Irrigation Science (2020) 38:365–371
https://doi.org/10.1007/s00271-020-00678-z

ORIGINAL PAPER

Plant height and its relationship with yield in wheat under different irrigation regime

Zhenxian Gao[1] · Yanxia Wang[1] · Guoying Tian[1] · Yankun Zhao[1] · Caihua Li[1] · Qiao Cao[1] · Ran Han[1] · Zhanliang Shi[1] · Mingqi He[1]

Received: 10 September 2018 / Accepted: 15 May 2020 / Published online: 7 June 2020

Abstract

The irrigating winter wheat one or two times each season was practiced in Huanghuai Winter Wheat Region in order to reduce the over-exploitation of groundwater. In this study, plant height (PH) and its relationship with yield were analyzed in a field study conducted over three growing seasons with 102 wheat varieties irrigated zero to two times at different growth stages. Here, we found that irrigation at the jointing stage increased wheat PH by 6.60–9.70%. Whereas irrigation at the early milking stage had almost no effect on it. Against the wildtype alleles *Rht-B1a* and *Rht-D1a*, the genetic background of *Rht-B1b* and *Rht-D1b* significantly reduced PH by 14.40–15.50% and 16.90–19.10%, respectively. The combined *Rht-B1b* and *Rht-D1b* can reduce PH by 29.10–32.50%. PH was strongly, negatively correlated with grain yield in jointing irrigation (W1) or jointing + milking irrigation (W2) over three growing seasons. In contrast, a significant positive correlation was detected in no-irrigation (W0) in the 2012/2013 wheat growing season, yet no correlation was found in 2013/2014 and 2014/2015. PH was positively correlated with drought coefficient (DRC) in W1 and W2. These results augment our understanding of the relationship between PH and grain yield in different irrigation regimes and provide PH traits for wheat improvement on water saving.

Introduction

The middle-south of Hebei Province belongs to Huanghuai Winter Wheat Region. Where rich soil and climate are favorable for growing winter wheat and summer maize as a double-crop system (Zhang et al. 2003). Traditionally the wheat production in this area is generally dependent on the extensive practice of irrigation, mainly using water pumped from deep wells (100 m deep or more) because annual rainfall in this area is approximately 600 mm and largely concentrated in summer after wheat is harvested (Li 1993; Zhang et al. 1998). The massive extraction of groundwater resources in this region has often made the water table decline rapidly (Mañas et al. 1999). To cope with the overdraft of aquifer reserves beyond their recharge capacity, measures should be taken to reduce irrigation water use. In China, the attempt of reducing irrigation frequency has been made on winter wheat since 1991 (Zhang et al. 1998). With an increasing amount of research available, the researcher found that the timing and amount of irrigation greatly affect the yield and water use efficiency (WUE) of wheat (Qiu et al. 2008; Wang et al. 2014; Zhang and Oweis 1999). The maximum WUE appeared during the jointing and milking periods while the differences in grain yield were not

✉ Zhenxian Gao
zhenxiangao@163.com

Yanxia Wang
yanxia-email@163.com

Guoying Tian
tguoying1@163.com

Yankun Zhao
kun262004@163.com

Caihua Li
licaihua415@126.com

Qiao Cao
qiaocao19@163.com

Ran Han
sjznkyhr@163.com

Zhanliang Shi
shizhanl@163.com

Mingqi He
hemingqi@163.com

[1] Shijiazhuang Academy of Agricultural and Forestry Sciences, Shijiazhuang 050041, China

significant in the North China Plain (Qiu et al. 2008), therefore, the irrigation at the jointing stage or jointing + milking stage has been widely used on local farms; it is also the reason why W1 and W2 irrigation regimes are chosen in the study presented in this paper.

