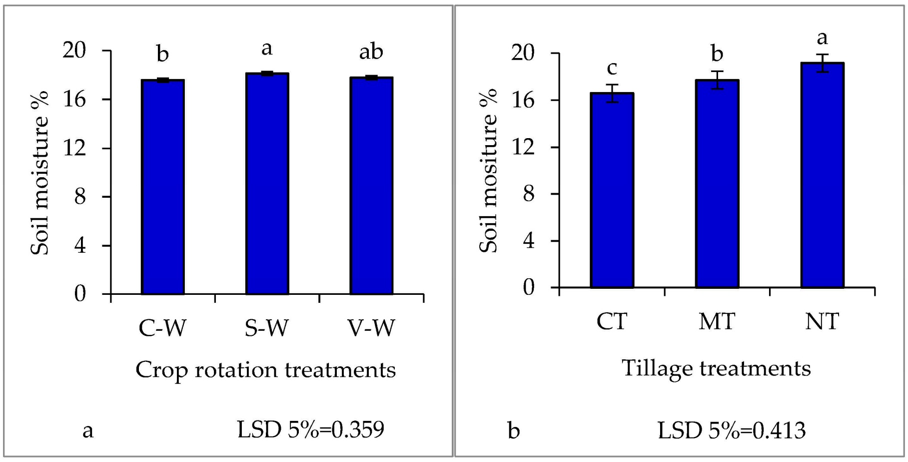

Figure 1. Soil moisture percentage changes in different crop rotations (**a**) and tillage treatments, (**b**) in the last year of the experiment. Vetch–wheat (V–W), chickpea–wheat (C–W), and safflower–wheat (S–W); conventional-tillage (CT), minimum-tillage (MT), and no-tillage (NT). Different lowercase letters indicate statistical differences ($p < 0.05$).

Soil moisture percentage in the plots of Azar2 was significantly more than Baran in the C–W rotation treatment. However, differences between Azar2 and Baran in the S–W and V–W treatments were statistically similar. The soil in the S–W treatment had more moisture storage than other crop rotation treatments (Figure 2). Studies showed that conservation tillage and residue maintenance are effective ways to improve soil structure, fertility, water permeability, and storage [21,22]. Somasundaram et al. [23] reported that soil moisture increases significantly in the 0 to 15 cm soil layer under the conservation agriculture system. Similarly, Asghari Maidani et al. [24] reported on safflower, and Khorsandi et al. [25] on dryland wheat reported that soil moisture retention and storage increase under the no-till system. Improvement of soil properties leads to improvement of soil water content, root growth, element cycling, and soil organic carbon formation [26].

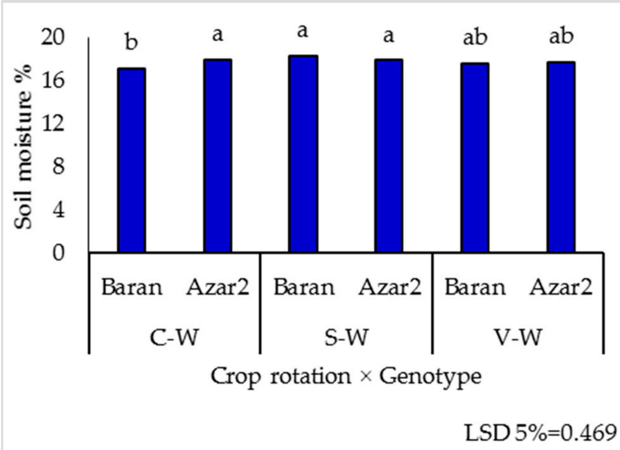

Figure 2. Soil moisture percentage of wheat genotypes under different crop rotations treatments. Vetch–wheat (V–W), chickpea–wheat (C–W), and safflower–wheat (S–W). Different lowercase letters indicate statistical differences ($p < 0.05$).

3.2. Physiological Traits

Combined analysis of variance of the data showed that the interactions effect of year × rotation × tillage × genotype was significant on normalized difference vegetative index (NDVI), crop water requirement (CWR), rainfall productivity (RP), 1000 grains weight (1000 GW), and grain yield (GY). The interaction of rotation × tillage × genotype on relative water content (RWC), transpiration rate (E), and biological yield (BY) was significant. Stomatal conductance (gs) was significantly affected by tillage × genotype and also crop rotation × genotype (Table 4).

Table 4. Combined analysis of variance of the physiological parameters, grain yield components, biological yield, rainfall productivity, and crop water requirement.

