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Water productivity of two wheat genotypes in response to no-tillage in the North China Plain

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Abstract: Uneven distribution of precipitation and overexploitation of groundwater resources threatens the sustainability of agriculture in the North China Plain. Adoption of water deficit-tolerant winter wheat genotypes coupled with timely, adequate farming practice is crucial to enhance sustainable crop production and water productivity in the region. The present study aimed to evaluate water consumption patterns and water productivity of two winter wheat genotypes (Tainong-18 and Jimai-22), under no-tillage or conventional tillage, over a period of four consecutive cropping seasons. Under no-tillage, Tainong-18 showed the lowest soil moisture consumption before sowing in the 30–110 cm soil profile. Jimai-22 under conventional tillage and Tainong-18 under no-tillage showed the highest and lowest evapotranspiration across cropping seasons, respectively. Compared with conventional tillage, no-tillage reduced grain yield and water productivity of winter wheat, and the difference between them increased for grain yield (6.79, 11.99, 14.78, and 15.73%) and water productivity (0.99, 8.14, 12.18, and 13.30%) over the 2015–2016, 2016–2017, 2017–2018, and 2018–2019 cropping seasons, respectively. In contrast, Tainong-18 showed lower evapotranspiration and increased grain yield and water productivity compared with Jimai-22. Further, Tainong-18 showed a compensatory effect on the reduction of water productivity under no-tillage, compared with Jimai-22. Our conclusions indicate that the combination of no-tillage and water-efficient winter wheat genotypes is an effective strategy to offset the reduction in water productivity caused by no-tillage and thus maximise water productivity in the North China Plain.

Keywords: *Triticum aestivum* L.; rainfall; drought tolerance; soil moisture before sowing

Winter wheat is one of the main staple food crops in the world, feeding more than 35% of the global population (Wakchaure et al. 2016). As the major producing area of China, the North China Plain (NCP) contributes to approximately 25% of the national grain production (Ma and Li 2020). However, water scarcity in the region has become a paramount concern for agricultural production systems and crop productivity (Yan et al. 2020) due to the uneven distribution of annual precipitation and accelerated depletion of groundwater resources. Crop yield increases have been attained at the expense of greater amounts of water used; therefore, the challenge is to reduce the rate of water use without a concomitant reduction in yield (Mei et al. 2013). Thus, we must aim to balance the relationship between water consumption and crop production and seek to ensure the stability of water productivity in the area.

Optimising tillage strategies decrease water consumption and enhance water productivity (WP). No-tillage (NT) has the potential to improve water productivity and optimise crop growth (Kan et al.

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2020). However, the effects of NT on crop yield and WP remain highly controversial (Pittelkow et al. 2015). Some studies indicate that NT improves soil structure and porosity, thereby increasing rainfall interception and consequently mitigating soil surface erosion and reducing water consumption; thus, NT ultimately enhances WP (Sisti et al. 2004). Conversely, conventional tillage affects soil moisture content (SMC) and water consumption mainly through soil structure changes and reducing water absorption due to lower root volume (Ali et al. 2018). However, there are several problems with NT. Wang et al. (2018) reported that compared with conventional tillage (T), NT had no significant effect on evapotranspiration, grain yield, or WP of winter wheat in northern and northwestern China, where mean annual precipitations are less than 600 mm. In addition, Licht and Al-Kaisi (2005) observed that SMC had no effect among tillage methods. NT showed a higher degree of soil compaction in the 0–20 cm topsoil layer and reduced root growth, especially at deeper soil levels (Kan et al. 2020). NT reduced the wheat crop yield mainly because of a reduction in 1 000-grain weight and the number of panicles produced per unit area (Guan et al. 2015). Therefore, the widespread application of NT would not seem best for winter wheat in the NCP as grain yield may be severely reduced.

Water productivity can be enhanced mainly by agronomic management practices and the selection of genotypes (Meena et al. 2019). Compared with water-saving agronomic practices, breeding new high-yielding wheat cultivars with higher WP has marked advantages of being less investment-intensive, promoting greater root efficiency for water uptake, and ultimately showing a more sustainable efficiency to the grower (Shan et al. 2006, Zhang et al. 2011). Thus, this approach would eventually seem more promising in the long run. Genotypic variability among wheat cultivars for the response of photosynthesis to water shortage might be useful for influencing water consumption and grain yield toward greater WP and drought tolerance (Liu et al. 2016). The numbers of tillers and kernels per spike affect WP and are the major determinants of wheat grain yield under genotype (Ali et al. 2018). Therefore, selecting genotypes with the appropriate tiller and elucidating water-saving strategies to improve crop yield and water management under NT are of the utmost importance.

