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Full Length Article

Regulated Deficit Irrigation Effect of Winter Wheat as Affected by Different Fertilizer Application Treatments

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Abstract

Field and pot experiments were conducted to evaluate the effect of fertilizers (no fertilizer (F0), compound fertilizer (F1) and organic fertilizer+compound fertilizer (F2) on wheat under water stress (RD1 (waterdeficit at flowering -milking stage), RD2 (water deficit at returning green-jointing stage) and RD3 (water deficit at returning green-jointing and flowering-milking stage).The control plants (CK) were subjected to 60–75% field water capacity (FWC) in the whole growing stage. The results showed that different fertilizer treatments had different effects on winter wheat with RDI treatments. At flowering stage, RD2 and RD3 lowered significantly population quantity, leaf area, plant height and dry weight per shoot of winter wheat in both F0 and F1 treatments. In F2 treatment, RD2 and RD3 lowered significantly plant height and leaf area and but had no significant effects on population quantity and dry weight per shoot of winter wheat. At jointing stage, RD2 and RD3 lowered significantly water use efficiency of leaf level (WUE_{leaf}) in F0 treatment, but increased WUE_{leaf} of winter wheat in F1 and F2 treatments. At flowering stage, RD2 had no effect on photosynthetic rate (P_N), transpiration rate (Tr) and WUE_{leaf} of winter wheat. RD3 lowered significantly P_N and Tr of wheat, but had no effect on WUE_{leaf} in F0 treatment. In F1 treatment, RD2 and RD3 had similar P_N, Tr and WUE_{leaf} with CK. In F2 treatment, RD2 increased significantly P_N, but had no effect on WUE_{leaf} of winter wheat. RD3 had no effect on P_N and but improved WUE_{leaf} by lowering Tr of winter wheat. RD2 lowered grain yield of winter wheat in F0 and F1 treatments, but had no effect on grain yield in F2 treatment. RD3 significantly reduced the grain yield in 3 fertilizer treatments. In addition, grain yield stability (GYS) of winter wheat in F2 treatment was higher than those in F0 and F1 treatments under the same RDI treatment. In conclusion, appropriate RDI and fertilizer treatment can significantly increase WUE_{leaf} and grain yield stability of winter wheat.

Keywords: Population quantity; Photosynthetic rate; Transpiration rate; WUE; Yield stability

Introduction

Water is the most limiting factor for wheat production in north China. Due to increasing competition in water usage by industry, domestic consumption and natural environment, the amount of agricultural water in many areas has become smaller and smaller (Jensen *et al*., 2010). Efficient use of water in irrigation is becoming increasingly important. However, nowadays, the shortage and serious wastage of water are the two confliting aspects in the usage of water resources worldwide. Therefore, it is needed to develop water-saving irrigation techniques and improve water use efficiency (WUE) of crop. Regulated deficit irrigation (RDI) is an important water-saving technique to improve WUE of crops (Du *et al*., 2010). It has been proven that RDI decreases vegetative growth, and increase yield and WUE of crop by optimizing water use (Santos *et al*., 2007; Ma *et al*., 2015; Zhang *et al*., 2017). Though it is rational in theory, it is still difficult for farmers to determine the allowable level of soil water deficit without significant reduction in crop yields when RDI is implemented. However, the appropriate degree of soil water deficit on crops varies with different planting conditions. The allowable level of soil water deficit on crops in different planting conditions still need to be investigated before it can be concluded whether it is practical in all conditions (Du *et al*., 2010).

Different from the traditional irrigation method, RDI strategy is based on plants' adaptive and specific responses to drought (Lambrecht *et al*., 2017). However, physiological and biochemical characteristics of plants in dry soil also are often affected by other factors, such as soil nutrient. Soil

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nutrients are also the most important factors in regulating the growth of plants (Chekli *et al*., 2017). And but these factors are not isolated but rather interactional and interdependent with each other. Crop production under drought condition depends not only on soil water content but also on soil nutrients. Numerous researches have proven the importance of water and nutrients interactions in optimizing crop productivity (Chintala *et al*., 2012; Soana and Balestrini, 2017). A proper amount of fertilizer can increase grain yield of winter wheat by enhancing drought tolerance of plants. But the sensitivity of plants to drought is increased with the increasing level of fertilizer application, which will restrain the growth and development of plants, and reduce crop yield (Yeboa *et al*., 2017). Therefore, the farmers also need to know how to apply fertilizer when RDI is implemented in the practice of water-saving irrigation. The effect of RDI should be better materialized only under appropriate soil fertility in the practice of water-saving agricultura lproduction. And there is some risk in crop RDI, regardless of soil fertility.