Plant height is one of the most important agronomic traits of production, and relates to plant architecture, lodging resistance, and yield performance (Wang et al. 2017). The introduction of reduced height *Rht-B1b* and *Rht-D1b* semi-dwarfing alleles substantial increases the yields of wheat during the Green Revolution (Hedden 2003; Van De Velde et al. 2017). To date, the distribution of dwarf genes *Rht-B1b* and *Rht-D1b* has been detected in wheat of Huanghuai Winter Wheat Region using functional markers (Gao et al. 2015). The wildtype alleles *Rht-B1a* and *Rht-D1a*, which encode DELLA proteins acting as the repressors of gibberellin (GA)-responsive growth (Peng et al. 1999). The dwarf phenotype conferred by *Rht-B1b* and *Rht-D1b* is due to a single nucleotide change introducing a premature stop codon in the DELLA proteins impairing gibberellin sensitivity (Lou et al. 2016). In a previous study, DELLA proteins have also been proposed to be involved in the acclimation responses of plants to some stress conditions (Nicholas and Harberd 2009). Irrigation is a critical factor for wheat growth in the environment, but there are few reports on the relationship between irrigation and plant height.

An efficient saving irrigation regime must be applied to improve WUE and to fulfill the sustainable development of agriculture in Hebei Province. Water-yield relations, water-use efficiency, deep root system, traits of spike, and corresponding physiological parameters etc. have been investigated in the previous studies and provide a guidelines to farmers and irrigation agencies for water-saving irrigation and efficient use of water resources in the plain where water is the most important limiting factor for wheat production (Kang et al. 2002; Monneveux et al. 2006; Xue et al. 2006; Zhang and Oweis 1999; Zhang et al. 1998, 2003). However, few studies have examined the plant height and the effects of plant height on yield under limited irrigation. The objectives of this study were (1) to examine the impact of limited irrigation on PH; (2) to investigate the PH of the genetic background of semi-dwarfing genes (*Rht-B1b* and *Rht-D1b*) under limited irrigation conditions; (3) to establish relationships among PH, crop yield, and DRC under different irrigation regimes.

Materials and methods

Plant materials

In total, one hundred and two semi-winter and winter wheat varieties suitable for sowing in Huanghuai Winter Wheat Region were used. These include 84 national authorized wheat varieties, 12 provincial authorized wheat varieties, 3 wheat varieties with outstanding yield in recent regional trials, 2 control wheat varieties and 1 commonly used as a transgenic receptor in the past decade (Gao et al. 2015).

The site and experimental design

Three field experiments were conducted in 2012/2013, 2013/2014, and 2014/2015 growing seasons at the experimental field of Zhaoxian Experimental Station, Shijiazhuang Academy of Agricultural and Forestry Sciences (114.8° E, 37.8° N, 43 m.a.s.l.). The texture of soils was light loam; the annual amount of water applied was about 45–75 mm each irrigation for wheat in Zhaoxian. The following three treatments were designed: a rainfed (W0) treatment with no irrigation, two local supplemental irrigation treatments, one was 60 mm irrigation at jointing (the end of March or the beginning of April; W1), the other was 60 mm irrigation at both jointing and milking (the beginning of May) stage (W2). In all treatments, basin irrigation was used about 4~6 days before sowing and which made the soil with enough moisture for good seeding emergence. The water was conveyed from the outlet of a pump to the plots using concrete canals; a flow meter was used to measure the amount of water applied. Nitrogen, phosphorus, and potassium were applied at the rate of 12 g Nm^{-2}, 12 g Pm^{-2}, and 12 g Km^{-2} respectively, at the time of sowing in W0 treatment. In W1 and W2 treatments, phosphorus and potassium were applied as the same as W0, while nitrogen (40%) was applied at sowing and the rest (60%) was broadcasted at the jointing stage along with irrigation. The others were managed using standard wheat production management. The plots were arranged in a split–plot design with three replicates. Each plot was 5 m in length and 1.2 m in width, which consisted of eight rows.

PH, yield, and DRC determinations

The PH was measured at 20 days after flowering using ten randomly selected plants from each plot; the means of PH was calculated using Microsoft Office Excel (2010). At maturity, the yield of individual plots was harvested by combine harvesters (WINTERSTEIGER, Austria) and their weight recorded. DRC (drought resistance coefficient) can be calculated according to the formula (Ji et al. 2007), as follows:

$$DRC = GYW0/GYW2 \text{ (or GYW1)},$$

where GYW0 and GYW2 are grain yield at W0 and W2 treatments, respectively.