Further progress in WP improvement must be achieved to reduce water use while maintaining current high production levels (Mei et al. 2013). However, neither the water consumption profiles across the rhizosphere nor water productivity for different winter wheat genotypes in response to tillage methods have been fully studied or discussed in the NCP. Accordingly, in the present study, we tested two winter wheat genotypes and two tillage methods. We hypothesised that although NT will reduce soil moisture consumption before sowing (SMCBS) and evapotranspiration, WP of winter wheat will also be reduced due to the concomitant yield loss; however, genotype will compensate for WP reduction, thereby maintaining a high yield. The purpose of our research was to document the following in a long-term study: (1) the water extraction pattern from each soil depth in the rhizosphere of winter wheat under NT; (2) effect of genotypes on grain yield under NT, and (3) genotypic compensatory effect on WP under NT. Our results provide sound theoretical support to maximise water productivity and promote sustainable agriculture in the NCP.

MATERIAL AND METHODS

Study site and soil properties. The study was conducted in the fields at the Experimental Station of Shandong Agricultural University in the NCP during the winter wheat growing seasons from 2015 to 2018. The study area is characterised by a temperate, continental monsoon climate. Total annual precipitation and average monthly temperature during the four growing seasons of the study are shown in Figure 1.

Wheat seeds were planted manually at a rate of 222 grains/m^2 in 3 × 3 m experimental plots delimited by cement rendering to prevent the lateral flow of soil moisture. The soil was classified as loamy clay. Available nitrogen, available phosphorus, and available potassium contents in the 0–20 cm topsoil layer were 108.3, 16.2, and 92.6 mg/kg, respectively.

Experimental design and management. Two tillage methods (NT and T) and two winter wheat genotypes (Tainong-18, G1; and Jimai-22, G2) were arranged in a random block design with three replicates, for a total of 12 experimental plots. The soil in the NT treatment plots was not plowed. Plots prepared as T treatment were manually ploughed to a depth of 25 cm using a shovel on October 7, 2015, October 6, 2016, October 7, 2017, and October 7, 2018, respectively. Jimai-22 shows high tillering capacity, showing an approximate rate of tiller formation

