ANALYSIS THE RELATIONSHIP OF DIFFERENT YIELD LEVELS AND WATER USE OF DRYLAND WHEAT (*TRITICUM AESTIVUM* L.) UNDER DIFFERENT FALLOW TILLAGE TYPES

DONG, S. – NOOR, H. – YANG, L. –REN, A. – LIN, W. – YU, S. – REN, J. – SUN, M.* – GAO, Z.

College of Agriculture, Shanxi Agricultural University, Taigu 030801, China

**Corresponding author*
e-mail: sm_sunmin@126.com

(Received 19th Dec 2021; accepted 25th Feb 2022)

Abstract. Tillage method does exert a certain regulatory effect on yield of rainfed crops. A field experiment was established on the Loess Plateau and was for 8 years during 2009–2017. Three types of fallow tillage (no-tillage, deep plough and subsoiling) were used, and divided the yield with cluster analysis, studied the relationship of the main yield components and precipitation, soil water storage and water use. The results showed that the yield of wheat was influenced by the adjustment of the distribution of yield components in different precipitation years, and the number of plural was the main factor to obtain higher yield, which was influenced by the precipitation during the fallow-period and the sowing-anthesis period, the reasonable distribution of grain number per spike and 1000-grain weight is the factor of high yield, which is mainly affected by precipitation and soil water consumption at the later growth stage. In addition, cultivation during fallow-period can achieve higher yield, but under the influence of precipitation type, DP during growth-dry year type was more favorable to the increase of field evapotranspiration, the growth-wet type of SS was more beneficial to the improvement of water use efficiency.

Keywords: *Loess Plateau, tillage regulation, yield components, water use efficiency, precipitation use efficiency*

Introduction

The Loess Plateau is one of the main wheat-producing areas in China, and food security is dependent on its yield. In this region, the dry-farming wheat area accounted for 80% of wheat farming and was the key that affected the yield (Su et al., 2007). Water is the main factor limiting the yield of the region by low precipitation, high variability in precipitation, high evaporation, and uneven concentration; 60% of the precipitation in the fallow period is inconsistent with the growth and development of wheat (Qiu et al., 2017; Kang et al., 2002; Ren et al., 2019). In the region, intensive agriculture has long been used to ensure food security, which has led to the destruction of soil structures, reduced fertility and severe soil erosion, and increased environmental damage; these are detrimental to the sustainable development of agriculture (Su et al., 2007; Hungria et al., 2009; Zhang et al., 2016).

Conservation tillage is an agricultural measure that reduces mechanical or non-tillage of the soil and provides a permanent organic mulch, which has an outstanding performance in increasing wheat yields in drylands (Friedrich et al., 2017). These techniques include no-tillage (NT), subsoiling (SS), and deep plowing (DP). NT (usually including Straw mulching) improves soil degradation and farmland erosion caused by intensive agriculture (Zhang et al., 2016; Camarotto et al., 2018), but long-term use may increase soil bulk density and permeability resistance and decrease total porosity, which are detrimental to water conservation. DP (depth of 25-30 cm) and SS (depth of 30–40 cm) are often used to reduce and break soil compaction and reduce soil bulk density

(Unger et al., 1994; López-Garrido et al., 2014; Costa et al., 2015). These reduced tillage practices positively affected rain penetration into the soil and soil water storage, thus improving soil water content and increasing tiller number, wheat grain yield, and plant water-use efficiency (WUE); however, the yield varied enormously from year to year.

Wheat yield components include tiller number, grain number per ear, and 1000-grain weight. Increased coordination among yield components is required to improve crop yield potential (Qin et al., 2015; Slafer et al., 2003; Sadras et al., 2012). However, some studies have shown that the contribution of the various yield components to the total yield differs for different yield-range levels, and correlation analysis between any single variable and yield does not fully explain the importance of each component to yield (Dewey et al., 1959; Singh et al., 1979; Cao et al., 2019). Furthermore, some studies have shown a significant correlation influenced by field water consumption between wheat yield and soil moisture status over multiple growth stages from sowing to maturity (Ozturk, 2004; Seddaiu et al., 2016; Wang et al., 2018).

In this study, the main objective was to determine the correlation between yield and soil water content and water consumption at different yield levels. Grain yield differences in dryland can be large, and the effects from different years and tillage methods on wheat yield are known to vary significantly. Therefore, studying the relationship between water content and yield components at different yield levels will help guide yield promotion at different yield levels and provide more detailed ideas for increasing yield. Based on this rationale, a long-term experiment was established in a typical semi-arid Loess Plateau region using fallow tillage (DP, SS, and NT). Based on production data, the objectives of this study were: 1) to clarify the correlation between yield and water during the growth period under different yield levels, 2) to compare the effects of year and tillage on yield components and water use, and 3) to evaluate the correlation differences between yield components and yield and water sources at different stages under different yield levels.

Materials and methods

Description of the study site

Field experiments were conducted during the winter wheat growing season from 2009 through 2017 in the Experimental Station at Shanxi Agricultural University, located in Wenxi County (34° 35′ N; 110° 15′ E), Shanxi Province, China. The site is characterized by the semi-arid climate of the northeast region of the Loess Plateau, with an average annual ambient temperature of 11–13 °C and annual precipitation of 335.0–671.30 mm (2009–2017). The elevation ranges between 450 and 700 m above sea level, and the annual precipitation tends to concentrate in the months from July through September. According to Guo et al. (2012), based on the precipitation distribution from 1987-2017, the follow period and growth period were divided according to the drought index (normal, dry, and wet), the results shown in *Table 1*. Monthly temperature and precipitation distribution during 2009–2017 are shown in *Figure 1*.

Experimental design and field management

During the winter-wheat fallow season, three different tillage methods were tested: 1) DP (stirring at a depth of 25–30 cm), 2) SS (loosening at a depth of 30–40 cm), and 3) NT (*Fig. 2*). When winter wheat was harvested at the end of June, 20–30 cm of stubble was retained in the field to reduce water evaporation and to provide soil organic matter for the next crop. In mid-late July, two different tillage machines were used for fallow cultivation, compared with no-tillage. Rotary tillage was conducted in late August to level the land to prepare it for sowing. All treatments were designed with complete block randomization and repeated 3 times with an area of 300 m^2 (6 m × 50 m). Before sowing, 150 kg N ha^{-1} (urea, 46%), P_2O_5 (38 kg ha^{-1}), and K_2O (75 kg ha^{-1}) were applied. The test material was ‘Hanyun20410,’ which was mechanically sown with a row spacing of 20 cm and a planting density of 315 × 10^4 plant ha^{-1}. Field management measures were adopted in Dryland, weeds were controlled artificially, and no irrigation was carried out during the growing period. The date of sowing is shown in *Table 2*.