Data analysis

Variance analysis of split–plot was performed using DPS software V 13.50 (Ksoft Tech, Tianjin, China). Differences of treatment and growing season were deemed statistically significant at $p < 0.05$ following the least significant difference (LSD) test. The correlation among PH, yield and DRC was analyzed with Pearson's correlation procedure using DPS software V 13.50 (Ksoft Tech, Tianjin, China). The correlation between traits was deemed statistically significant at $p < 0.05$.

Rainfall in the growing season

The rainfall conditions during the three seasons of winter wheat are shown in Table 1. The 2013/2014 season was a dry year, with rainfall only third of the amount of 2012/2013 and 2014/2015 seasons for winter wheat. For the three wheat growing seasons, the unbalanced distribution of rainfall was found, with greater accumulation at the seedling stage and grain-filling stage, while less at the dormancy stage of winter wheat. It is worth noting that the wheat at booting stage met snow on April 19, 2013, which was the latest snow in a century in Zhaoxian Experimental Station.

Results

Jointing irrigation significantly increases the PH and grain yield of wheat

The PH of winter wheat has not changed at the middle milking stage. At that time, we analyzed the effects of different irrigation regimes on plant height using three years data (Fig. 1). Supplying water at the jointing stage (W1) increased PH by 6.60–9.70% when compared with no irrigation (W0), but it was similar to those for supplying water at both jointing and milking stages (W2). Statistical analysis showed that there was a significantly different ($p < 0.01$) between W0 and W1 and between W0 and W2, but not between W1 and W2 treatments (Table 2). The results indicated that irrigation at the jointing stage not milking stage had considerable effects on wheat PH. When compared with the W0 treatment, the grain yield values in the W1 and W2 treatments significantly increased by 13.98–15.95% and 14.31–19.96%, respectively, across the three growing seasons (Table 2). When compared with W1, W2 increased the grain yield values by 0.40%, 3.46%, and 0.29% in the 2012/2013, 2013/2014, and 2014/2015 seasons,

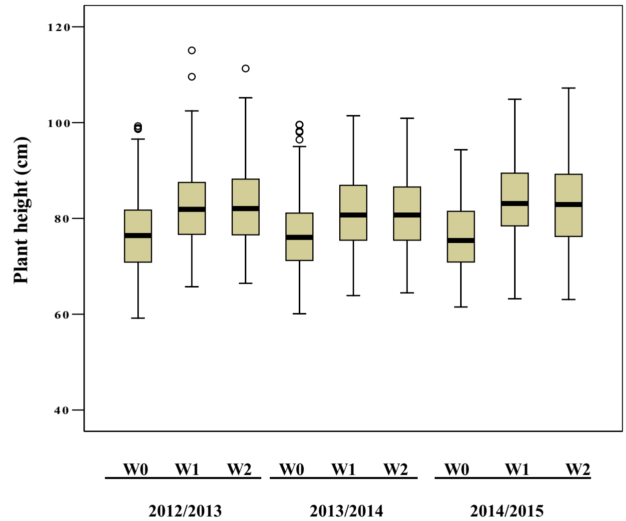

Fig. 1 The plant height of wheat in different irrigation regime

respectively. However, only a significant difference was found in the 2013/2014 growing season (Table 2). We found that the total rainfall amounts in Zhaoxian were 228.3 mm, 71.3 mm, and 191 mm during the growing seasons of 2012/2013, 2013/2014, and 2014/2015, respectively (Table 1). During the 2013/2014 growing season, the rainfall was one-third of that in 2012/2013 (the highest rainfall) season. This result indicated that W2 increased the wheat yield significantly in the drought years of middle-south of Hebei province, but not obvious in normal years. Statistical analysis of the yield and PH traits revealed significant differences ($p < 0.01$ or $p < 0.05$) among year, irrigation regime, variety, year × irrigation regime, year × variety, irrigation regime × variety, and year × irrigation regime × variety interactions (Table2), confirming the strong environmental, and varietal influences on these traits.