As a rule, researches on RDI mainly focused on the level of soil water deficit, yield and WUE of crop and the response of plant to water shortage (Jensen *et al*., 2010; Bourgault *et al*., 2013). Although previous results have confirmed some positive effects of RDI (Fereres and Soriano 2007; Spree *et al*., 2007; Iniesta *et al*., 2009), we still needed more knowledge on how RDI affect the grain yield and what the consequences are for crops production under different soil fertility conditions. However, there is not much information on the effect of soil fertility on RDI effects of crop. Previous studies on RDI mainly based on a specific soil fertility condition, which could not provide scientific guidance for crop RDI under different field soil conditions. Consequently, it is very necessary to study the effect of RDI on crop production when plants are under different soil fertility (or different fertilizer treatments) conditions. In the present study, plants were subjected to 3 fertilizer treatments, and in each fertilizer treatment, plants were exposed to 3 different soil water deficit treatments. The objective of this study was to investigate the effects of different fertilizer treatments on RDI effect of winter wheat.

Materials and Methods

Plant Materials and Experimental Design

Experiments were conducted from October 2009 to June 2010 at the Shangqiu experimental station of the Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences. In the field experiment, each plot was 2 m×2 m. In order to highlight the effect of fertilizer, the topsoil (0-15 cm) was scraped off before sowing. The experimental soil is aquic soil with a field capacity of 26.6% (gravimetrically. Table 1 is for chemical and physical properties of experimental soil. Plants were subjected to 3 different fertilizer treatments: no fertilizer (F0), NPK compound fertilizer (F1, 600kg ha^{-1}, corresponding to 72, 108 and 90 kg ha^{-1} of N, P and K, respectively) and Organic fertilizer + NPK compound fertilizer (F2, applied 600 kg ha^{-1}, respectively, corresponding to 210, 72, 108 and 90 kg ha^{-1} of organic matter, N, P and K, respectively. The content of N, P and K in compound fertilizer is 12%, 18% and 15%, respectively. The content of organic matter is above 35%, and total nutrient ($N+P_2O_5+K_2O$) is above 5% in organic fertilizer. All fertilizers were added as basic fertilizer at sowing. Winter wheat (*Triticum aestivum* L., Zhoumai 18) was sown in rows 25 cm apart on 10 October. The total density was 2.25 million basic seedlings per hectare. In the pot experiment, each pot was filled with 15 kg of sieved upper soil from plots above of different fertilizer treatments. 30 seeds of wheat were sown in plastic pots (30 cm diameter and 50 cm height) and thinned to 15 seedlings per pot at the 3-leaf stage. All plots and pots were randomly arranged under a transparent rain-shelter. In field and pot experiments, plants in each fertilizer treatment included three regulated deficit irrigation (RDI) treatments (RD1, RD2 and RD3. Three RDI treatments were carried out as shown in Table 2. The control plants (CK) were maintained at 60–75% FWC in whole growing stage. Each treatment repeats plots/pots.

Experimental Methods

Monitoring Irrigation Amount and Soil Water Contents (SWC) in Field Experiment

The irrigation amount (*IA*) at each irrigation time was calculated as:

$$IA = \gamma\ (\theta_f - \theta)\ H / 10 \quad (1)$$

Where *IA* is irrigation amount per time, mm; γ is soil bulk density in planned wetting soil zone, g/cm^3; H is the depth of planned wetting soil zone, cm; θ_f is the expected SWC in planned wetting soil zone, %; θ is pre-irrigation SWC in planned wetting soil zone, %. SWC was measured gravimetrically in all plots in 20 cm increments to a depth of planned wetting soil zone.