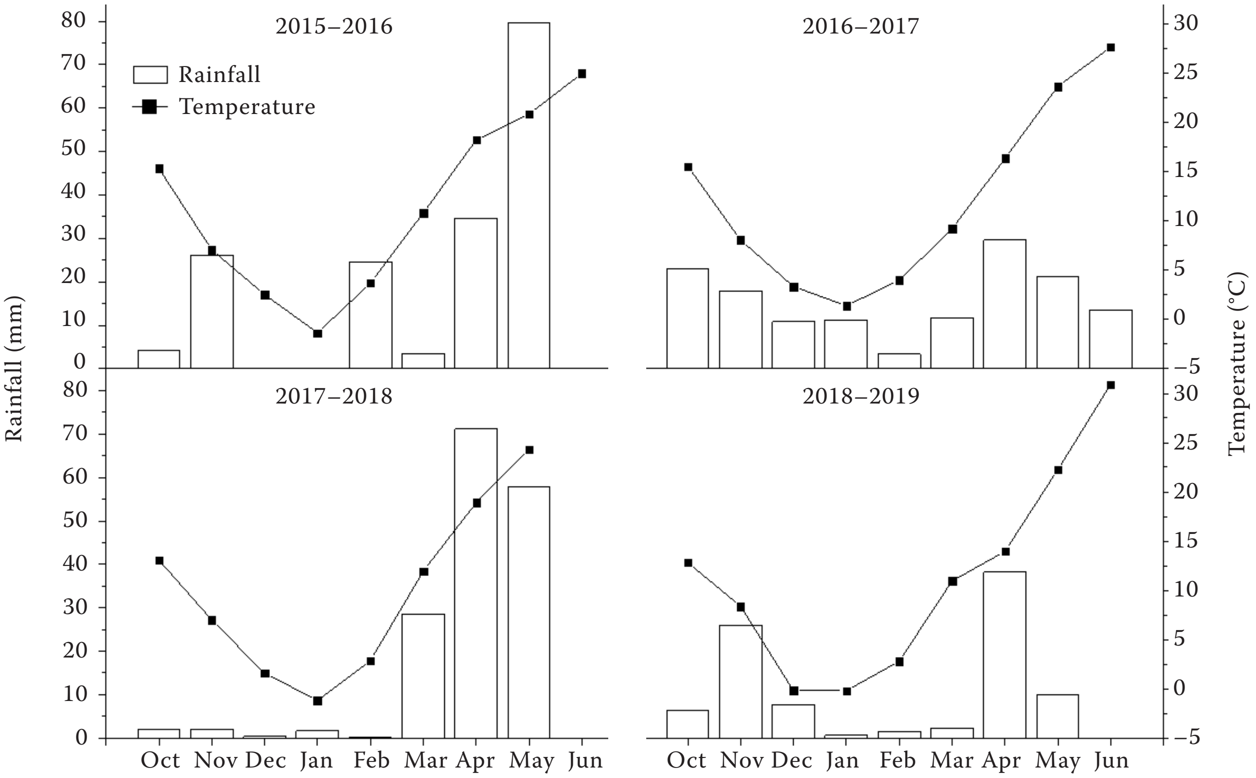

Figure 1. Monthly total precipitation and mean monthly air temperature from 2015 to 2019 winter wheat growing seasons, at the Experimental Station of Shandong Agricultural University. Total precipitation and mean air temperature in October were from seeding time to the end of October, and total precipitation and mean air temperature in June was from the beginning of June to the harvest time (especially total precipitation and mean air temperature in May was from beginning of May to the harvest time in 2017–2018) (which was observed by a meteorological station near the study site)

of 54.4%. In contrast, Tainong-18 shows a moderate tillering capacity at a rate of 39.2% (Ren et al. 2018).

The same amount and type of fertiliser was applied in each plot before seeding [urea (15.0 g/m^2), potassium phosphate (30.0 g/m^2), and potassium chloride (7.5 g/m^2)] followed by 60 mm pre-sowing irrigation. An additional 15.0 g/m^2 of urea and 60 mm irrigation water was applied at the jointing stage (March 17, 2016, March 15, 2017, March 16, 2018, and March 15, 2019, respectively). Flood irrigation was used for all irrigation, and the volume of irrigation was controlled by a flow meter. Winter wheat was harvested on June 1, 2016, June 3, 2017, May 31, 2018, and June 5, 2019.

Data collection. Wheat grain yield was measured on a 0.45 m^2 area (two rows, each 1.5 m long) in each plot with three replicates. Grain yield was adjusted to 13.0% moisture.

Soil moisture content (SMC) was measured within the range from 0 cm to 160 cm of soil depth at 10 cm intervals, using a CNC503D neutron moisture meter (Super Energy Nuclear Technology Ltd., Beijing, China).

Soil moisture content before sowing (SMCBS, mm) was estimated as the initial minus the final SMC from 0 cm to 160 cm soil layer at 10 cm intervals.

Evapotranspiration and WP over each complete growing season were calculated using Eqs. (1) and (2), respectively:

$$ET = I + P - R - D - SW \quad (1)$$

$$WUE = Y/ET \quad (2)$$

where: ET (mm) – evapotranspiration; I (mm) – irrigation water volume (measured directly using the flow meter); P (mm) – precipitation in the entire growing season; R (mm) – surface runoff (as there was no heavy precipitation in any of the four growing seasons, we assumed surface runoff was negligible); D (mm) – downward flux (as soil water measurements showed that surface drainage at the site was negligible, deep percolation was ignored because it was deemed

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insignificant); SW (mm) – change in soil storage water, calculated as the initial minus the end soil moisture content in each growing season; and lastly, Y (g/m^2) – grain yield.

Statistical analysis. Differences among treatment means were subjected to analysis of variance (ANOVA) using the general linear model procedure at a significance level of $\alpha = 0.05$. The normality of variances was tested before performing the ANOVAs. Multiple comparisons for significant effect were performed using the least significant difference (*LSD*) test at $\alpha = 0.05$. Microsoft Excel 2010 (Redmond, USA) and PASW Statistics 18 (Armonk, USA) were used to organise and analyse the data, respectively.