The effect of *Rht* gene on plant height in different irrigation regimes

The distribution of dwarfing genes (*Rht*) have been detected in our recent study (Gao et al. 2015). Linyuan 8 and Xinong 928 are heterozygous in *RhtB1* locus and Zhengmai 9023 is heterozygous in both *Rht-B1* and *Rht-D1* loci. Therefore, 99 of 102 wheat varieties were selected to further investigate the height-reducing effects of the *Rht-B1b* and *Rht-D1b* alleles. In the three kinds of irrigation regime, *Rht-B1b* and *Rht-D1b*

Table 1 Monthly and total rainfall (mm) for winter wheat growing seasons from 2012 to 2015

Seasons	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
2012/2013	1.8	26.1	7.8	4.8	12.8	1.1	20.8	23.8	129.3	228.3
2013/2014	5.5	9	0	0	8.2	0.2	23.9	19	5.5	71.3
2014/2015	54.5	4.2	7.9	0	1.6	5.3	0.6	30.7	75.3	191

Table 2 Comparison of the grain yield and PH of wheat in different irrigation regime

		Grain yield			Plant height		
		2012–2013	2013–2014	2014–2015	2012–2013	2013–2014	2014–2015
W0		6046.13b	8110.93c	7991.16b	77.11b	76.87b	76.10b
W1		6904.85a	9404.38b	9108.02a	82.64a	81.96a	83.49a
W2		6932.67a	9730.12a	9134.67a	83.22a	82.01a	83.30a
F value	Year (Y)	2060.47**			84.54**		
	Water (W)	1671.68**			2925.38**		
	Variety (V)	32.96**			417.99**		
	Y × W	44.79**			36.16**		
	Y × V	5.64**			7.57**		
	W × V	2.49**			3.03**		
	Y × W × V	1.15*			1.63**		

Different letters in the same column indicate significant differences at 0.01 level (LSD method)

**$p < 0.01$; *$p < 0.05$

significantly reduced PH by 14.40–15.50% and 16.90–19.10% when compared with *Rht-B1a* and *Rht-D1a* against the background of *Rht-D1a* and *Rht-B1a*, respectively (Fig. 2). Combination *Rht-B1b* and *Rht-D1b*, they can reduce PH by 29.10–32.50% (Fig. 2).

Statistical analysis of wheat PH in different *Rht* genotype showed that *Rht-D1b* was more effective than *Rht-B1b* to reduce wheat PH (Table 3). The PH of wheat varieties with *Rht-B1b* was significantly higher than that of wheat varieties with *Rht-D1b* over three years in W0 treatment. However, W1 and W2 treatments reduced the difference in the PH of the two genotypes; no significant difference was detected in the three growing seasons (Table 3). *Rht-B1b* and *Rht-D1b* showed additive effects in at least two growing seasons, the PH of *Rht-B1b* + *Rht-D1b* genotype was significantly lower than *Rht-B1b* (Table 3).

In this study, we found that the PH of Cangmai 6005 (*Rht-B1b* + *Rht-D1a*) and Luohan 13 (*Rht-B1a* + *Rht-D1a*) varied from 96 to 101 cm and 84 to 87 cm, respectively, in the three kinds of irrigation regimes. Higher (Cang 6005) and Lower (Luohan 13) than the PH of other similar *Rht* background of wheat varieties, suggesting the natural allelic variation exists in the two wheat varieties and which requires further investigation.