Table 1. *Annual precipitation amount and type in the fallow, growth, and whole cropping seasons at the Wenxi Dryland Agriculture Research Station from 2007 to 2017*

Planting season	**Fallow season (Late June - Mid September)**			**Growth season (Late September - Mid June)**		
	Precipitation	**Drought index**	**Type**	**Precipitation**	**Drought index**	**Type**
2009-2010	173.1	-0.75	dry	161.9	-1.25	dry
2010-2011	401.5	1.65	wet	133.2	-1.84	dry
2011-2012	459.9	2.27	wet	213.2	-0.21	normal
2012-2013	171.1	-0.77	dry	171.8	-1.05	dry
2013-2014	283.7	0.41	wet	190.5	-0.67	dry
2014-2015	365.6	1.28	wet	151.1	-1.47	dry
2015-2016	94.7	-1.58	dry	292.1	1.40	wet
2016-2017	165.4	-0.83	dry	240.9	0.36	wet

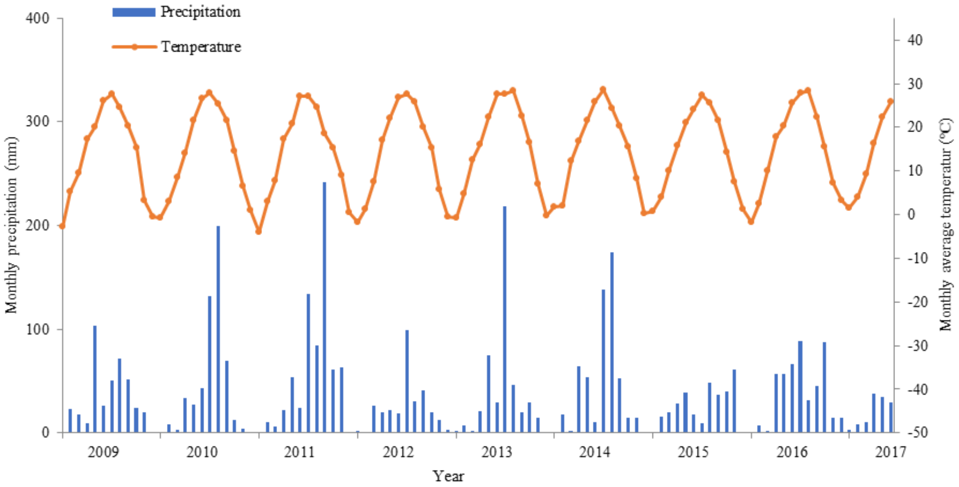

Figure 1. *Temporal distribution of monthly precipitation and temperature from 2009 to 2017*

Table 2. *Information on experimental land preparation*

Items	**Growing season**							
	2009-2010	**2010-2011**	**2011-2012**	**2012-2013**	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**
Date of subsoiling and deep plowing	15 July	15 July	10 July	15 July	15 July	15 July	15 July	15 July
Date of rotary tillage and land leveling	20 Aug	28 Aug	25 Aug	25 Aug	23 Aug	22 Aug	26 Aug	27 Aug

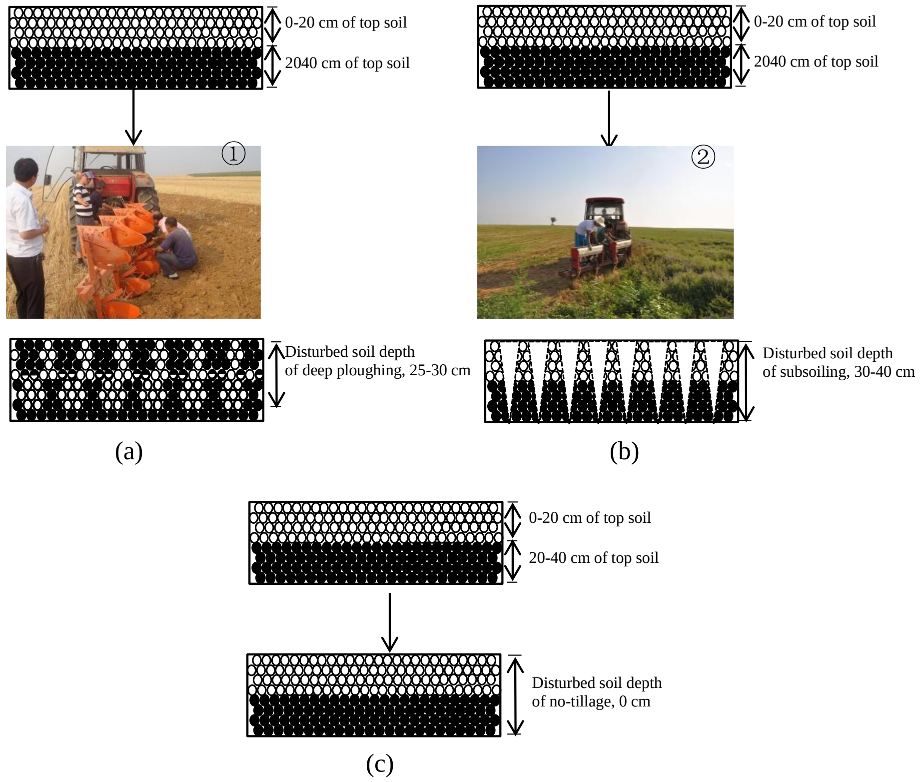

Figure 2. *Sketch map of topsoil structure of 0–40 cm after deep plowing, subsoiling, and no-tillage. ○ Sketch map structure of 0–20 cm soil particle before tillage. ● Sketch map structure of 20–40 cm soil particle before tillage. ▽ Sketch map of the voids in the soil after subsoiling*

Cluster analysis in 2009–2017 of wheat yield

The distribution of yield and cluster analysis for wheat yields from 2009–2017 were analyzed. Wheat yields ranged from 1.50 t ha^{-1} to 6.50 t ha^{-1} (*Fig. 3*). According to the method of cluster analysis, the yield was divided into three levels: low yield (2.14–2.92 t ha^{-1}), medium yield (3.64–4.27 t ha^{-1}), and high yield (4.58-6.01 t ha^{-1}) (*Fig. 4*).

Measurements

Soil moisture

Soil gravimetric moisture content (GSW, %) and soil water storage (SWS, mm) were measured gravimetrically at each plant growth stage. Soil samples were collected to a depth of 300 cm at 20-cm intervals, as described by (Sun et al., 2019). One sample was considered as one replicate. GSW and SWS were obtained using *Equations 1* and *2*, respectively:

$$\mathrm{GSW}(\%) = \frac{\mathrm{Mw}-\mathrm{Md}}{\mathrm{Md}} \times 100 \qquad \text{(Eq.1)}$$

$$\mathrm{SWS\ (mm)} = \mathrm{GSW\ (\%)} \times \rho\mathrm{b\ (g\ cm^{-3})} \times \mathrm{SD\ (cm)} \qquad \text{(Eq.2)}$$

where M_w and M_d are the weights (g) of wet and dry soil, respectively; ρb is soil bulk density of the given soil layer, and SD refers to soil depth.