SOV	Df	NDVI	E	gs	RWC	GW	GY	BY	RP	CWR
Year (Y)	2	152 ns	0.04 ns	1.26 ns	39.8 ns	50.16 *	3612 *	28,725 *	635.40 *	27,957 *
EY	6	19.54	0.08	44.1	204.8	3.16	19	124.33	1.20	0.32
Rotation (R)	2	18.64 **	0.02 *	38.5 *	24.15 *	29.57 *	781 *	487.28 *	46.77 *	2.32 ns
Y × R	4	0.44 *	0.0001 ns	0.0001 ns	0.0001 ns	1.24 *	79 *	20.78 ns	4.37 *	5.03 *
E	12	0.02	0.0001	0.196	0.13	0.13	3	8.49	0.20	0.22
Tillage (T)	2	103 ns	1.58 *	93.20 *	47.31 *	50.66 *	225 ns	3708 ns	6.98 ns	13.35 ns
Y × T	4	28.95 *	0.03 **	6.86 *	18.81 *	4.83 *	374 *	3282 **	23.82 *	6.91 *
R × T	4	0.22 ns	0.0006 ns	6.47 *	0.54 **	2.35 ns	6 ns	67.40 *	0.41 ns	9.54 ns
Y × R × T	8	0.55 ns	0.0006 ns	0.0001 ns	0.0001 ns	0.93 *	3 ns	22.37 ns	0.19 ns	8.67 *
E	36	1.06	0.0097	0.64	0.16	0.31	3	18.28	0.25	0.35
Genotype (G)	1	2.93 *	0.0024 *	73.16 *	1.60 *	20.05 *	570 **	120.60 **	35.66 *	582.1 **
Y × G	2	5.68 *	0.0001 ns	0.0001 ns	0.0001 ns	1.38 *	15 *	1.54 ns	1.89 *	64.11 **
R × G	2	0.82 *	0.0012 *	1.70 **	0.68 *	0.72 *	13 **	0.30 ns	0.87 *	0.24 ns
T × G	2	1.46 *	0.0004 ns	1.78 **	0.50 **	0.96 **	9 **	1.12 ns	0.55 *	0.37 ns
Y × R × G	4	0.07 ns	0.0001 ns	0.0001 ns	0.0001 ns	0.05 ns	0.9 ns	1.60 ns	0.08 ns	0.87 *
Y × T × G	4	0.03 ns	0.0001 ns	0.0001 ns	0.0001 ns	0.13 ns	0.5 ns	2.32 ns	0.04 ns	1.67 *
R × T × G	4	0.59 ns	0.0009 *	0.29 ns	0.91 *	0.40 ns	3 ns	17.12 *	0.22 *	1.74 ns
Y × R × T × G	8	0.38 *	0.0001 ns	0.0001 ns	0.0001 ns	0.65 **	2 **	2.37 ns	0.13 **	1.34 *
E	54	152	0.0002	1.26	0.1056	0.23	0.8	3.23	0.053	0.30

*, **, and ns: significant at $p \leq 5\%$, at $p \leq 1\%$ probability levels, and non-significant, whereas, NDVI, E, gs, RWC, GW, GY, BY, HI, RP, and CWR are normalized difference vegetative index, transpiration rate, stomatal conductance, relative water content, grain yield, biological yield, harvest index, rainfall productivity, and crop water requirement, respectively.

Differences between Baran and Azar2 inside of each tillage treatment for RWC and E were not significant, but tillage significantly affected them. Maximum RWC and E were recorded in NT treatment in all crop rotation patterns. The highest RWC and E were obtained from Baran in NT under V–W treatment. BY of Baran at almost all the tillage and crop rotation treatments was higher than that of Azar2. Plants from CT treatment had more BY than MT and NT treatments in all crop rotation patterns. The highest BY was recorded for CT in V–W treatment in both Baran and Azar2 (Table 5). It seems that increases in soil moisture storage in the no-tillage system (Figure 1) have been able to provide more water for plants and cause these plants to have higher RWC and E. Wang et al. [27] reported that plant growth increased due to the use of CT compared to the system without tillage. However, other researchers have pointed out that plant growth and characteristics improved in the conservation agriculture system in the long term due to the improvement of soil characteristics [22,23,28].

Table 5. Changes in RWC, E, and BY of winter wheat genotype under different crop rotations and tillage treatments.