Monitoring Soil Water Contents (SWC) in Pot Experiment

Soil moisture levels were determined gravimetrically by the method of weighing and irrigating every day. Soil water contents (SWC) were expressed as percentage of FWC. The SWCs were calculated according to following formula:

$$SWC = (W_t - W_d - W_e - W_p) / (W_d \times FWC) \times 100\% \quad (2)$$

Where W_t is the temporary whole pot weight, W_d the net weight of dried soil in pot, W_e the weight of empty pot, W_p the estimated fresh weight of all plants in the pot, respectively. The estimated fresh weight of all plants in one pot was determined in advance in extra pots. FWC is field water capacity

Table 1: Chemical and physical properties of experimental soil

Entry	Unit weight ($g·cm^{-3}$)	Organic matter content ($g·kg^{-1}$)	Total nitrogen ($g·kg^{-1}$)	Available nitrogen ($mg·kg^{-1}$)	Available phosphorus ($mg·kg^{-1}$)	Available potassium ($mg·kg^{-1}$)
Measured values	1.44	0.83	0.45	31.11	5.51	38.62

Table 2: Details of regulated deficit irrigation

Treatments	Planting–stem elongation		Stem elongation-booting		Booting Heading		Milking and harvesting	
	SWC (%)	Planned wetting depth (cm)	SWC (%)	Planned wetting depth (cm)	SWC (%)	Planned wetting depth (cm)	SWC (%)	Planned wetting depth (cm)
CK	60-65	60	60-65	80	65-75	100	65-75	100
RD1	60-65	60	60-65	80	65-75	100	50-55	100
RD2	60-65	60	50-55	80	65-75	100	60-70	100
RD3	60-65	60	50-55	80	65-75	100	50-55	100

Population Quantity, Plant Height, Leaf Area and Dry Weight per Shoot

At the jointing and anthesis stages, population quantity, leaf area, plant height and dry weight per shoot of winter wheat were measured. Leaf area was calculated as:

$$\text{Leaf area} = \text{Leaf length} \times \text{Leaf width} \times 0.83 \quad (3)$$

Photosynthetic Rate (P_N), Stomatal Conductance (*gs*) Transpiration Rate (T_r) and WUE $_{Leaf}$

At the jointing and flowering stage, P_N and Gs of the leaf was measured using a LI-6400 portable photosynthesis system (LI-Cor, Inc., Lincoln, Nebraska, USA) during 9: 00–11: 00 am. 9 replicate samples (3 leaves × 3 plots / pots) were measured in each treatment. WUE $_{Leaf}$ was equivalent to the ratio of P_n to T_r.

At maturity, the spike number, grain number per spike, 1000 kernel weight and grain yield were measured. There were 3 replications per treatments. The grain yield stability (GYS) of each treatment was calculated as the percentage of grain yield in RDI groups relative to that of CK groups.

Statistical analyses were conducted using Excel 2003 and SPSS 13.0. Statistically significant differences were identified using analysis of variance (ANOVA) and least significant difference (LSD) test at the 5%.

Results

Population Quantity of Winter Wheat under Different Treatments

In the field experiment, at jointing stage, RD1 had no significant effect on population quantity of winter wheat in 3 different fertilization treatments, but RD2 and RD3 lowered population quantity of winter wheat compared to the control (CK. At flowering stage, RD1 had similar population quantity to the control in 3 different fertilization treatments, RD2 and RD3 lowered significantly population quantity of winter wheat in both no fertilizer (F0) and compound fertilizer (F1) treatments, and but had no significant effects on population quantity of winter wheat compared to the control (CK) in organic fertilizer+ compound fertilizer (F2) treatment (Fig. 1). It is thus clear that different fertilization treatments had various effects on population quantity of winter wheat with different RDI treatments. In the pot experiment, at jointing and flowering stage, RD1 had no significant effects on population quantity of winter wheat in 3 different fertilization treatments. RD2 and RD3 lowered population quantity of winter wheat at jointing stage. But, at flowering stage, RD2 and RD3 all had similar population quantity to the control in 3 different fertilization treatments (Fig. 1).