DOI: http://dx.doi.org/10.15666/aeer/2003_26092623

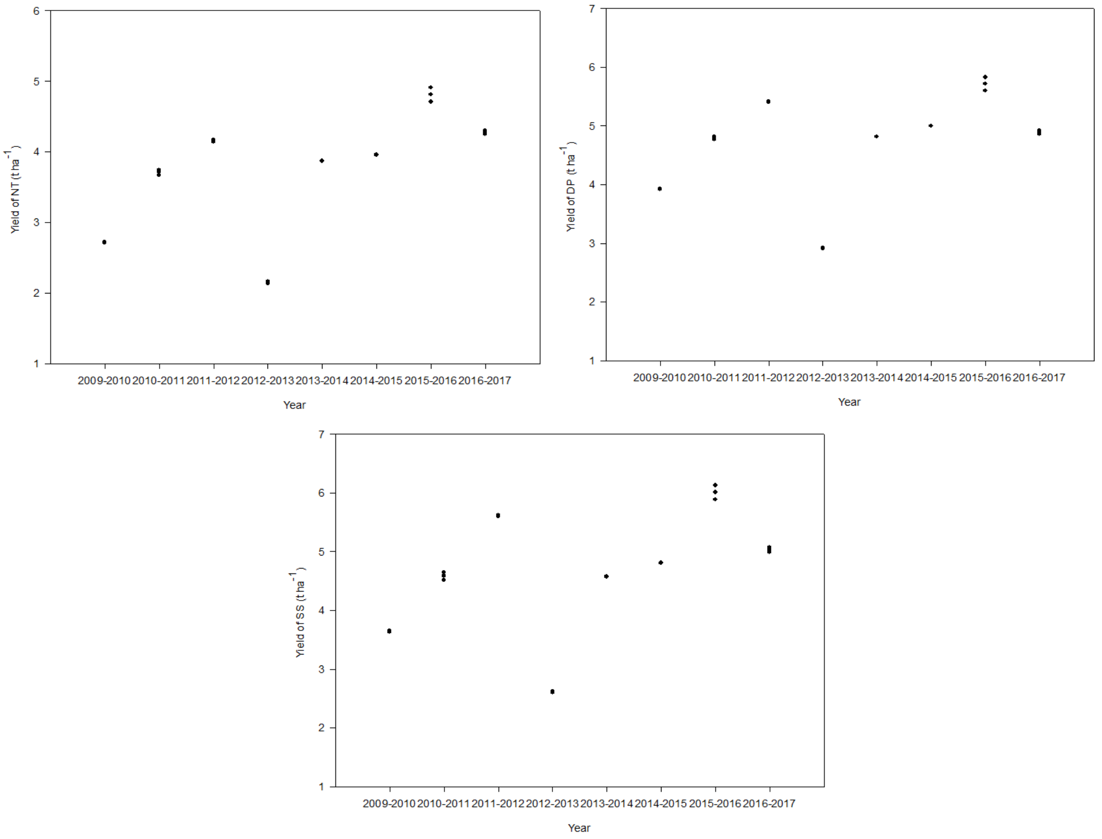

Figure 3. *Distribution of wheat yield from 2009 to 2017*

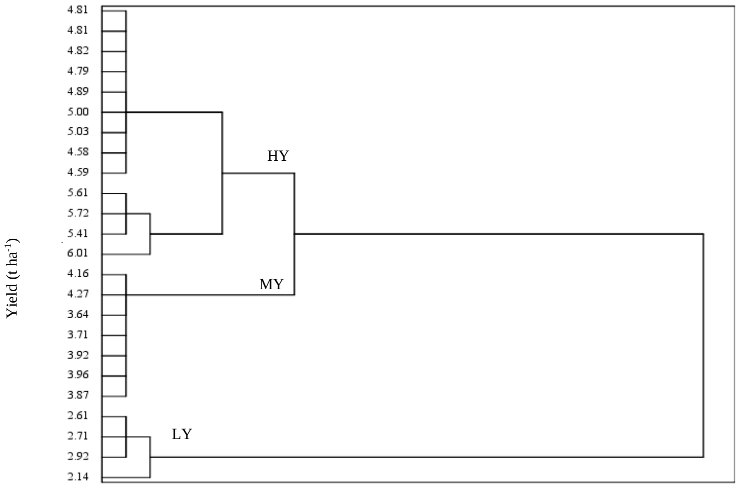

Figure 4. *Yield cluster analysis under different tillage methods (deep plowing, subsoiling, no-tillage). LY = Low yield level; MY = Medium yield level; HY = High yield level*

Evapotranspiration, precipitation, and WUE

Evapotranspiration (ET) over the whole growing season, WUE, and precipitation use efficiency (PUE) were calculated using *Equations 3, 4* and *5:*

$$ET = SW_0 - SW_1 + P - R - D \tag{Eq.3}$$

$$WUE\ (kg\ ha^{-1}\ mm^{-1}) = grain\ yield/ET \tag{Eq.4}$$

$$PUE\ (kg\ ha^{-1}\ mm^{-1}) = grain\ yield/P \tag{Eq.5}$$

where SW_0 is soil water storage before sowing and SW_1 is soil water storage after harvest. P is precipitation during the wheat growth period, R is soil surface runoff, D is deep percolation, and Pt is the total precipitation from tillage to harvest. Because the field was flat and the experimental plots were surrounded by ridges to prevent runoff, R was estimated to be 0 in this research. The ground water table was deeper than 50 m in the research region and there was no water percolated to the deep soil layers; therefore, D was also considered to be 0.

Yield and yield components

Fifty plants from each plot were randomly sampled at maturity from the inner rows to determine yield components, including spike numbers, grains per spike, and 1000-grain weight. Plot grain yield was determined by harvesting all plants in a 20 m^2 area, shelling them mechanically, and determining grain yield after air-drying.

Statistical analysis

Analysis of variance and the least significant difference were performed using SPSS 25.0 (SPSS Inc., Chicago, IL, USA) to determine treatment effects and to identify significant differences among treatments. Differences were considered significant at $P < 0.05$. Figures and tables were designed using Microsoft Excel 2015.