Crop Rotation	Tillage	Genotype	RWC %	E (mm)	BY (kg ha^{-1})
C–W	CT	Baran Azar2	0.53 0.52	0.45 0.44	7103.1 7015.4
	MT	Baran Azar2	0.53 0.54	0.6 0.61	6776 6731.4
	NT	Baran Azar2	0.58 0.58	0.78 0.79	6630.8 6589.7
S–W	CT	Baran Azar2	0.48 0.51	0.4 0.43	7049.2 6937.4
	MT	Baran Azar2	0.51 0.52	0.58 0.6	6671 6678.4
	NT	Baran Azar2	0.56 0.57	0.76 0.77	6463.7 6420.4
V–W	CT	Baran Azar2	0.53 0.55	0.45 0.47	7221.6 7233.9
	MT	Baran Azar2	0.57 0.56	0.63 0.63	6791.6 6695
	NT	Baran Azar2	0.6 0.59	0.8 0.79	6751.1 6665.1
	LSD 5%		0.02	0.055	89.89

Vetch–wheat (V–W), chickpea–wheat (C–W), and safflower–wheat (S–W); conventional-tillage (CT), minimum-tillage (MT), and no-tillage (NT); RWC (relative water content), E (transpiration), and BY (biological yield).

In all crop rotation treatments, gs of plants in NT were more than that of MT and CT. The highest gs were obtained from NT in the V–W treatment (Figure 3A). Baran in all crop rotation and tillage treatments had more gs than Azar2. Nevertheless, the highest gs of Baran were shown in the V–W and NT treatments (Figure 3B,C). It seems that in NT conditions, with increasing soil moisture storage (Figure 1b), the RWC of plants has increased (Table 5) and the plants have a higher rate of gs. Similarly, it has been reported that increasing the RWC of leaves leads to an increase in gs [29]. More residues reduce erosion, allow more water to penetrate into the soil, reduce runoff, reduce evaporation, maintain humidity, and improve the water status of the plant. These results are confirmed by the findings of Baker et al. [26]. They reported that higher water available for the plant is the primary consequence of no-tillage, and crop residues led to reduces evaporation and increases water permeability. Soil compaction in CT has a negative effect on soil water permeability, root growth, and crop yield [30].

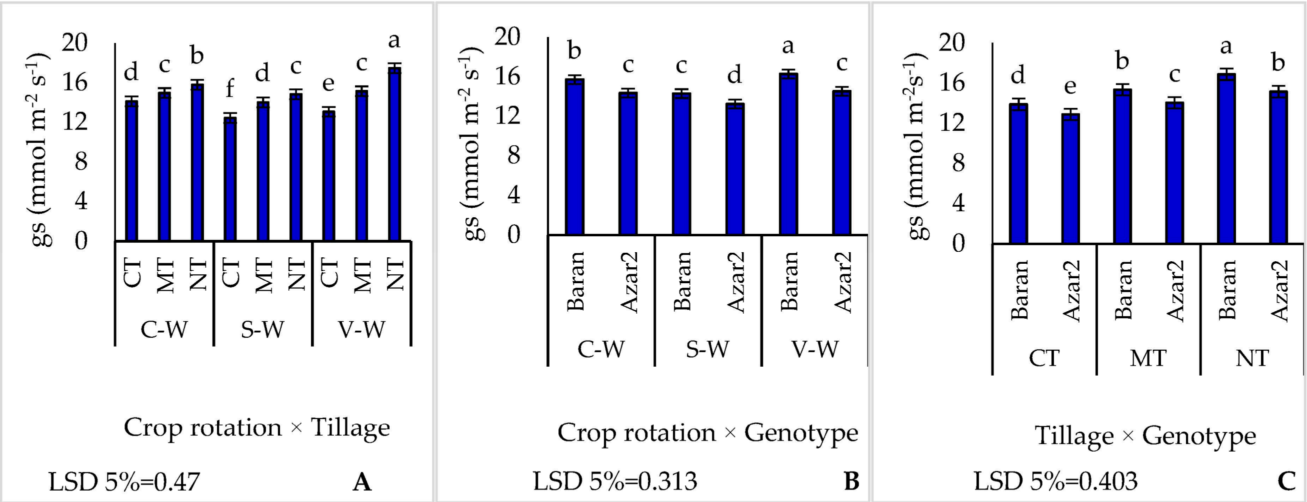

Figure 3. Stomatal conductance (gs) of winter wheat genotypes under interactions of crop rotation × tillage treatments (**A**), crop rotation × genotype (**B**) and tillage × genotype (**C**). Vetch−wheat (V–W), chickpea−wheat (C–W), and safflower−wheat (S–W); conventional-tillage (CT), minimum-tillage (MT), and no-tillage (NT), and gs (stomatal conductance). Different lowercase letters indicate statistical differences ($p < 0.05$).