Correlation analysis among plant height, grain yield and drought coefficient

In the field-grown wheat varieties, the grain yield with 1–2 irrigation was 859~1619 kg/ha higher than that of no irrigation (Table 2). To provide a suitable PH for wheat breeding in different irrigation regime, correlation analysis was

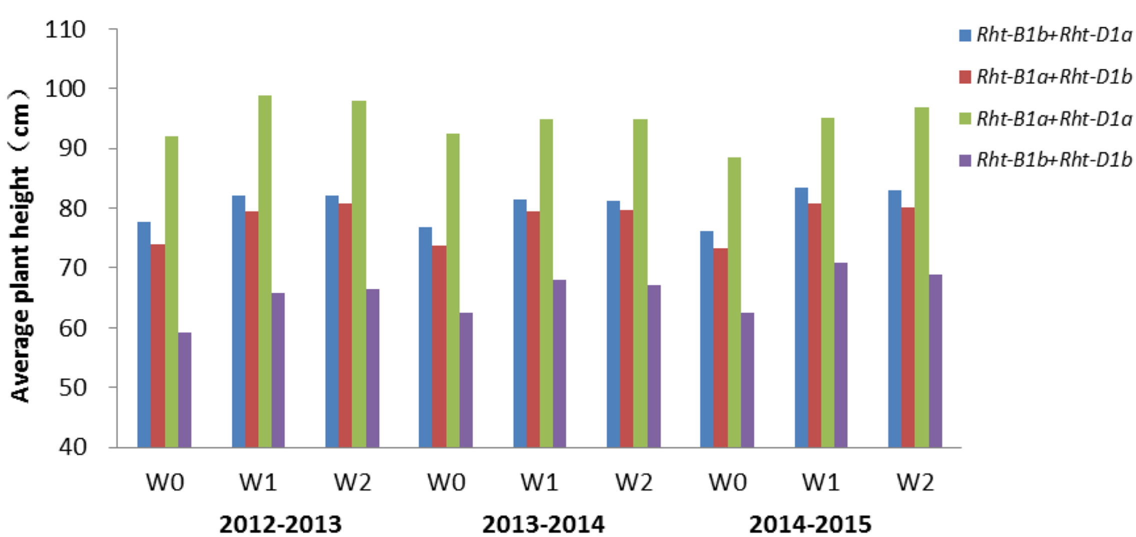

Fig. 2 The average PH of wheat in different *Rht* genotype

Table 3 Comparison of the grain yield and PH of different *Rht* genotype in different irrigation regime

Genotype	Treatment	Grain yield (kg/ha)			Plant height (cm)		
		2012–2013	2013–2014	2015–2016	2012–2013	2013–2014	2015–2016
Rht-B1b + Rht-D1a	W0	6287.58b	8455.57c	8158.91b	77.64b	76.79b	76.28b
	W1	7003.79a	9622.75b	9327.17a	82.19a	81.43a	83.47a
	W2	6982.46a	10,019.23a	9326.51a	82.06a	81.30a	83.08a
Rht-B1a + Rht-D1b	W0	5968.63b	8113.44c	8188.64b	73.88c	73.75b	73.21b
	W1	6944.69a	9478.83b	9321.25a	79.58b	79.58a	80.79a
	W2	7025.00a	9843.41a	9361.65a	80.86a	79.68a	80.13a
Rht-B1a + Rht-D1a	W0	5932.61b	7584.74b	6685.96b	91.95b	92.55b	88.45b
	W1	6533.30a	8763.33a	7731.99a	98.78a	94.90a	95.08a
	W2	6497.38a	8680.99a	7749.64a	97.96a	94.91a	96.96a
Rht-B1b + Rht-D1b	W0	5610.94b	7087.94b	8372.26b	59.20b	62.44b	62.47b
	W1	6499.97a	8835.13a	9547.45a	65.80a	68.00a	70.80a
	W2	6760.00a	9353.57a	9346.14a	66.43a	67.22a	68.99a

Different letters in the same column indicate significant differences at 0.01 level (LSD method)

performed among PH, grain yield, and DRC. A significant negative correlation between PH and grain yield was detected in 1–2 irrigation over 3 years (Table 4). This suggested that lower PH is helpful to improve wheat yield in W1 and W2. The negative correlation was well illustrated by the finding that the wheat varieties with *Rht-B1a + Rht-D1a* alleles were easier to lodge by 1–2 irrigation, although they were helped up artificially in time in our trials. However, PH showed no correlation with grain yield by no irrigation except for the 2012/2013 growing season that met the latest snowfall record for nearly 100 years. PH had a positive correlation with grain yield by no irrigation in the 2012/2013 growing season with the extreme weather. In our previous study, we found that more wheat varieties with *Rht-B1a + Rht-D1a* alleles (high plant) were selected in Province Shanxi, where drought prevails almost all years. Taken together, these results suggest that wheat with high PH is prone to be selected under W0 treatment, especially in extreme weather years.