Results

Differences in SWS and yield formation at different growth stages

The correlation between yield formation and SWS differed for different yield levels (*Fig. 5*). At the low yield level, the yield was not significantly related to SWS at sowing, jointing, or anthesis, but with increasing SWS, the yield decreased first and then increased. This indicated that SWS higher than 388.2 mm, 331.2 mm, and 258.0 mm at sowing, jointing, and anthesis, respectively, was beneficial for yield formation (*Fig. 5A–C*). At the medium yield level, the yield showed an increasing trend with increasing SWS, and the correlation between yield and SWS at the jointing stage was higher (*Fig. 5B*). Lastly, at the high yield level, the yield was mainly related to SWS at jointing, anthesis, and maturity, and the trend was similar to that observed for the medium yield level (*Fig. 5A–C*). These results indicate that higher SWS during the late growth period is crucial for the formation of a higher yield.

Correlation between field water consumption and yield formation

The correlation between yield formation and water consumption during growth was different for each yield level (*Fig. 6*). Thus, at the low yield level, yield increased with increasing soil water consumption at each growth stage, although differences were not significant (*Fig. 6A–C*). In turn, yield increased with increasing field water consumption and correlated with water consumption from jointing to anthesis at the medium yield level (*Fig. 6B*). On the other hand, at the high yield level, yield correlated with water consumption at anthesis and maturity and increased with increasing water consumption (*Fig. 6A–C*). These results indicate that higher field water consumption during late growth is essential to high yield.

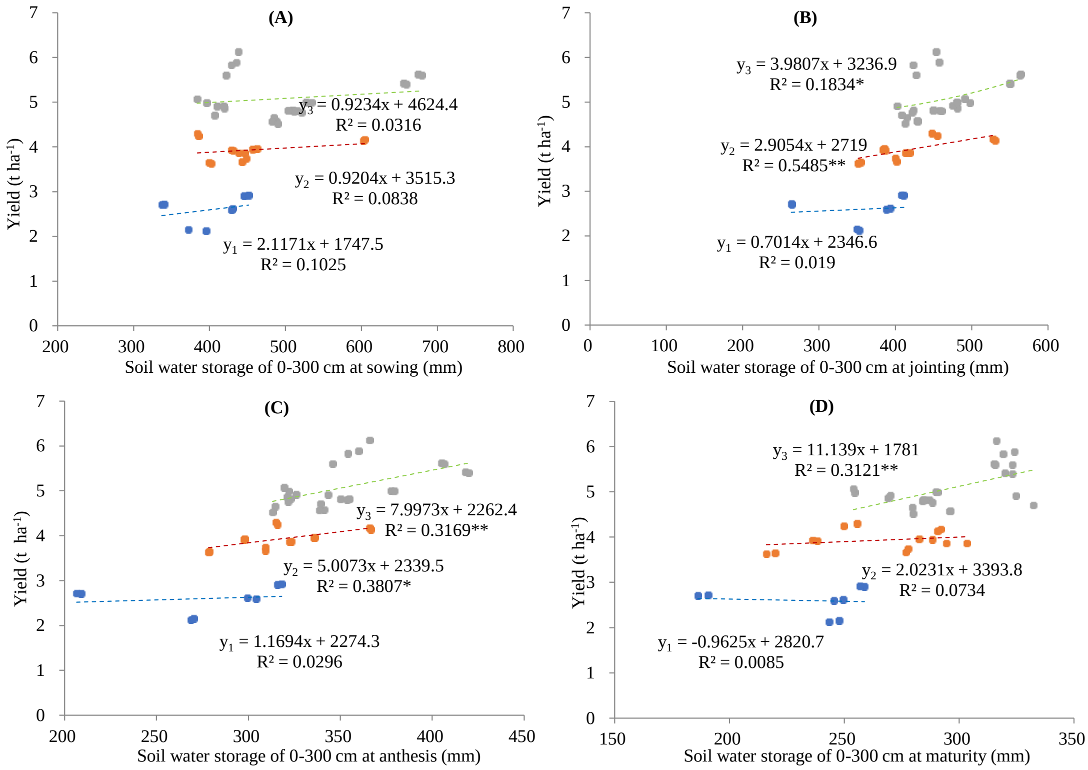

Figure 5. *Correlation between soil water content at sowing and anthesis and low, medium, and high yield levels of winter wheat.* y_1 *= Low yield;* y_2 *= Medium yield;* y_3 *= High yield;* * *and* ** *indicates difference at the 0.05 and 0.01 probability levels, respectively*

Yield components and WUE

In 2009-2017, the fluctuation range of wheat yield was large, and the yield varied with different treatments in the same year (*Table 3*). No-tillage treatment, 2009-2010, 2012-2013 in low-yield level, 2010-2012, 2013-2015, 2016-2017 in the middle-yield level, 2015-2016 in high-yield level. The precipitation patterns were similar at the same yield level, the low-yield level included dry of all the season, the middle-yield level included wet-fallow and dry-growth season, dry-fallow and wet-growth season, the high-yield level included dry-fallow and wet-growth season. Compared with NT, SS and DP were conducive to crop production, especially between 2009-2010 and 2010-2012, 2013-2015, 2016-2017, the level of output changes, low yield to middle, middle to high yield. Compared with SS, DP had higher yield in 2009-2011 and 2012-2015, and had similar annual pattern, all of which were dry-growth season types. But in other years, the yield of SS was higher, and the annual pattern was normal-growth or wet-growth season types. In dry-growth, DP was more advantageous to improve the PUE and increase the ET. In normal-growth, SS was more advantageous to improve the PUE and increase the ET. In wet-growth, SS was more advantageous to improve the PUE and WUE.