Leaf Area, Plant Height and Dry Weight per Shoot of Winter Wheat under Different Treatments

Under both field and pot experiment conditions, different fertilization treatments had various effects on leaf area, plant height and dry weight per shoot of winter wheat with different RDI treatments. At booting stage, RD1 had no effect on leaf area and plant height of winter wheat, but RD2 and RD3 lowered significantly leaf area and plant height of winter wheat in 3 different fertilization treatments (Table 3). At flowering stage, RD1 had no significant effect on leaf area, plant height and dry weight per shoot of winter wheat in 3 different fertilization treatments (Table 3). RD2 and RD3 lowered significantly leaf area, plant height and dry weight per shoot of winter wheat in both no fertilizer (F0) and compound fertilizer (F1) treatments. In organic fertilizer+ compound fertilizer (F2) treatment, RD2 and RD3 had no significant effects on leaf area and dry weight per shoot, and but lowered significantly plant height of winter wheat compared to the control (CK. Different letters in the same column imply that there is a significant difference at p= 0.05. F0: no fertilizer; F1: compound fertilizer; F2: Organic fertilizer+ compound fertilizer; RD1: water deficit at flowering -milking stage; RD2: water deficit at returning green-jointing stage; RD3; water deficit at returning green-jointing and flowering -milking stage; CK: the control plants.

Table 3: Leaf area, plant height and dry weight per shoot of winter wheat under different treatments

Treatments		At booting stage				At flowering stage				
		Leaf area per shoot (cm^2)		Plant height (cm)		Leaf area per shoot (cm^2)		Plant height (cm)		Dry weight per shoot (g)
		Field	Pot	Field	Pot	Field	Pot	Field	Pot	Field
F0	CK	52.6d	50.2d	45.5c	45.4c	56.4d	58.4d	70.5d	69.5d	1.21d
	RD1	53.1d	51.0d	45.1c	46.0c	56.1d	58.2d	70.5d	70.1d	1.23d
	RD2	41.1e	39.3e	39.3d	38.3d	53.2e	52.7e	67.8e	67.2e	0.93e
	RD3	40.9e	38.9e	39.1d	38.1d	53.4e	52.9e	67.8e	68.0e	0.92e
F1	CK	72.1c	70.4c	48.1b	47.9b	68.5b	70.2b	78.8b	77.9b	1.51b
	RD1	71.9c	69.8c	48.4b	48.0b	69.1b	71.0b	78.9b	77.2b	1.50b
	RD2	56.8d	58.8d	45.8c	44.8c	64.7c	66.8 c	76.4 c	75.8c	1.45c
	RD3	56.1d	57.9d	44.9c	44.3c	65.c	67.1c	75.c	74.2c	1.43c
F2	CK	96.9a	97.9a	52.4a	51.9a	76.1a	80.1a	81.6a	80.6a	1.71a
	RD1	96.1a	97.1a	53.1a	51.3a	75.9a	79.8a	81.2a	81.2a	1.73a
	RD2	88.9b	86.7b	50.3b	48.7b	75.6a	79.6a	78.2b	78.8b	1.70a
	RD3	88.5b	86.2b	49.8b	49.0b	75.2a	79.4a	78.9b	77.8b	1.69a