DRC reflects the close degree of wheat products in two environments. A significant positive correlation between PH and DRC was found in W1 and W2 (Table 4), indicating that larger grain yield variance tends to exist in the semi-dwarfing wheat varieties when irrigation frequency changed from 0 to 2.

Discussion

Phenotyping for the ability to deal effectively with abiotic stresses such as drought, waterlogging, salinity and high temperature, is an important pursuit for crop breeders (Monneveux et al. 2012; Passioura 2012). PH is one of the most important phenotypic traits in wheat due to its involvement in plant architecture and ultimate grain yield (Bellucci et al. 2015; Hassan et al. 2019). In the adverse environment, plants with a means of regulating growth appropriate to environmental conditions, enabling a slowing of growth

Table 4 Correlation analysis among the wheat plant height, yield, and drought tolerance in wheat

Year	Trait		Grain yield			DRC	
			W0	W1	W2	W1	W2
2012–2013	PH	W0	0.393**				
2013–2014		W1	0.134				
2014–2015		W2	−0.169				
2012–2013		W0		−0.210*		0.551**	
2013–2014		W1		−0.218*		0.358**	
2014–2015		W2		−0.428**		0.3189**	
2012–2013		W0			−0.338**		0.586**
2013–2014		W1			−0.251*		0.346**
2014–2015		W2			−0.444**		0.239*

$^{**}p < 0.01$; $^{*}p < 0.05$

and reduced energetic commitment through the GA signaling pathway (Harberd et al. 2009). In the middle-south of Hebei Province, irrigation has been reduced from normally four times to one or two at the key stage to save groundwater. The effects of limited irrigation on the yield and water use efficiency of winter wheat have been investigated broadly (Kang et al. 2002; Zhang and Oweis 1999; Zhang et al. 2003). However, the PH of wheat and its relationship with grain yield are unclear in water-saving irrigation practices. Therefore, discovering the character of PH with a relative irrigation regime is markedly beneficial in improving wheat yield. In this study, irrigation at the jointing stage not milking stage increased PH. In March, winter wheat began to turn green, the end of the dormancy. It may have been that suitable irrigation at jointing promoted root growth under 60 cm, and maintaining soil moisture in the 0–40 cm soil profile facilitated root growth, which provided moderate soil moisture for over-ground parts accumulation (Lv et al. 2010; Man et al. 2015). As growing taller results in more available light and the ability to shade avoiding soil evaporation. The milking stage occurs at the beginning of May and the second irrigation was applied, yet no significant difference in PH occurred. Perhaps water irrigation at this stage was mainly beneficial for transporting assimilate from vegetative to reproductive organs. Additionally, the PH was hardly affected by rainfall although it is highly variable between seasons. Probably because of a little rain each time that could be employed for only covering the surface and most of which was then evaporated. Soil evaporation accounting for 30% of the total evaporation was reported in this region (Zhang et al. 2003).