RESULTS AND DISCUSSION

Soil moisture consumption before sowing. The effects of the tillage method, wheat genotype, and years on SMCBS during the 2015–2018 winter wheat growing seasons are shown in Figure 2. Among the four tillage/genotype combination treatments, SMCBS was the highest in TG2 (106.69, 165.77, 51.67, and 183.78 mm, in 2015–2016, 2016–2017, 2017–2018, and 2018–2019, respectively), and lowest in NTG1 (59.01, 122.18, 29.19, and 163.60 mm, in 2015–2016, 2016–2017, 2017–2018, and 2018–2019, respectively). Compared with TG1, NTG1 registered lower SMCBS in the below 30–150 cm (except for below 100–110 cm in the second growing season). A lower SMCBS was calculated in the below 40–110 cm for NTG2 than TG2 during the four growing seasons.

Overall, SMCBS was higher at the topsoil layer (0–20 cm) in NT than T; this finding was consistent with the results reported by Guan et al. (2015) and was lower at deeper soil layers and then reduced evapotranspiration, regardless of the genotype. Most roots were found in the topsoil (due to the greater availability of water and nutrients) (Ball-Coelho et

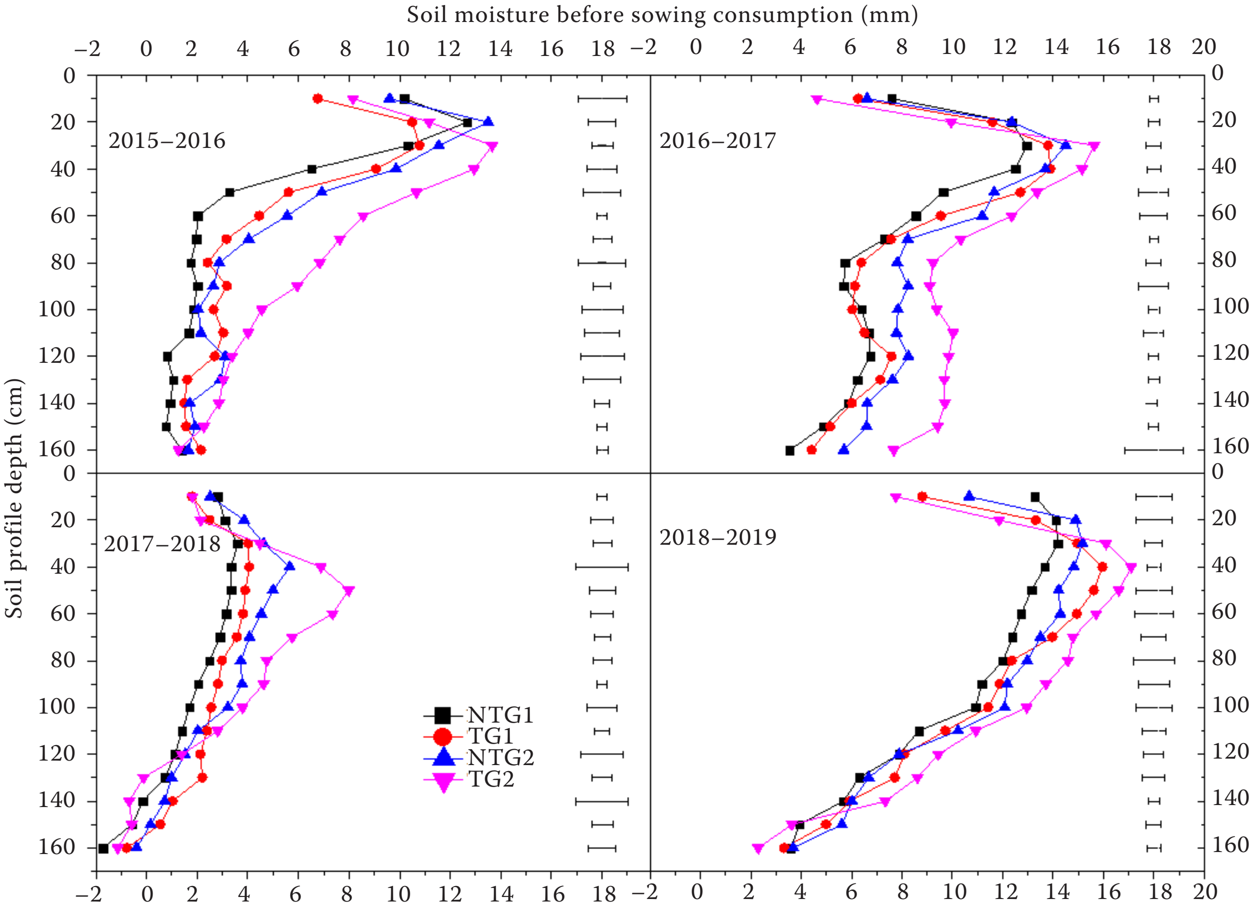

Figure 2. Soil moisture content before sowing consumption within a depth range of 0–160 cm from 2015 to 2019 winter wheat growing seasons. NTG1 – no-tillage with Tainong-18; NTG2 – no-tillage with Jimai-22; TG1 – conventional tillage with Tainong-18; TG2 – conventional tillage with Jimai-22. The horizontal bar at a given depth represented maximum standard errors

al. 1998), which confirmed that NT showed greater water consumption at the 0–20 cm soil layer in this study. Furthermore, compared with G2, G1 registered lower SMCBS in the 30–150 cm under NT, which likely reduced evapotranspiration, thus compensating for the reduction in WP under NT.

Winter wheat extracted moisture from the 0–160 cm soil profile (except for below 130 cm in the 2017–2018 season) in all combination treatments. However, due to the uneven distribution of precipitation (96.2% of the rainfall occurred from March to May in the 2017–2018 growing season); winter wheat extracted more of the shallow water while more water was stored deeper in the soil profile.

Evapotranspiration. Tillage methods and wheat genotypes influenced evapotranspiration during the experimental growing seasons (Table 1). Compared with T, NT significantly reduced evapotranspiration for G1 and G2 (4.08, 2.62, 3.98 and 2.97%, and 7.74, 5.84, 1.91 and 2.57%, in 2015–2016, 2016–2017, 2017–2018, and 2018–2019 growing seasons, respectively). NT enhanced total soil water storage in the 0–150 cm soil profile, mainly