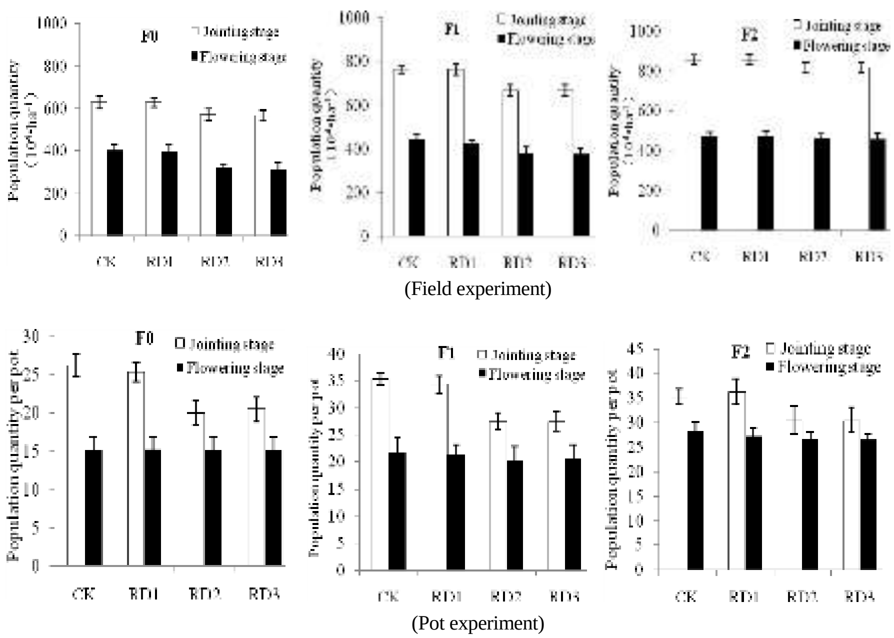

Fig. 1: Population quantity of winter wheat under different treatments. F0: no fertilizer; F1: compound fertilizer; F2: Organic fertilizer+ compound fertilizer; RD1: water deficit at flowering -milking stage; RD2: water deficit at returning green-jointing stage; RD3: water deficit at returning green-jointing and flowering -milking stage; CK: the control plants

P_N, Tr and WUE_{leaf} of Winter Wheat under Different Treatments

In the field experiment, at jointing stage, RD1 had similar P_N, *T*r and WUE_{leaf} with the control in 3 different fertilizer treatments. RD2 and RD3 lowered significantly P_N, *T*r and WUE_{leaf} of winter wheat compared to the control in F0 treatment. In F1 and F2 treatments, RD2 and RD3 had no significant effect on P_N, but increased WUE_{leaf} of winter wheat by reducing leaf *T*r (Fig. 2). At flowering stage, RD1 and RD3 had significantly lower leaf P_N and *T*r compared to the control, but had no significant effect on WUE_{leaf}, and RD2 had similar P_N, *T*r and WUE_{leaf} with the control in F0 treatment. In F1 treatment, RD1 lowered significantly leaf P_N and *T*r and had no effect on WUE_{leaf} of winter wheat compared to the control. RD2 and RD3 had similar P_N, *T*r and WUE_{leaf} with the control. In F2 treatment, RD1 and RD3 had no effect on leaf P_N and but lowered significantly *T*r of winter wheat, which resulted in improved WUE_{leaf}. RD2 significantly increased leaf P_N and *T*r, but had no effect on WUE_{leaf} compared to the control (Fig. 2).

Yield Traits and Yield Stability of Winter Wheat under Different Treatments

In the field experiment, RD1 had no effect on spike number and but lowered grain number per spike and 1000 kernel weight of winter wheat, which resulted in lower grain yield in 3 fertilizer treatments.