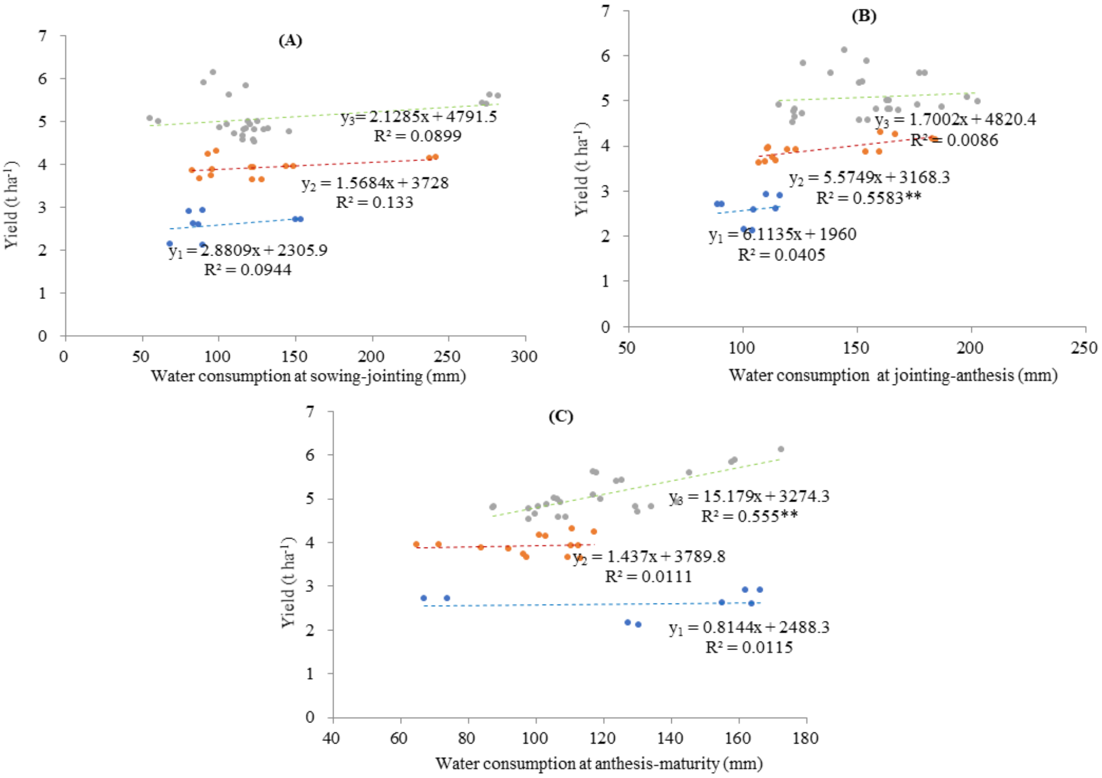

Figure 6. *Correlation between field water consumption at different growth stages and yield at y_1 = Low yield; y_2 = Medium yield; y_3 = High yield; * and ** indicates difference at the 0.05 and 0.01 probability levels, respectively*

Tillage method, the year, and their interaction significantly affected water consumption, WUE, and PUE, all of which showed an increasing trend with increasing production level. At the low yield level, average field water consumption, WUE, and PUE were 334.7 mm, 7.8 kg ha^{-1} mm^{-1}, and 7.6 kg ha^{-1} mm^{-1}, respectively, and water consumption was highest in the year with the highest yield, while WUE was also relatively high. WUE and PUE were also significantly higher at all yield levels when the yield was higher, compared to years when the yield was low. In addition, compared with NT, DP and SS effectively improved WUE by 11.7%-11.9%, and PUE by 24.2%-26.7%, respectively, in the same year.

Correlation analysis of yield, yield components, and contribution of water sources

The contribution of the various yield components to yield formation varied with yield level (*Table 4*). Thus, at the low yield level, tillers, grain number per ear, and 1000-grain weight were positively correlated with yield. Meanwhile, at the medium yield level, 1000-grain weight was negatively correlated with yield, while tiller number and grain number per ear were the key components for increasing grain yield. Lastly, at the high yield level, the correlation between the 1000-grain weight and yield was non-significant, but the latter was significantly increased by tiller number and grain number per ear.

At the low yield level, the fallow precipitation and precipitation from sowing to jointing and jointing to anthesis were positively correlated with tillers. However, from anthesis to maturity, the correlation was negative (*Table 5*)—the grain number per ear and 1000-grain weight correlated negatively with precipitation. Soil water consumption from sowing to jointing was positively correlated with tillers, but it was negative from jointing to anthesis. Grain number per ear and 1000-grain weight were positively correlated with soil water consumption from jointing to anthesis and from anthesis to maturity. In turn, at the medium yield level, the precipitation from sowing to jointing was positively correlated with tiller number, but from jointing to anthesis and from anthesis to maturity, the correlation was negative. Precipitation from sowing to jointing was negatively correlated with grain number per ear. Finally, the correlation between precipitation and tillers at the high yield level was similar to that detected at the low yield level, and fallow precipitation and precipitation from sowing to jointing were negatively correlated with grain number per ear. In contrast, the correlations were positive with precipitation from jointing to anthesis and from anthesis to maturity. On the other hand, soil water consumption from sowing to jointing and jointing to anthesis was positively correlated with the tiller number, whereas the same variables correlated negatively with water consumption from anthesis to maturity.

Table 3. *Differences in yield components and water use efficiency among LY, MY, HY*

Yield level	**Treatment**	**Tillers (10^4 ha^{-1})**	**Grain number per ear**	**1000-grains weight (g)**	**Yield (t ha^{-1})**	**ET (mm)**	**WUE (kg ha^{-1} mm^{-1})**	**PUE (kg ha^{-1} mm^{-1})**
LY	2009-2010 NT	407.71 a	20.38 c	36.14 c	2.71 b	311.98 c	8.70 a	8.10 b
	2012-2013 NT	300.25 d	20.37 c	36.46 c	2.14 d	310.17 c	6.90 d	6.24 d
	2012-2013 SS	341.50 c	22.29 b	38.81 b	2.61 c	354.10 b	7.37 c	7.61 c
	2012-2013 DP	350.25 b	23.17 a	40.67 a	2.92 a	362.43 a	8.04 b	8.50 a
Mean		349.93	21.55	38.02	2.59	334.67	7.75	7.61
MY	2009-2010 SS	427.18 c	21.70 f	39.04 c	3.64 f	344.88 d	10.55 f	10.87 b
	2009-2010 DP	453.72 b	23.78 e	42.08 a	3.92 c	354.37 c	11.07 e	11.71 a
	2010-2011 NT	401.04 e	26.22 c	40.51 b	3.71 e	301.65 g	12.28 a	6.93 f
	2011-2012 NT	485.50 a	24.33 d	35.44 d	4.12 b	525.20 a	7.91 g	6.17 g
	2013-2014 NT	386.65 f	27.55 b	39.12 c	3.87 d	334.05 e	11.58 c	8.15 d
	2014-2015 NT	417.00 d	27.48 b	39.14 c	3.96 c	325.22 f	12.16 b	7.66 e
	2016-2017 NT	452.12 b	33.36 a	35.66 d	4.27 a	373.02 b	11.46 d	10.52 c
Mean		431.89	26.35	38.71	3.93	365.48	11.00	8.86
HY	2010-2011 SS	446.58 k	28.24 g	40.59 cd	4.59 h	340.81 j	13.46 c	8.58 i
	2010-2011 DP	481.08 h	28.38 fg	42.58 a	4.80 g	361.01 i	13.28 c	8.97 h
	2011-2012 DP	603.00 b	26.56 h	37.15 f	5.41 d	549.04 b	9.86 h	8.04 k
	2011-2012 SS	616.50 a	26.74 h	38.63 e	5.61 c	575.02 a	9.76 h	8.34 j
	2013-2014 SS	454.41 j	28.31 fg	41.04 bc	4.58 h	379.48 f	12.06 f	9.65 f
	2013-2014 DP	466.00 i	29.63 e	41.55 b	4.82 fg	409.82 c	11.76 g	10.16 e
	2014-2015 SS	488.33 fg	28.79 f	40.30 d	4.81 fg	380.16 f	12.64 e	9.30 g
	2014-2015 DP	522.98 c	29.72 e	41.01 bc	5.00 e	391.54 e	12.77 de	9.68 f
	2015-2016 NT	425.75 l	34.78 d	39.06 e	4.81 fg	371.90 h	12.94 d	12.44 c
	2015-2016 DP	484.50 gh	36.23 b	39.11 e	5.72 b	396.09 d	14.44 b	14.79 b
	2015-2016 SS	493.25 ef	37.80 a	41.26 b	6.01 a	408.60 c	14.71 a	15.54 a
	2016-2017 DP	496.25 e	35.57 c	33.12 h	4.90 f	390.33 e	12.53 e	12.04 d
	2016-2017 SS	503.36 d	35.54 c	34.21 g	5.03 e	376.52 g	13.36 c	12.38 c
Mean		498.61	31.25	39.20	5.08	410.02	12.58	10.76
ANOVA results								
Tillage (T)	< 0.001							
Year (Y)								
T×Y								