Gas exchanges of plants in each year for NT were higher than that of MT and CT. Maximum stomatal conductance (gs) and transpiration rate (E) were recorded for NT in the last year of the experiment (Table 6). Biological yield in the first and the second years of CT treatment was higher than that of the MT and NT, whereas, in the last year, the highest biological yield was obtained from NT (Table 6). Bojarszczuk [31] reported that the rate of gas exchange in reduced tillage compared with conventional tillage was higher in fodder pea plants. It was also found that the amount of carbon dioxide in the chamber under the stomata in NT was higher than in other tillage treatments. Biomass production in plants is directly related to the amount of radiation absorbed by the canopy and is influenced by crop management [32]. Similar to our results, Bronick [33] reported that the water storage in NT with residue retention systems is more than 1.1 times compared to residue removal of CT condition and it supports high plants' biomass production.

Table 6. Gas exchanges and biological yield in plants under different tillage treatments during 2017–2020.

Year	Tillage	gs (mmol $m^{-2}S^{-1}$)	E (mm)	BY (Kg ha^{-1})
2017–2018	CT	13.74	0.4656	8427.9
	MT	14.55	0.5961	7351.3
	NT	15.67	0.7622	7126.1
2018–2019	CT	13.66	0.5066	6736.2
	MT	14.47	0.6371	6498.6
	NT	15.59	0.8032	6228.8
2019–2020	CT	12.77	0.3666	6116.2
	MT	15.06	0.6032	6321.9
	NT	16.78	0.8002	6405.5
LSD 5%		3.13	0.13	172.2

Conventional-tillage (CT), minimum-tillage (MT), and no-tillage (NT). Gs (stomatal conductance), E (transpiration rate), and BY (biological yield).

3.3. Crop Water Requirement and Rainfall Productivity

CWR was affected by the years. Maximum and minimum values for Baran and Azar2 were recorded for 2017–2018 (241.7 and 240.5) and 2019–2020 (201.4 and 194.5), respectively. The main effect of crop rotation and tillage had no significance on CWR (Table 4). Baran had more CWR than Azar2 in all crop rotation and tillage treatments (Table 7). Rainfall productivity (RP) of Baran was higher than that of Azar2 in all crop rotation and tillage treatments. Moreover, both genotypes had more RP in the V–W treatment in comparison to other crop rotation treatments. Results clearly indicated that the RP of plants in the first year of the experiment in CT treatment was more than that in MT and NT; however, RP in the last year of the experiment in NT was higher than in MT and CT. RP of NT treatment from 2017–2018 to 2019–2020 was increased from 0.4 to 0.7 kg m^{-3} (Table 7). Normalized difference vegetative index (NDVI) in all years of the experiment in the NT treatment were more than others. Moreover, it was found that plants from V–W had higher NDVI, compared with C–W and S–W treatments (Table 7). NDVI has already been related to water status in plants [34] despite being strictly influenced by the relative water content and cell wall elasticity of leaf tissues. Such physiological responses were also remarked by the SPAD readings, which are known to be a good indicator of chlorophyll concentration [35].

Table 7. Changes in WR, RP, and NDVI of winter wheat genotypes under crop rotation and tillage treatments during 2017–2020.

Year	Crop Rotation	Tillage	CWR (mm)		RP (Kg m^{-3})		NDVI	
			Baran	Azar2	Baran	Azar2	Baran	Azar2
2017–2018	C–W	CT	241.6	240.4	0.52	0.49	0.54	0.52
		MT	241.2	239.2	0.47	0.44	0.56	0.55
		NT	236.1	233.2	0.44	0.42	0.57	0.52
	S–W	CT	241.7	240.5	0.49	0.46	0.51	0.47
		MT	241.5	236.4	0.42	0.41	0.54	0.51
		NT	241.1	239.3	0.41	0.4	0.53	0.51
	V–W	CT	241.2	238.5	0.57	0.55	0.56	0.52
		MT	241.3	238.6	0.52	0.5	0.58	0.54
		NT	241	238.8	0.51	0.49	0.61	0.55
2018–2019	C–W	CT	238.8	233.6	0.48	0.44	0.58	0.56
		MT	236.5	234.3	0.46	0.43	0.61	0.62
		NT	236.5	234.1	0.43	0.4	0.63	0.64
	S–W	CT	236.5	234.1	0.46	0.44	0.55	0.56
		MT	236.5	234	0.43	0.42	0.58	0.61
		NT	236.5	233.7	0.39	0.37	0.62	0.62
	V–W	CT	236.5	234.5	0.5	0.46	0.59	0.6
		MT	236.5	234.2	0.48	0.45	0.63	0.64
		NT	236.5	234.2	0.43	0.41	0.65	0.62