RD2 resulted in lower grain yield by lowering spike

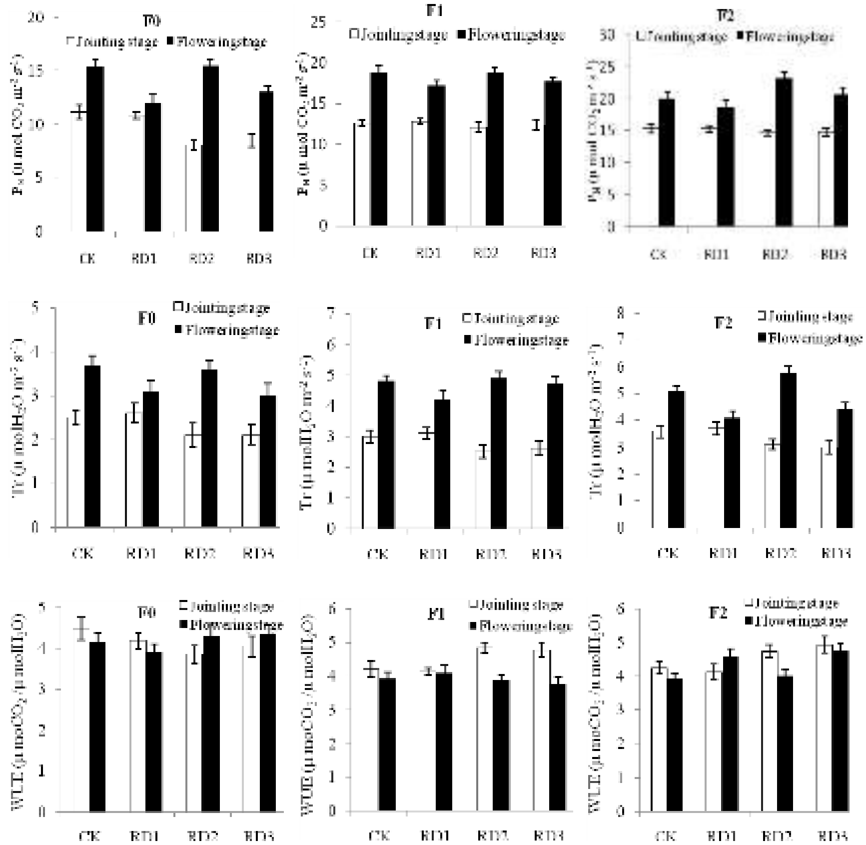

Fig. 2: Leaf photosynthetic rate (P_N), transpiration rate (*T*r) and water use efficiency (WUE_{leaf}) of winter wheat under different treatments (Field experiment. F0: no fertilizer; F1: compound fertilizer; F2: Organic fertilizer+ compound fertilizer; RD1: water deficit at flowering -milking stage; RD2: water deficit at returning green-jointing stage; RD3; water deficit at returning green-jointing and flowering -milking stage; CK: the control plants

number of winter wheat compared to the control in F0 and F1 treatments, but RD2 had no effect on spike number, grain number per spike, 1000 kernel weight and grain yield in F2 treatment. RD3 significantly reduced grain yield compared to the control by lowering spike number of winter wheat in F0 and F1 treatments, but by reducing 1000 kernel weight of winter wheat in F2 treatment (Table 4). In pot experiment, RD1, RD2 and RD3 had no effects on spike number in 3 fertilizer treatments. RD1, RD2 and RD3 resulted in lower grain yield compared to the control by reducing grain number per spike and 1000 kernel weight of winter wheat in F0 treatment. In F1 treatment, RD1, RD2 and RD3 also significantly reduced grain yield by lowering grain number per spike of winter wheat. In F2 treatment, RD1 significantly lowered grain number per spike and 1000 kernel weight of winter wheat, which resulted in lower grain yield. RD2 had no effects on spike number, grain number per spike, 1000 kernel weight and grain yield. RD3 also significantly reduced grain yield of winter wheat compared to the control due to a lowered 1000 kernel weight (Table 4).

Under both field and pot experiment conditions, for the same RDI treatment, GYS of winter wheat in F2 treatment was higher than those in F0 and F1 treatments. In the same fertilizer treatment, GYS of winter wheat with RD2 treatment was higher than those with RD1 and RD3 treatments (Table 4).

Discussion

Under the field condition, appropriate population quantity is very important for increasing the yield of crop. Soil water and fertilizer shortage can lower population quantity of wheat, which will ultimately affect grain yield (Lu, *et al.*, 2007). In our study, water deficit at jointing stage promoted earlier ineffective tiller to death and restrained the formation of later tiller, therefore leading to less population quantity of winter wheat in RD2 and RD3 compared to CK, and but fertilization (F1 and F2) treatments can increase population quantity compared to F0. At flowering stage, RD2 and RD3 had similar spike number to CK in F2 treatment, but lowered it in F0 and F1 treatments. Our study showed F2 treatment is helpful for maintaining spike number of winter wheat when RDI is implemented at jointing stage.

Plants invest relatively more assimilates into roots and

Table 4: Yield Traits and Yield Stability of Winter Wheat under Different Treatments