Rht-B1b and *Rht-D1b* both can reduce PH; the relative effects of the two *Rht* loci on PH were remarkably consistent across different irrigation regimes. Our results are similar to those of Flintham et al. (1997) and Butler et al. (2005) on the basis of genetic population in different environments (Butler et al. 2005; Flintham et al. 1997), indicating the importance of genetic background in determining the magnitude of height reduction. However, we found two wheat varieties (Cangmai 6005 and Luohan 13) that PH and *Rht* genes were inconsistent. Maybe some new allelic variations will be found at the *Rht-B1* and *Rht-D1* loci in wheat for further research. The allelic variations include single nucleotide polymorphism (SNP) change, small insertions or deletions and tandem segmental duplication, etc. (Li et al. 2013; Lou et al. 2016; Pearce et al. 2011; Peng et al. 1999). Recently, eight new *Rht-B1* allelic variations (*Rht-B1h–o*), and six new *Rht-D1* allelic variations (*Rht-D1e–j*) have been identified in Chinese wheat germplasm by a modified EcoTILLING method (Li et al. 2013), indicating that allelic variations widely existed in the Chinese wheat cultivars. Such as the new natural allelic variation *Rht-B1i*, which contains a single missense SNP (A614G) in the coding region resulting in E205G substitution, may increase PH (Li et al. 2013; Lou et al. 2016). In contrast, the extreme dwarfism of *Rht-D1c* is due to overexpression of the semi-dwarfing *Rht-D1b* allele, caused by an increase in gene copy number (Pearce et al. 2011). The novel allelic variations will provide an understanding of the diversity of *Rht-B1b* and *Rht-D1b* that could be used for modulating PH in breeding programs.

The height–yield relationship was inconsistent in the three irrigation regimes (Table 4). One potential reason is that higher plants are easier to lodging by irrigation and have a greater proportion of decreasing grain yield, although they were helped up artificially in time in our trials. Therefore, when irrigation was performed 1–2 times during the growing seasons, the negative correlation between PH and grain yield was detected (Table 4). Second, in the severely stressed environment, taller plants had a clear advantage (Butler et al. 2005). Twelve of 102 wheat varieties with the wildtype alleles *Rht-B1a* and *Rht-D1a* were cultivated mostly by Shanxi Academy Agricultural Science where drought prevails almost all years (Gao et al. 2015). This fact is also in agreement with our findings of significant positive correlations between PH and grain yield in extreme weather (the latest snowfall in 2013). Third, the complex synergy and antagonism between GA and other phytohormones maybe play essential roles in PH and grain yield control (Wang et al. 2017). The height-increasing allele *Rht-B1i-1* participates in the regulation of phytohormones (IAA, GA3, and IAA/GA3) signaling pathways because of the auxin response element AUXREPSIAA4 in its promoters (Lou et al. 2016). The gibberellin–ethylene and gibberellin–jasmonate interplay occurs under abiotic stress conditions (Qi et al. 2011; Wild et al. 2012). A positive correlation was found between PH and DRC (Table 4), which means the grain yield of higher plants decreases less than shorter plants when irrigation alters from 2 to 0 times. The PH–DRC relationship indicated that the wildtype alleles *Rht-B1a* and *Rht-D1a* could be involved in the stress response of some phytohormones and improved the grain yield in abiotic stress. Further comprehensive studies should be launched to elucidate the mechanism of pleiotropic effects on drought resistance for *Rht-B1* and *Rht-D1*.

Conclusions

Grain yield and PH for different irrigation regimes to winter wheat and the effects of *Rht* genotype on PH for different irrigation regimes were examined. W1 to winter wheat resulted in a significant increase in wheat yield and PH. W2 did not produce significant grain yield and PH increasing when compared with W1 except for special drought year (2013/2014). Thus, W1 had an advantage in this region with a serious groundwater overdraft problem for an average year. *Rht-B1b* and *Rht-D1b* significantly reduced PH by 14.40–15.50% and 16.90–19.10% when compared with the wide type (Fig. 2). A negative correlation between grain yield and PH indicated *Rht-B1a* + *Rht-D1a* genotype could be omitted in the region under W1 and W2.

Acknowledgements This study was supported by The National Key Research and Development Program of China (Grant no. 2016YFD0300407) and The Science Technology Research and Development Program of Shijiazhuang (Grant no. 181490392A). We also thank Dr. Wenlong Yang, IVF·CAAS, China, and Dr. Guangbin Luo, UFL, USA, for their excellent assistance in the structure and grammar of the English manuscript.

Compliance with ethical standards

Conflict of interest We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "Plant Height and Its Relationship with Yield in Wheat under Different Irrigation Regime".

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