WUE = water use efficiency, PUE = precipitation use efficiency, LY = Low yield level, MY = Medium yield level, HY = High yield level, NT = no-tillage, SS = subsoiling, DP = deep plowing, Significant difference between different yield level groups are indicated with different letters in the same treatment ($P < 0.05$)

Table 4. *Correlation between yield and yield components*

Yield level	Y1	Y2	Y3	Simulation equation
LY	0.676**	0.661*	0.634*	$Y = 5.694*Y1 + 111.949*Y3-3653.974$, $R^2 = 0.999$
MY	0.626**	0.641**	-0.700**	$Y = 4.558*Y1 + 42.942*Y2 + 831.857$, $R^2 = 0.999$
HY	0.540**	0.375*	-0.088	$Y = 8.836*Y1 + 111.52*Y2 + 93.9*Y3-6489.48$, $R^2 = 0.999$

Y = Yield, Y1 = Tillers, Y2 = Number per ear, Y3 = 1000-grains weight, * and ** indicates the correlation level $P < 0.05$ and $P < 0.01$

Table 5. *Correlation between yield components and water source contribution*

Yield level	Yield composition	X1	X2	X3	X4	X5	X6	X7
LY	Y1	0.869**	0.951**	0.869**	-0.698**	0.869**	-0.199	-0.869**
	Y2	-0.551*	-0.338	-0.551*	0.765**	-0.551*	0.949**	0.551*
	Y3	-0.585*	-0.370	-0.585*	0.779**	-0.585*	0.944**	0.585*
MY	Y1	0.012	-0.033	0.812**	0.665**	-0.611**	0.939**	-0.483*
	Y2	-0.112	-0.785**	0.368	0.242	0.120	-0.167	0.069
	Y3	-0.212	0.360	-0.869**	-0.730**	0.259	-0.470*	0.356
HY	Y1	0.345*	0.630**	0.819**	0.524**	0.629**	-0.482**	-0.559**
	Y2	-0.872**	-0.099	-0.478**	-0.949**	0.311*	0.253	0.695**
	Y3	0.605**	-0.708**	-0.211	0.269*	-0.822**	0.451**	0.160

LY = Low yield level, MY = Medium yield level, HY = High yield level, Y1 = Tillers, Y2 = grain number per ear, Y3 = 1000-grain weight, X1 = Precipitation of fallow period, X2 = Soil water consumption of sowing–jointing, X3 = Precipitation of sowing–jointing, X4 = Soil water consumption of jointing–anthesis, X5 = Precipitation of jointing–anthesis, X6 = Soil water consumption of anthesis–maturity, X7 = Precipitation of anthesis–maturity; * and ** indicates the correlation level $P < 0.05$ and $P < 0.01$

The simulation equation (*Table 4*) indicated that soil water consumption from anthesis to maturity mainly influenced the formation of grain number per ear and 1000-grain weight at the low yield level. Furthermore, at the medium yield level, tiller number was positively affected by soil water consumption from jointing to maturity; grain number per ear was affected by soil water consumption from anthesis to maturity, and 1000-grain weight was affected by precipitation from seeding to jointing, and soil water consumption from anthesis to maturity. Finally, tiller number was positively affected by fallow precipitation from seeding to anthesis at the high yield level; grain number per ear was affected by water consumption from seeding to anthesis and precipitation from jointing to maturity, while 1000-grain weight was affected by fallow precipitation and precipitation at each growth stage.

Discussion

Effect of water on wheat yield

Precipitation is the important source of water supply in arid and semi-arid regions; therefore, it is the main limiting factor for winter wheat production (He et al., 2016).

Field water consumption, WUE, and PUE were all affected by year and tillage treatment, thereby affecting wheat yield (Sun et al., 2019, 2018). In addition, wheat yield was significantly correlated with soil water status at various developmental stages from sowing to maturity. Wang et al. (2017) reported that soil water storage from jointing to maturity was the key factor for increasing wheat yield in the Loess Plateau. Further, Lin and Wang et al. (2017) suggested that the key periods for water demand of winter wheat were sowing, jointing, and anthesis. Meanwhile, according to Deng et al. (2006) and Su et al. (2007), soil moisture from jointing to heading stage is particularly important in determining yield formation. The correlation between yield and soil water storage at each growth stage was different, which is not only related to regional differences but to wheat growth stage and yield level. In this study, when yield was lower than 3.00 t ha^{-1}, it was more strongly related to soil water storage at sowing, jointing, and anthesis. In contrast, when yield reached between 3.00 and 4.50 t ha^{-1} it was more related to soil water storage at jointing and anthesis; whereas, when it reached over 4.50 t ha^{-1} it was more related to soil water storage at jointing, anthesis, and maturity. Sufficient soil moisture is beneficial for providing water for wheat growth, especially under the conditions of low precipitation. Tillage in the fallow period improved soil water storage, field evapotranspiration, and WUE in the same year, which was conducive to the improvement of yield (Xue et al., 2019). In addition, this study also showed that DP was more advantageous to the formation of wheat yield in growth-dry year, possibly because DP water moved down shallowly, water supply was more convenient in early growth period, and promoted the formation of crop yield components, higher ET was also evidence. In growth-normal or growth-wet years, SS was more effective, probably because SS water moved down more deeply, and precipitation was adequate for yield construction in the early growth stage, and soil water construction consumed less water, which could mainly serve for grain formation, higher WUE could be demonstrated.