Treatments		Spike number (10^4 ha^{-1})	Grain number per spike	1000 kernel weight (g)	Yield ($kg \cdot hm^{-2}$)	Yield stability (%)
Field experiment						
F0	CK	405.12c	24.5e	32.8c	3255.54g	-
	RD1	400.08c	20.9f	30.9d	2583.76i	79.37
	RD2	315.23e	26.4e	32.9c	2737.96h	84.10
	RD3	310.01e	24.1e	29.8d	2226.43j	68.39
F1	CK	443.28b	30.6bc	33.4c	4530.50d	-
	RD1	440.11b	27.8de	30.1d	3682.75f	81.29
	RD2	382.04d	31.3ab	35.6bc	4256.99e	93.96
	RD3	381.96d	28.2d	33.7c	3629.92f	80.12
F2	CK	473.45a	32.9ab	38.5a	5996.95a	-
	RD1	471.91a	29.1dc	36.2b	4971.19c	82.90
	RD2	468.19a	33.2a	38.7a	6018.06a	100.35
	RD3	465.13a	32.8a	36.1b	5507.51b	91.84
Pot experiment						
F0	CK	15.0c	22.2d	31.2cd	10.79g	-
	RD1	15.0c	19.5e	26.9e	7.86h	72.85
	RD2	15.0c	18.5f	30.9d	8.57h	79.43
	RD3	15.0c	18.2f	26.8e	6.51i	60.33
F1	CK	21.7b	29.6f	32.4c	21.81d	-
	RD1	20.3b	26.7c	29.2d	15.23f	69.83
	RD2	19.3b	28.1bc	33.7c	19.27e	88.35
	RD3	19.7b	26.1c	29.7d	15.27f	70.01
F2	CK	28.3a	31.8a	36.8a	33.12a	-
	RD1	27.3a	27.1c	34.4bc	25.45c	76.84
	RD2	26.7a	31.6a	36.9a	33.13a	100.03
	RD3	26.6a	29.8ab	34.6bc	29.88b	90.22

Different letters in the same row imply that there is a significant difference at p=0.05. F0: no fertilizer; F1: compound fertilizer; F2: Organic fertilizer+ compound fertilizer; RD1: water deficit at flowering -milking stage; RD2: water deficit at returning green-jointing stage; RD3; water deficit at returning green-jointing and flowering -milking stage; CK: the control plants

less into shoot when plants are in dry soil. Increasing proportion of dry matter distributed to the root will restrain the growth of shoot and result into reduced leaf area, stem weight and plant height of crop (Stamatiadis *et al*., 2015). RDI at early growing stage of crop restrains the growth of shoot, but plants have compensatory growth effect, leaf area and dry weight per shoot of winter wheat can recover to a similar level to the controls after re-watering (Kisekka *et al*., 2017). But compensation effect of re-watering was also often affected by soil fertility. Improving soil fertility could enhance compensation effects of rewatered drought-stressed winter wheat (Sandhu *et al*., 2016). In our study, at booting stage, RD2 and RD3 both lowered leaf area and plant height of winter wheat in 3 fertilizer treatments. At flowering stage, RD2 and RD3 had similar leaf area and dry weight per shoot to CK in F2 treatment, but lowered them in F0 and F1 treatments. These showed that F2 treatment can enhance compensatory effect of shoot growth of winter wheat after re-watering.

Water and fertilizer are important factors which limit plant growth. Roots in progressively drying soil will produce root-sourced signals (ABA), which are transported through the transpiration stream to the shoots where leaf expansion rate and stomatal opening are regulated (Xiong *et al*., 2007; Jensen *et al*., 2010). Thus, root-sourced signals may substantially reduce the water loss through stomata. RDI can regulate stomatal opening and the growth of plant by managing soil water (Memmi *et al*., 2016; Zhang *et al*., 2017). And that stomatal opening is connected with photosynthesis and transpiration rate of leaf (Sack and Scoffoni, 2012). Previous study showed that moderate water deficit suppressed transpiration rate, but had no effect on photosynthetic rate, which resulted into an improved WUE_{leaf} of winter wheat (Xue *et al*., 2006). Nitrogen application can lower transpiration rate and increase net photosynthetic rate, resulting in improved WUE_{leaf} of winter wheat (Sang *et al*., 2016). In our stduy, at jointing stage, RD2 and RD3 lowered significantly leaf P_N, *T*r and WUE_{leaf} of winter wheat in no fertilizer (F0) treatment. RD2 and RD3 had no significant effect on P_N, but increased WUE_{leaf} of winter wheat due to a declined *T*r in F1 and F2 treatments. The results above also showed soil fertility had significant effect on photosynthetic rate and WUE_{leaf} of winter wheat under RDI conditions.