Table 7. *Cont.*

Year	Crop Rotation	Tillage	CWR (mm)		RP (Kg m^{-3})		NDVI	
			Baran	Azar2	Baran	Azar2	Baran	Azar2
2019–2020	C–W	CT	201.4	195	0.64	0.58	0.42	0.4
		MT	201.4	195.1	0.67	0.62	0.5	0.51
		NT	201.4	195.1	0.7	0.66	0.59	0.6
	S–W	CT	201.4	195.3	0.61	0.57	0.39	0.4
		MT	201.4	194.5	0.62	0.61	0.47	0.5
		NT	201.4	195.1	0.65	0.61	0.58	0.58
	V–W	CT	201.4	195.5	0.66	0.6	0.43	0.44
		MT	201.4	195.3	0.7	0.64	0.52	0.53
		NT	201.4	194.6	0.71	0.68	0.61	0.58
	LSD 5%		0.213		0.023		0.066	

Vetch–wheat (V–W), chickpea–wheat (C–W), and safflower–wheat (S–W); conventional-tillage (CT), minimum - tillage (MT), and no-tillage (NT), CWR (crop water requirement), RP (rainfall productivity), and NDVI (normalized difference vegetative index).

3.4. Grain Weight and Yield

In the first year of the study, 1000 grain weight of both Baran and Azar2 in different tillage treatments under C–W and S–W rotations was not significant. However, grain weight in NT treatment under V–W treatment was higher than MT and CT, in the same year. In the remaining years of the experiment, maximum grain weight was obtained from plants grown in NT, and the difference was more evident in the last year of the experiment. Differences between Baran and Azar2 in almost all of the treatments were statistically similar, but the most grain weight was recorded for Baran in the NT treatment in the last year of the experiment (Table 8). In the first two years of the project, grain yield was higher in CT than in MT and NT, but in the last year, grain yield in NT from different crop rotation treatments was similar and, in some cases, it was higher than in CT. During the 4 years of the project, the grain yield of Bran and Azar2 increased by about 6–9% and 6–14%, respectively, in NT than that of CT (Table 8).

Vetch–wheat (V–W), chickpea–wheat (C–W), and safflower–wheat (S–W); conventional-tillage (CT), minimum-tillage (MT), and no-tillage (NT), 1000 GW (1000 grain weight) and GY (grain yield).

It seems that during the time in the NT system, maintaining the residues, especially in the V–W rotation, increasing the soil moisture storage, and also improving soil fertility (legume-cereal rotation) are reasons for better plant growth and increasing grain weight and yield (Table 8). Studies in relation to the long-term effects of different crop rotations and different methods of tillage showed that the yield of wheat in rainfall conditions increases by 78% in the NT compared with CT [10,36]. Hobbs et al. [37] have determined that NT treatment reduces soil water loss due to evaporation and increases grain yield. Gupta et al. [38] reported that wheat grain yields of 5393, 5056, and 4537 kg/ha were obtained under NT, MT, and CT conditions, respectively. Under insufficient rainfall and drought stress conditions, the efficiency of rainfall consumption in NT conditions has increased due to the reduction of water evaporation and has led to an increase in grain yield in the short term [39]. However, Mousavi Fazl et al. [40] found that CT leads to the highest density and root growth of wheat. Moreover, a similar result was reported by Cárceles Rodríguez et al. [41] that indicated the highest and the lowest grain yield was, respectively, related to CT and NT treatments. Full implementation of the conservation agriculture components means low tillage + preservation of crop residues + crop rotation has been reported that is evident positive effects on soil and plants performance [4].

Table 8. 1000 grain weight and yield of Baran and Azar2 in different crop rotations and tillage treatments during 2017–2020.