Effects of yield components on wheat grain yield

Optimizing spike number per hectare is a important method to maximize yield in most cereal crops beside of genotype-specific because it can increase plant vigor and hence plant grain yield (Weiner et al., 2001). Both, the number of tillers and yield were positively correlated at different yield levels, indicating that a larger number of tillers may guarantee a higher yield from winter wheat. These results are consistent with previous studies (Del Blanco et al., 2001; Cao et al., 2019). However, grain number per ear and 1000-grain weight showed different correlations with yield at different yield level. Thus, for example, Duan et al. (2018) suggested that at a low yield level (less than 7.50 t ha^{-1}), yield was positively correlated with the number of grains per ear but negatively correlated with 1000-grain weight, whereas at high yield level (i.e., yields greater than 7.50 t ha^{-1}), yield was correlated with grain number per ear, but not with 1000-grain weight. In the present study, a significant relationship was found between yield and tiller number. However, when yield was lower than 3.00 t ha^{-1}, it was correlated with 1000-grain weight, and when yield was between 3.00 and 4.50 t ha^{-1}, it was significantly and negatively correlated with 1000-grain weight. In addition to number of tillers, at low and intermediate yield levels, 1000-grain weight and number of grains per ear were the key yield components responsible for increasing crop yield. Similarly, at the high yield level, the key to high crop yield was higher grain number per ear and 1000-grain weight, in addition to number of tillers. Compared with NT, fallow tillage can improve PUE, regulate water and promote the formation of yield components. In growth-dry or growth-normal years, water mainly regulated the growth factors of wheat, and the ET was higher, but in growth-wet years, it promoted wheat filling and WUE was higher.

Effects of water and wheat yield formation

The key yield components responsible for the formation of yield are well known to be affected by soil moisture at each growth stage and to influence each other (Li et al., 2017; Yao et al., 2015; Dong et al., 2019; Slafer, 2003). The early growth stage is conducive to the formation of spike number, while the latter growth stage is important for the formation of spike number and 1000-grain weight (Hochman, 1982). At different yield levels, the correlation between components and water sources in the different stages varied. In the low-yielding years, ear-forming stage precipitation was less in 2009–2010 and 2012–2013. Especially in 2012–2013, when fallow cultivation was adopted, it was difficult to make up for the deficit in the grain number per ear caused by the lack of precipitation in the sowing–jointing stage. In 2009–2010, the precipitation in the sowing–jointing period was 31 mm higher than that in 2012–2013, and the precipitation in the fallow period was accumulated to make up the inadequate water consumption under NT to ensure that the yield reached the medium-level of the same year. The medium-yield years were distributed in 2010–2012, 2013–2015, and 2016–2017, among which 2010–2012 and 2014–2015 rainfall distribution was similar, its follow period rainfall was sufficient, reaching 360 mm and above; although the growth stage rainfall was less. However, DP and SS accumulated water in the soil during the fallow period, ensured water consumption in the later period and increased the yield. The precipitation in 2013–2014 and 2016–2017 was similar, although the precipitation in the fallow period was less and that in the key growth stage was more. DP and SS could improve the physical and chemical properties of soil, absorb more precipitation in the fallow and key growth periods, reduce water stress in wheat, and promote high yield in the same year. The high-yield years were mainly from 2015 to 2016, with precipitation being less in the fallow period. However, in the two key periods sowing–jointing and flowering–maturing periods, the precipitation was sufficient to meet the needs of population construction and grain filling of wheat. During the fallow period, tillage increased the spike number and 1000-grain weight slightly, which mainly regulated the formation of grain number per spike and increased the yield. Although precipitation varied with year, water supply in the key stages was still the primary factor affecting yield components. In the fallow period, DP and SS had the advantage of increasing yield at different levels, which may be attributed to the improvement of soil structure that promoted the PUE and then made up for the difference caused by the lack of precipitation, especially in the low–medium yield years.

Conclusions

At different yield levels, precipitation distribution is different in fallow and growth periods. Using DP and SS in the fallow period, PUE can be improved and yield components negatively affected by precipitation can be improved. In low and medium yield years, DP and SS were mainly responsible for 1000-grain weight and grain number per spike. In the high-yield years, fallow cultivation can help adjust the relationship among the components, promote reasonable distribution, and improve yield. In addition, this study also found that under growth-dry, DP was more beneficial to the contribution of water to the growth of wheat and to the improvement of yield, while SS was more effective under the growth-normal or growth-wet, it may be that water accumulation is more favorable for the use of grain filling. However, whether the yield components of different wheat genotypes have the same effect on the response to water stress needs further study.

Acknowledgements. This research was partially supported by the "Modern Agriculture Industry Technology System Construction" (No. CARS-03-01-24), the National Key Research and Development Program of China (No. 2018YFD020040105), National Natural Science Foundation of China (No. 31771727), the "Crop Ecology and Dry Cultivation Physiology Key Laboratory of Shanxi Province" (No. 201705D111007), and the "1331" Engineering Key Innovation Cultivation Team-Organic Dry Cultivation and Cultivation Physiology Innovation Team (No. SXYBKY201733), 2019 Graduate Education Innovation Plan Project (No. 2019SY222), the scientific and technological innovation project of Shanxi University (2019l0385), the science and technology innovation fund project of Shanxi Agricultural University (2019001), and the scientific research project of Shanxi excellent doctor working in Shanxi Province (sxybky2018044).

REFERENCES

[1] Camarotto, C., Ferro, N. D., Piccoli, I., Polese, R., Morari, F. (2018): Conservation agriculture and cover crop practices to regulate water, carbon and nitrogen cycles in the low-lying Venetian plain. – Catena 167: 236-249.

[2] Cao, H., Li, Y., Chen, G., Chen, D., Qu, H., Ma, W. (2019): Identifying the limiting factors driving the winter wheat yield gap on smallholder farms by agronomic diagnosis in North China Plain. – Journal of Integrative Agriculture 18(8): 1701-1703.

[3] Costa, J. L., Aparicio, V., Cerda, A. (2015): Soil physical quality changes under different management systems after 10 years in the Argentine humid pampa. – Solid Earth 6(1): 361-371.

[4] Del Blanco, I. A., Rajaram, S., Kronstad, W. E. (2001): Agronomic potential of synthetic hexaploid wheat-derived populations. – Crop Science 41: 670-676.

[5] Deng, X., Shan, L., Zhang, H., Turner, N. C. (2006): Improving agricultural water use efficiency in arid and semiarid areas of China. – Agricultural Water Management 80: 23-40.

[6] Dewey, D. R., Lu, K. (1959): A correlation and path-coefficient analysis of components of crested wheatgrass seed production. – Agronomy Journal 51: 70-74.