because of the increase in mean root weight density under NT (Huang et al. 2012). However, Guan et al. (2015) indicated that NT inhibited root growth (root length density, root surface area density, and root weight density) and decreased leaf area index (Liu et al. 2020), whereby evapotranspiration was reduced. Similar results were reported by Kan et al. (2020). The texture of the soil studied by Guan et al. (2015) was light loam, whereas Huang et al. (2012) studied silty loam soil. This may be the main reason for the root growth difference under NT.

G1 showed significantly lower evapotranspiration than G2 across the 2015–2018 winter wheat growing seasons (29.27, 28.64, 14.26, and 10.78 mm, respectively). Specifically, evapotranspiration was lower in G1 than in G2 by 7.57, 6.37, 6.26, and 3.45%, under NT, and by 11.09, 9.46, 4.24, and 3.06%, under T, in the successive experimental cropping seasons, respectively. Winter wheat genotypes with higher tillering capacity and tiller formation rate tend to develop a larger number of spikes per unit area (Liu et al. 2020),

Table 1. Evapotranspiration (mm) of winter wheat from 2015–2019 growing seasons

Treatment	Growing season			
	2015–2016	2016–2017	2017–2018	2018–2019
Tillage methods				
NT	287.62	335.48	261.09	321.65
T	306.03	350.59	268.95	330.81
P-value	0.08	0.14	0.12	0.13
Genotypes				
G1	282.19	328.82	257.89	320.84
G2	311.46	357.26	272.15	331.62
P-value	0.00	0.00	0.00	0.00
Coupling				
NTG1	276.31^{d}	324.45^{c}	252.65^{c}	316.00^{c}
TG1	288.07^{c}	333.18^{b}	263.13^{b}	325.67^{b}
NTG2	298.93^{b}	346.51^{b}	269.53^{b}	327.30^{b}
TG2	323.99^{a}	368.00^{a}	274.77^{a}	335.94^{a}
P-value	0.00	0.00	0.00	0.00
Interaction				
Tillage × genotypes		0.00		
Year × tillage		0.00		
Year × genotypes		0.00		
Year × tillage × genotypes		0.00		

NTG1 – no-tillage with Tainong-18; NTG2 – no-tillage with Jimai-22; TG1 – conventional tillage with Tainong-18; TG2 – conventional tillage with Jimai-22. Values followed by different letters are significant ($P < 0.05$) different among treatments using *LSD* (least significant difference) post-hoc test resulting in larger plant populations. Plant population and water consumption correlate positively under suitable conditions. Hence, G1 showed lower water consumption than G2 at each soil depth due to the moderate tillering capacity of the former. Further, the difference in evapotranspiration between treatments NTG1 and NTG2 as well as TG1 and TG2 decreased with the cropping season. Therefore, the genotypic effect on evapotranspiration under the same tillage method diminished over our long-term experiment.