Year	Crop Rotation	Tillage	1000 GW (g)		GY (Kg ha^{-1})	
			Baran	**Azar2**	**Baran**	**Azar2**
2017–2018	C–W	CT	35.333	35.333	2208.7	2104
		MT	35	35	2015.3	1899
		NT	36.333	35.667	1891.7	1804.3
	S–W	CT	34.667	34	2088	1989
		MT	34.667	34.333	1819	1751
		NT	34.333	34	1755.7	1732
	V–W	CT	35.667	36	2442.3	2342.3
		MT	36	34.667	2211.7	2158
		NT	38	38	2164	2101.3
2018–2019	C–W	CT	34.333	34	2422.3	2205.3
		MT	35	34.333	2307	2154.3
		NT	36.333	35.667	2137.7	1998
	S–W	CT	34	33.333	2314.3	2193
		MT	34.667	33	2150	2126.7
		NT	35.333	34.333	1971.3	1833
	V–W	CT	35	34.333	2473	2295.3
		MT	35	34.667	2398.3	2227.3
		NT	37.333	35.333	2159.7	2056.7
2019–2020	C–W	CT	35.667	35.333	2117.3	1900.3
		MT	36.667	36	2198	2045.3
		NT	39	38.333	2315.7	2176
	S–W	CT	35.333	34.667	2009.3	1888
		MT	36.333	34.667	2041	2017.7
		NT	38	37	2149.3	2011
	V–W	CT	36.333	35.667	2168	1990.3
		MT	36.667	36.333	2289.3	2118.3
		NT	40	38	2337.7	2234.7
LSD 5%			1.07		90.87	

4. Conclusions

Soil moisture storage in NT conditions was higher than that of MT and CT conditions, and in the S–W rotation, it was better, which can be related to safflower plant root structure compared to legume plants. The rate of E, gs, RWC, and NDVI in the NT system improved over time, and as a result, the plants had more BY and GY in the conservation agriculture system. In the last year of the experiment, especially in S–W and V–W, RP under NT increased compared to the CT. Maximum RP was observed in Baran with values of 0.71 and 0.70 kg m^{-3} under NT and MT treatments, respectively. CWR of plants was not affected by crop management and it changed over the years with the changes in climatic characteristics. Development of conservation agriculture, especially NT in dryland areas for winter wheat production, in addition to the stability of grain yield, can be important in water and soil resource saving in the long term.