[7] Dong, Z., Zhang, X., Li, J., Zhang, C., Wei, T., Yang, Z., Cai, T., Zhang, P., Ding, R., Jia, Z. (2019): Photosynthetic characteristics and grain yield of winter wheat (Triticum aestivum L.) in response to fertilizer, precipitation, and soil water storage before sowing under the ridge and furrow system: a path analysis. – Agricultural and Forest Meteorology 272: 12-19.

[8] Duan, J., Wu, Y., Zhou, Y., Ren, X., Shao, Y., Feng, W., Zhu, Y., Wang, Y., Guo, T. (2018): Grain number responses to pre-anthesis dry matter and nitrogen in improving wheat yield in the Huang-Huai Plain. – Scientific Reports 8: 1-10.

[9] Friedrich, T., Derpsch, R., Kassam, A. (2017): Overview of the global spread of conservation agriculture, sustainable development of organic agriculture. – Apple Academic Press, Palm Bay, FL, pp. 75-90.

[10] Guo, S., Zhu, H., Dang., T., Wu, J., Liu, W., Hao, M., Li, Y., Syers, J. K. (2012): Winter wheat grain yield associated with precipitation distribution under long-term nitrogen fertilization in the semiarid Loess Plateau in China. – Geoderma 189: 442-450.

[11] He, G., Wang, Z., Li, F., Dai, J., Li, Q. (2016): Soil water storage and winter wheat productivity affected by soil surface management and precipitation in dryland of the Loess Plateau. – China. Agricultural Water Management 171: 1-9.

[12] Hochman, Z. (1982): Effect of water stress with phasic development on yield of wheat grown in a semi-arid environment. – Field Crops Research 5: 55-67.

[13] Hungria, M., Franchini, J. C., Brandão-Junior, O., Kaschuk, G., Souza, R. A. (2009): Soil microbial activity and crop sustainability in a long-term experiment with three soil-tillage and two crop-rotation systems. – Applied Soil Ecology 42: 288-296.

[14] Kang, S. Z., Zhang, L., Liang, Y., Hu, X., Cai, H., Gu, B. (2002): Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. – Agricultural Water Management 55: 203-216.

[15] Lin, X., Wang, D. (2017): Effects of supplemental irrigation on water consumption characteristics, grain yield and water use efficiency in winter wheat under different soil moisture conditions at seeding stage. – Acta Agronomica Sinica 43(09): 1357-1369.

[16] López-Garrido, R., Madejón, E., León-Camacho, M., Girón, I., Moreno, F., Murillo, J. M. (2014): Reduced tillage as an alternative to no-tillage under Mediterranean conditions: a case study. – Soil and Tillage Research 140: 40-47.

[17] Ozturk, A., Aydin, F. (2004): Effect of water stress at various growth stages on some quality characteristics of winter wheat. – Journal of Agronomy and Crop ence 190: 93-99.

[18] Qin, X., Zhang, F., Liu, C., Yu, H., Cao, B., Tian, S., Liao, Y., Siddique, K. H. M. (2015): Wheat yield improvements in China: past trends and future directions. – Field Crops Research 177: 117-124.

[19] Qiu, L., Hao, M., Wu, Y. (2017): Potential impacts of climate change on carbon dynamics in a rain-fed agroecosystem on the Loess Plateau of China. – Science of the Total Environment 577: 267-278.

[20] Ren, A., Sun, M., Xue, L., Deng, Y., Wang, P., Lei, M., Lin, W., Yang, Z., Gao, Z. (2019): Spatio-temporal dynamics in soil water storage reveals effects of nitrogen inputs on soil water consumption at different growth stages of winter wheat. – Agricultural Water Management 216: 379-389.

[21] Sadras, V. O., Slafer, G. A. (2012): Environmental modulation of yield components in cereals: heritabilities reveal a hierarchy of phenotypic plasticities. – Field Crops Research 127: 215-224.

[22] Seddaiu, G., Iocola, I., Farina, R., Orsini, R., Iezzi, G., Roggero, P. P. (2016): Long term effects of tillage practices and N fertilization in rainfed Mediterranean cropping systems: durum wheat, sunflower and maize grain yield. – European Journal of Agronomy 77: 166-178.

[23] Singh, D., Singh, M., Sharma, K. C. (1979): Correlation and path coefficient analysis among flag leaf area, yield and yield attributes in wheat (Triticum aestivum L.). – Cereal Research Communications 7(2): 145-152.

[24] Slafer, G. A. (2003): Genetic basis of yield as viewed from a crop physiologist's perspective. – Annals of Applied Biology 142: 117-128.

[25] Su, Z., Zhang, J., Wu, W., Cai, D., Lv, J., Jiang, G., Huang, J., Gao, J., Hartmanne, Roger., Gabrielset, Donald. (2007): Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China. – Agricultural Water Management 87: 307-314.

[26] Sun, M., Ren, A., Gao, Z., Wang, P., Mo, F., Xue, L., Lei, M. (2018): Long-term evaluation of tillage methods in fallow season for soil water storage, wheat yield and water use efficiency in semiarid southeast of the loess plateau. – Field Crops Research 218(9): 24-32.

[27] Sun, L., Wang, R., Li, J., Wang, Q., Lyu, Wei., Wang, X., Cheng, K., Mao, H., Zhang, X. (2019): Reasonable fertilization improves the conservation tillage benefit for soil water use and yield of rain-fed winter wheat: a case study from the Loess Plateau, China. – Field Crops Research 242-253.

[28] Unger, P. W., Kaspar, T. C. (1994): Soil compaction and root growth: a review. – Agronomy Journal 86: 759-766.

[29] Wang, D. (2017): Water use efficiency and optimal supplemental irrigation in a high yield wheat field. – Field Crops Research 217: 213-220.

[30] Wang, Y., Zhang, Y., Zhou, S., Wang, Z. (2018): Meta-analysis of no-tillage effect on wheat and maize water use efficiency in China. – Science of the Total Environment 635: 1372-1382.

[31] Weiner, J., Griepentrog, H. W., Kristensen, L. (2001): Suppression of weeds by spring wheat Triticum aestivum increases with crop density and spatial uniformity. – Journal of Applied Ecology 38: 784-790.

[32] Xue, L., Khan, S., Sun, M., Anwar, S., Ren, A., Gao, Z., Lin, W., Xue, J., Yang, Z., Deng, Y. (2019): 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 and Tillage Research 191: 66-74.

[33] Zhang, Q., Liu, D., Cheng, S., Huang, X. (2016): Combined effects of runoff and soil erodibility on available nitrogen losses from sloping farmland affected by agricultural practices. – Agricultural Water Management 176: 1-8.