Regarding evapotranspiration, the interaction between tillage methods and the experimental year as well as the experimental year and the genotypes were detected in this study. In addition, there were interaction effects between the genotype and tillage method. Furthermore, a three-way interaction effect among experimental year, tillage method, and genotype was also evident.

Grain yield. Tillage methods and wheat genotypes had significant effects on grain yield across growing seasons (Table 2). The TG1 combination treatment showed the highest grain yield (748.23, 904.67, 729.41, and 777.41 g/m^2, over the successive cropping seasons, respectively), whereas the NTG2 combination treatment showed the lowest grain yield (673.04, 749.63, 569.10 and 605.39 g/m^2, over the successive cropping seasons, respectively). Overall, grain yield was significantly decreased (6.79, 11.99, 14.78, and 15.73%, respectively) for NT relative to T. We believe that numerous factors affected yield under various tillage methods. Thus, for example, NT can significantly decrease light radiation interception by the upper canopy (Liu et al. 2020) and reduce temperature, which might affect leaf area and biomass accumulation (Liang and Richards 2012). Together, these effects might partly explain the decrease in grain yield in NT plots. Grain yield was enhanced mainly by the increase in spike number and 1 000-kernel weight under T (Guan et al. 2015); however, Ren et al. (2018) reported that although T improved grain yield by increasing the number of spikes per unit area, it significantly decreased 1 000-kernel weight. Additionally, Su et al. (2007) concluded that the greater amount of soil water available under NT

Table 2. Grain yield (g/m^2) of winter wheat from 2015 to 2019 growing seasons

Treatment	Growing season			
	2015–2016	2016–2017	2017–2018	2018–2019
Tillage methods				
NT	690.87	778.35	585.94	630.69
T	741.21	884.39	687.58	748.45
P-value	0.00	0.00	0.00	0.00
Genotypes				
G1	728.46	855.87	666.09	716.75
G2	703.62	806.87	607.43	662.38
P-value	0.16	0.18	0.11	0.17
Coupling				
NTG1	708.70^{c}	807.07^{c}	602.77^{c}	656.09^{c}
TG1	748.23^{a}	904.67^{a}	729.41^{a}	777.41^{a}
NTG2	673.04^{d}	749.63^{d}	569.10^{d}	605.29^{d}
TG2	734.20^{b}	864.11^{b}	645.75^{b}	719.48^{b}
P-value	0.00	0.00	0.00	0.00
Interaction				
Tillage × genotypes		0.22		
Year × tillage		0.00		
Year × genotypes		0.00		
Year × tillage × genotypes		0.00		

NTG1 – no-tillage with Tainong-18; NTG2 – no-tillage with Jimai-22; TG1 – conventional tillage with Tainong-18; TG2 – conventional tillage with Jimai-22. Values followed by different letters are significant ($P < 0.05$) different among treatments using *LSD* (least significant difference) post-hoc test than T explained the increased grain yield. Because no-tillage with mulching improved fallow rainfall storage efficiency (Su et al. 2007), our research was no mulching. Therefore, soil water availability is the overriding determinant of wheat yield (Urban et al. 2018).

G1 showed significantly greater grain yield than G2 under NT over the successive cropping seasons (5.30, 7.66, 5.92, and 8.39%, respectively). One dominating reason that had a strong effect on grain yield was yield composition. In our study, we selected two winter wheat genotypes that possessed different tillering capacities. Even though G1 is characterised by a moderate tillering capacity and G2 typically shows a high tillering capacity and consequently grows a greater number of spikes per unit area G2 shows a significantly lower number of kernels per spike than G1 (Ren et al. 2018).

Significant interactions for grain yield between the experimental year and tillage methods as well as the experimental year and genotypes were found. However, there was no significant interaction effect on grain yield between tillage methods and genotypes. In contrast, the corresponding three-way interaction effect was evident among the tillage method, genotype, and the experimental years.