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References

1. Agriculture and Consumer Protection Department (FAO), Rome. 2000. Available online: http://www.fao.org/ag/ca/ (accessed on 20 March 2004).
2. UNCCD. *United Nations Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification*; International Organization for Migration: Paris, France, 1994.
3. Dehghani, M.; Salehi, S.; Mosavi, A.; Nabipour, N.; Shamshirband, S.; Ghamisi, P. Spatial Analysis of Seasonal Precipitation over Iran: Co-Variation with Climate Indices. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 73. [CrossRef]
4. Jayaraman, S.; Dang, Y.P.; Naorem, A.; Page, K.L.; Dalal, R.C. Conservation Agriculture as a System to Enhance Ecosystem Services. *Agriculture* **2021**, *11*, 718. [CrossRef]
5. Xuea, L.; Khana, S.; Suna, M.; Anwarc, S.; Rena, A.; Gaoa, Z.; Lina, W.; Xuea, J.; Yanga, Z.; Deng, Y. Effects of tillage practices on water consumption and grain yield of dryland winter wheat under different precipitation distribution in the loess plateau of China. *Soil Tillage Res.* **2019**, *191*, 66–74. [CrossRef]
6. Sammi Reddy, K.; Pratibha, G.; Sharma, K.L.; Srinivas, K.; Indoria, A.K.; Kundu, S.; Prasad, J.V.N.S.; Gopinath, K.A.; Singh, V.K. Conservation agriculture in dryland ecosystem: Prospects and opportunities. *Indian J Agron. (5th IAC Spec. Issue)* **2021**, *66*, S44–S56.
7. Bender, S.F.; Wagg, C.; van der Heijden, M.G.A. An underground revolution: Biodiversity and soil ecological engineering for agriculture sustainability. *Trends Ecol. Evol.* **2016**, *31*, 440–452. [CrossRef]
8. Zhao, J.; Yang, Y.; Zhang, K.; Jeong, J.; Zeng, Z.; Zang, H. Does crop rotation yield more in China? A meta-analysis. *Field Crops Res.* **2020**, *245*, 107659. [CrossRef]
9. German, R.N.; Thompson, C.E.; Benton, T.G. Relationships among multiple aspects of agriculture's environmental impact and productivity: A meta-analysis to guide sustainable agriculture. *Biol. Rev.* **2017**, *92*, 716–738. [CrossRef] [PubMed]
10. Wang, X.; Dai, K.; Zhang, D.; Zhang, X.; Wang, Y.; Zhao, Q.; Cai, D.; Hoogmoed, W.B.; Oenema, O. Dryland maize yields and water use efficiency in response to tillage/crop stubble and nutrient management practices in China. *Field Crops Res.* **2011**, *120*, 47–57. [CrossRef]
11. Sharma, K.L.; Grace, J.K.; Srinivas, K.; Ramakrishna, Y.S.; Korwar, G.R.; Shankar, M.G.; Mandal, U.K.; Ramesh, V.; Bindu, H.V.; Madhavi, M.; et al. Influence of tillage and nutrient sources on yield sustainability and soil quality under sorghum–mungbean system in rainfed semi–arid tropics. *Commun. Soil Sci. Plant Anal.* **2009**, *40*, 579–602. [CrossRef]
12. O'Leary, G.J.; Connor, D.J. Stubble retention and tillage in a semi-arid environment. 1. Soil water accumulation during fallow. *Field Crops Res.* **1997**, *52*, 209–219. [CrossRef]
13. Dolan, M.S.; Clapp, C.E.; Allmaras, R.R.; Baker, J.M.; Molina, J.A.E. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. *Soil Tillage Res.* **2006**, *89*, 221–231. [CrossRef]
14. Mbuthia, L.W.; Acosta-Martínez, V.; DeBruyn, J.; Schaeffer, S.; Tyler, D.; Odoi, E.; Mpheshea, M.; Walker, F.; Eash, N. Long-term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. *Soil Biol. Biochem.* **2015**, *89*, 24–34. [CrossRef]
15. Hemmat, A.; Eskandari, I. Dryland winter wheat response to conservation tillage in a continuous cropping system in northwestern Iran. *Soil Tillage Res.* **2006**, *86*, 99–109. [CrossRef]
16. Jalal-Kamali, M.R.; Najafi-Mirak, T.; Asadi, H.; Aghaei, M. *Wheat: Research and Management Strategies in Iran*; Agricultural Education Publication: Tehran, Iran, 2012; p. 250.
17. Monjardino, M.; Hochman, Z.; Horan, H. Yield Potential Determines Australia Wheat Growers' Capacity to Close Yield Gaps While Mitigating Economic Risk. *Agron. Sustain. Dev.* **2019**, *39*, 49. [CrossRef]
18. ASTM. *Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils, D2974-07a*; ASTM International: West Conshohocken, PA, USA, 2007.
19. Rosolem, C.A.; Pivetta, L.A. Mechanical and biological approaches to alleviate soil compaction in tropical soils: Assessed by root growth and activity (Rb uptake) of soybean and maize grown in rotation with cover crops. *Soil Use Manag.* **2017**, *33*, 141–152. [CrossRef]
20. Wang, L.; Wang, H.; Tian, Z.; Lu, Y.; Gao, W.; Ren, T. Structural changes of compacted soil layers in northeast china due to freezing-thawing processes. *Sustainability* **2020**, *12*, 1587. [CrossRef]
21. Chen, G.; Weil, R.R. Penetration of cover crop roots through compacted soils. *Plant Soil.* **2010**, *331*, 31–43. [CrossRef]