During the long evolutionary period, plants not only adopted different strategies for resistance to the stress of adverse situation, but also can partly or completely recover their physiological functions and growth and development to unaffected level after being freed from such stress and alleviate the damage to the plants caused by adverse condition, which shows obvious compensatory or super compensatory effect (Messina *et al*., 2002; Kisekka *et al*., 2017). Previous study showed that the compensatory effect of RDI on photosynthetic characteristic and grain yield appeared after re-watering (Xue *et al*., 2006). The compensatory effect of rewatered drought-stressed plant was closely related to soil fertilities and fertilizer applications (Sandhu *et al*., 2016). Soil with high fertility is beneficial to recovering photosynthetic capacity and improving leaf water use efficiency after rewatering on winter wheat suffering from droughts (Sang *et al*., 2016). In our study, at flowering stage, RD1 and RD3 had significantly lower leaf P_N, and RD2 had similar P_N to the control in no fertilizer (F0) treatment. In F1 treatments, RD1 lowered significantly leaf P_N of winter wheat. RD2 and RD3 had similar P_N to the control. In F2 treatment, RD1and RD3 had no effect on leaf P_N. RD2 had significantly higher leaf P_N compared to the control. These also showed that there were different compensatory effects in leaf P_N of winter wheat with RDI under different fertilization treatments.

RDI can improve the WUE of crop that has generally been accepted, but yield effects on RDI varied in different researches (Zhang *et al*., 2006; Bourgault *et al*., 2013; Hernandez-Santana *et al*., 2017). Crop yield is affected by many factors, such as climates, soil conditions and cultivation technique and so on, among which soil water and fertilizer are two main factors. Previous research has shown the importance of water and nutrients interactions in optimizing crop productivity (Chintala *et al*., 2012). Fertilization is most effective when plants are under appropriate soil water condition, and that irrigation is most effective when nutrients are not scarce (Lai *et al*., 2017). Previous research also showed that it was possible for deficit irrigation during the vegetative growth stages of crop without sacrificing significant grain yield, and but this irrigation effect was dependent on the N application rate (Stamatiadis *et al*., 2015). Our study also showed that the effect of RDI on grain yield varied under different fertilization treatments. RD2 lowered grain yield of winter wheat in F0 and F1 treatments, but had no effect on grain yield in F2 treatment. RD1 and RD3 reduced grain yield of winter wheat in 3 fertilizer treatments.

In addition, Grain yield is closely related to the ability of drought tolerance of crop under soil deficit condition. The ability of drought tolerance can be affected by improving the capacity for osmotic adjustment of plant. Osmotic regulation abilit of plants may depend on nutrient availability, plants with more nutrient availability exhibiting greater osmotic adjustment than plants with less nutrient availability (Gonzalez-Dugo *et al*., 2011). Fertilizer can improve photosynthetic characteristic and water status of leaf by increasing the capacity for osmotic adjustment and retard effect of soil water on grain yield of winter wheat in dry soil. Our study also showed that different fertilizer treatments reduce negative effect of soil water deficit on crop yield. Different fertilizer treatments had different effects on GYS of winter wheat with RDI treatments. Under the same RDI treatment, GYS of winter wheat in F2 treatment was higher than those in F0 and F1 treatments.

Conclusion

Different fertilizer treatments had different effects on winter wheat in different RDI treatments. RD2 and RD3 lowered significantly population quantity, leaf area, plant height and dry weight per shoot of winter wheat in both F0 and F1 treatments and but had no effects on population quantity and dry weight per shoot of winter wheat in F2 treatment at flowering stage. At jointing stage, RD2 and RD3 lowered significantly WUE_{leaf} in F0 treatment, but increased WUE_{leaf} of winter wheat in F1 and F2 treatments. At flowering stage, RD2 had no effect on P_N, *T*r and WUE_{leaf}, RD3 lowered P_N and Tr, but had no effect on WUE_{leaf} in F0 treatment. In F1 treatment, RD2 and RD3 had similar P_N, *T*r and WUE_{leaf} with CK. In F2 treatment, RD2 increased significantly P_N, but had no effect on WUE_{leaf}. RD3 had no effect on P_N and but improved WUE_{leaf} by lowering *T*r of winter wheat. RD2 lowered grain yield of winter wheat in F0 and F1 treatments, but had no effect on grain yield in F2 treatment. RD3 significantly reduced the grain yield in 3 fertilizer treatments. In addition, grain yield stability of winter wheat in F2 treatment was higher than those in F0 and F1 treatments under the same RDI treatment. In conclusion, appropriate RDI and fertilizer treatment can significantly increase WUE and grain yield stability of winter wheat.

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