Water productivity. Table 3 shows the effect of the tillage method, genotype, and experimental growing season on WP. Overall, compared with T, NT showed lower WP in the 2015–2018 winter wheat growing seasons (0.99, 8.14, 12.18 and 13.29%, respectively). The difference of WP was increased with the increase of winter wheat planting years. This finding indicates that NT might affect the sustainability of agricultural production. WP was lower for NT than for T, under G1 and G2 across the 2015–2018 growing seasons (1.15, 8.46, 13.72, and 12.97%, and 0.88, 8.09, 10.21, and 13.55%, respectively). Therefore, it is essential to develop strategies to compensate for the reduction of WP under NT. Compared with G2, G1 showed significantly greater WP under NT and T in the four experimental growing seasons (14.22, 15.28, 13.27, and 14.43%, and 14.54, 15.74, 17.87, and 11.68%, respectively). Therefore, G1 seemingly showed a compensatory effect

Table 3. Water productivity (kg/m^3) of winter wheat from 2015 to 2019 growing seasons

Treatment	Growing season			
	2015–2016	2016–2017	2017–2018	2018–2019
Tillage methods				
NT	2.41	2.33	2.25	1.96
T	2.43	2.53	2.56	2.26
P-value	0.82	0.09	0.02	0.00
Genotypes				
G1	2.58	2.60	2.5	2.23
G2	2.26	2.26	2.231	2.00
P-value	0.00	0.00	0.01	0.03
Coupling				
NTG1	2.57^a	2.49^b	2.39^b	2.08^b
TG1	2.60^a	2.72^a	2.77^a	2.39^a
NTG2	2.25^b	2.16^d	2.11^c	1.85^d
TG2	2.27^b	2.35^c	2.35^b	2.14^c
P-value	0.00	0.00	0.00	0.00
Interaction				
Tillage × genotypes	0.00			
Year × tillage	0.00			
Year × genotypes	0.00			
Year × tillage × genotypes	0.04			

NTG1 – no-tillage with Tainong-18; NTG2 – no-tillage with Jimai-22; TG1 – conventional tillage with Tainong-18; TG2 – conventional tillage with Jimai-22. Values followed by different letters are significant (*P* < 0.05) different among treatments using *LSD* (least significant difference) post-hoc test on WP under NT. Yield and evapotranspiration were the main factors affecting WP. These findings are in accordance with those reported by Wang et al. (2018), who proposed that the increase in wheat WP under NT in regions with a mean precipitation of ≤ 400 mm was due to an increase in yield and a concomitant decrease in evapotranspiration.

Compared with T, NT reduced grain yield and WP during four winter wheat growing seasons over the years (6.79, 11.99, 14.78 and 15.73%, and 0.82, 7.91, 12.11 and 13.27%, respectively). Further, there was no significant difference in WP between NTG1 and TG1 or between NTG2 and TG2 in the first growing season, but a significant effect of the tillage method on WP of G1 and G2 was recorded for the rest of the growing seasons. He et al. (2007) indicated that four consecutive years of NT practice followed by one year of subsoiling might mitigate the increasing level of soil compaction resulting from NT. The reason for the reduction of grain yield and WP under NT over the years may be the reduction in spike number (Liu et al. 2020) due to the increase in soil compaction, which in turn likely limits root growth and, consequently, plant access to soil water and nutrients.

Regarding WP, significant interaction effects between tillage methods and wheat genotypes as well as the experimental year and tillage methods were detected. There was an interaction effect involving the experimental year and the wheat genotypes under analysis, in addition to which a three-way interaction among tillage method, genotype, and experimental years was detected.

Limitations and future research prospects. The relationship between water consumption and root distribution was close. Mosaddeghi et al. (2009) reported that the tillage effects on aboveground plant growth and grain yield were attributed to the root system. The roots of different winter wheat genotypes show different capacities for deep-soil penetration. Moreover, genotypes differ in root biomass partitioning at different depths under water and nutrient stress conditions, tolerant genotypes produce deeper and more vigorous roots in search for water and nutrients (Farooq et al. 2019), and large genotypic variability for WP under different conditions of water availability has been documented (Mei et al. 2013). Due to varying water conditions at different growth stages over the growing season in the NCP, future research must focus on seeking the appropriate water-deficit tolerant genotypes and exploring the relationship between water consumption and root distribution patterns at each soil layer under different tillage method. In this study, the reduction in grain yield and WP under NT, relative to T, worsened over the years. Therefore, to reduce the negative effect of time under NT on grain yield and WP, long-term experiments should analyse the effect of NT duration to determine the number of years of continuous NT after which subsoiling would be the most beneficial.

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