22. Somasundaram, J.; Salikram, M.; Sinha, N.K.; Mohanty, M.; Chaudhary, R.S.; Dalal, R.C.; Mitra, N.G.; Blaise, D.; Coumar, M.V.; Hati, K.M.; et al. Conservation agriculture effects on soil properties and crop productivity in a semiarid region of India. *Soil Res.* **2019**, *57*, 187–199. [CrossRef]
23. Somasundaram, J.; Sinha, N.K.; Dalal, R.C.; Lal, R.; Mohanty, M.; Naorem, A.K.; Hati, K.M.; Chaudhary, R.S.; Biswas, A.K.; Patra, A.K.; et al. No-Till Farming and Conservation Agriculture in South Asia—Issues, Challenges, Prospects and Benefits. *Crit. Rev. Plant Sci.* **2020**, *3*, 236–279. [CrossRef]
24. Asghari Maidani, J.; Karimi, I.; Pourmohamed, A. The effect of different tillage and planting methods on soil moisture and yield of safflower in rotation with wheat in dry areas. *Water Soil Sci.* **2013**, *23*, 237–245. (In Persian)
25. Khorsandi, H.; Ferdowsi, R.; Abdulahi, A.V. Technical and economic evaluation of tillage methods and nitrogen fertilizer consumption in dry wheat. *Iran. Dryland Agric. J.* **2019**, *9*, 108–191. (In Persian)
26. Baker, J.M.; Ochsner, T.E.; Venterea, R.T.; Griffis, T.J. Tillage and soil carbon sequestration—What do we really know? *Agric. Ecosyst. Environ.* **2007**, *118*, 1–5. [CrossRef]
27. Wang, X.B.; Cai, D.X.; Hoogmoed, W.B.; Oenema, O.; Perdok, U.D. Developments in Conservation Tillage in Rainfed Regions of North China. *Soil Tillage Res.* **2007**, *93*, 239–250. [CrossRef]
28. Meena, R.K.; Vashisth, A.; Das, T.K.; Meena, S.L. Effect of tillage practices on productivity of wheat (*Triticum aestivum* L.). *Ann. Agric. Sci.* **2018**, *39*, 12–19.
29. Fuentes, M.; Govaerts, B.; De Leon, F.; Hidalgo, C.; Dendooven, L.; Sayre, K.D.; Etchevers, J.; Etchevers, D. Fourteen years of applying zero and conventional tillage, crop rotation, and residue management systems and their effect on physical and chemical soil quality. *Eur. J. Agron.* **2009**, *30*, 228–237. [CrossRef]
30. Tracy, S.R.; Black, C.R.; Roberts, J.A.; Mooney, S.J. Soil compaction: A review of past and present techniques for investigating effects on root growth. *J. Sci. Food Agric.* **2011**, *91*, 1528–1537. [CrossRef]
31. Bojarszczuk, J. The Influence of Soil Tillage System on Changes in Gas Exchange Parameters of *Pisum sativum* L. *Agronomy* **2021**, *11*, 1000. [CrossRef]
32. Zibilske, L.M.; Bradford, J.M.; Smart, J.R. Conservation Tillage Induced Changes in Organic Carbon, Total Nitrogen and Available Phosphorus in a Semi-Arid Alkaline Subtropical Soil. *Soil Tillage Res.* **2002**, *66*, 153–163. [CrossRef]
33. Bronick, C.J.; Lal, R. Soil structure and management: A review. *Geoderma* **2005**, *124*, 3–22. [CrossRef]
34. Zhang, J.; Xu, Y.; Yao, F.; Wang, P.; Guo, W.; Li, L.; Yang, L. Advances in estimation methods of vegetation water content based on optical remote sensing techniques. *Sci. China Technol. Sci.* **2010**, *53*, 1159–1167. [CrossRef]
35. Pagnani, G.; Angelica, G.; D'Egidio, S.; Visioli, G.; Stagnari, F.; Pisante, M. Effect of Soil Tillage and Crop Sequence on Grain Yield and Quality of Durum Wheat in Mediterranean Areas. *Agronomy* **2019**, *9*, 488. [CrossRef]
36. El-Mejahed, K.; Sander, D.H. Rotation, tillage, and fertilizer effects on Wheat-based rain-fed crop rotation in semiarid Morocco. Proceeding of the third European conference of grain legumes. In *Opportunities for High-Quality, Healthy and Added-Value Crops to Meet European Demands*; AEP, European Association for Grain Legume Research: Valladolid, Spain, 1998.
37. Hobbs, P.R.; Sayre, K.; Gupta, R. The role of conservation agriculture in sustainable agriculture. *Philos. Trans. R. Soc. B Biol. Sci.* **2008**, *363*, 543–555. [CrossRef] [PubMed]
38. Gupta, R.; Gopal, R.; Jat, M.L.; Jat, R.K.; Sidhu, H.S.; Minhas, P.S.; Malik, R.K. Wheat Productivity in Indo-Gangetic Plains of India during 2010: Terminal Heat Stress and Mitigating Strategies. In *Conservation Agriculture Newsletter, Getting Agriculture to Work for People and the Environment*; PACA: New Delhi, India, 2010.
39. Beach, H.M.; Laing, K.W.; Walle, M.V.; Martin, R.C. The Current State and Future Directions of Organic No-Till Farming with Cover Crops in Canada, with Case Study Support. *Sustainability* **2018**, *10*, 373. [CrossRef]
40. Mousavi Fazl, M.; Barzegar, A.; Asudar, M. Effect of tillage methods on wheat root development and density, In The 9th Soil Science Congress of Iran. *Soil Cons. Watershed Res. Ins.* **2004**, *9*, 320–321.
41. Cárceles Rodríguez, B.; Durán-Zuazo, V.H.; Soriano Rodríguez, M.; García-Tejero, I.F.; Gálvez Ruiz, B.; Cuadros Tavira, S. Conservation Agriculture as a Sustainable System for Soil Health: A Review. *Soil Sys.* **2022**, *6*, 87. [CrossRef]