Application of Supplemental Irrigation Based on Testing Soil Moisture in Winter Wheat

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Abstract: Water shortage is a serious problem threatening sustainable development of agriculture in the North China Plain, where winter wheat is the largest water-consuming crop. The objective of this study was to optimize irrigation scheme for high yield and high water use efficiency (WUE) in wheat (*Triticum aestivum* L.), on the basis of Jimai 22, a represented cultivar in production. In the field experiments conducted in growing seasons, unfixed amount of water was supplied at sowing, jointing, and anthesis stages to adjust the soil moisture into a controlled ladder. For example, the relative soil moisture contents in the W0 treatment were 85% at sowing, 80% at jointing, and 70% at anthesis; in the W1 treatment, they were 85%, 85%, and 70%, respectively; analogically, they were 85%, 85%, and 75% in the W2 treatment and 85%, 90%, and 80% in the W3 treatment. The results showed that WUE was higher in W0 than in other treatments. However, the grain yield was the lowest in treatment W0. In growing seasons, the grain yield, irrigation water use efficiency (WUE_I), precipitation use efficiency (WUE_P), and irrigation benefit (IB) in W1, W2, and W3 were decreased significantly because more water was supplied. Under the experimental condition, the W1 regime was considered as the optimum. In this regime, the relative soil moisture contents at 0–140 cm soil layer were controlled to 85% at sowing, 80% at jointing, and 70% at anthesis stages. When 15.32 mm of water was supplied in growing seasons, the final grain yields of W1 treatment were 8185.75 kg ha^{-1}, and the WUE_I and WUE_P were the highest among the 4 treatments. The deep soil water content (0-140 cm) can be estimated by shallow soil moisture content (0-60 cm), which is more conducive to estimate the deep soil water content through shallow soil and reduce the workload of supplemental irrigation based on testing soil moisture.

Keywords: Winter wheat, Supplemental irrigation based on testing soil moisture, Soil moisture content, Water use efficiency.

INTRODUCTION

Water shortage has become a global problem to be solved urgently. China is one of 13 countries with serious water shortage, in which the capita possession of water resource is only a quarter of the world's average [1]. The North China Plain is a major agricultural area in China, especially for wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) production. However, crop yield in this area is often restricted by water shortage and uneven distribution of precipitation. Moderately limited irrigation is an encouraged practice in wheat production because it is not only favorable for dry matter accumulation and grain filling [2-5] but also able to reduce water consumption and increase water use efficiency (WUE) [6]. Irrigation regime for wheat growing in different ecological environments is a hotspot in wheat cultivation research, and many experiments have been conducted with fixed irrigation amount. However, requirement of irrigation water amount is determined by soil moisture content in wheat field and the growth stage of wheat plant. In this study, we monitored the soil moisture content at 0–140 cm soil layer during wheat growth and controlled the relative moisture content to designed levels at critical growth stages. Based on soil moisture contents, the irrigation amounts were estimated and implemented at sowing, jointing, and anthesis stages. Four irrigation regimes were evaluated with characteristics of dry matter accumulation and redistribution, final grain yield, and indices of WUE. The aim of this study was to guide water management in wheat field in the North China Plain for high-yielding and water-saving production.

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MATERIALS AND METHODS

Wheat Cultivar and Field Experiments Design

The field experiments were conducted with the wheat cultivar of Jimai 22 in Xinxiang (35.28°N, 113.94°E), Henan Province, China. The top layer of soil (0–20 cm) contained 1.55% of organic matter, 0.14% of total nitrogen (N), 143.6 mg kg^{-1} of available N, 21.7 mg kg^{-1} of available phosphate (P), and 153.4 mg kg^{-1} of available potassium (K) in growing season. The precipitations in growing season were as follows: 104.6 mm from sowing to jointing stage, 23.6 mm from jointing to anthesis stage, and 105.6 mm from anthesis to maturity stage. Soil field capacities before sowing of

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0–20, 20–40, 40–60, 60–80, 80–100, 100–120, and 120–140 cm soil layers were 25.63%, 25.13%, 28.64%, 26.70%, 27.30%, 28.55%, and 27.56%; soil bulk densities were 1.54, 1.52, 1.44, 1.50, 1.48, 1.48, and 1.51 g cm^{-3}; and relative moisture contents were 70.49%, 68.12%, 80.41%, 91.79%, 96.61%, 98.81%, and 99.50%, respectively.

Treatments were designed in growing seasons with controlled relative soil moisture contents at sowing, jointing, and thesis stages (Table **1**). The irrigation amount (mm) was calculated with the following formula: $m = 10\ \rho bH\ (\beta_i - \beta_j)$ [7], where, H is the depth of designed moist layer soil at that period (cm), $\rho b$is the soil bulk density of designed moist layer soil (g cm^{-3}), β_i is the designed moisture content (soil field capacity × designed relative moisture content), β_j is the natural moisture content, *i.e.*, soil moisture content before irrigation.

The field was prepared in a randomized block design with 3 replicates. The plot (16 m^2) was 4 m in length and 4 m in width and separated from each other by a 1.0 m zone. The preceding crop was corn. Stalks residues of corn were crushed and inversely buried into field before wheat sowing. In the growing season, 105.0 kg ha^{-2} N, 112.5 kg ha^{-1} P_2O_5, and 112.5 kg ha^{-1} K_2O were applied before sowing, and another 112.5 kg ha^{-1} N was applied at jointing stage. The fertilizers were urea (contained 46.4% N), diammonium phosphate (contained 46% P_2O_5 and 18% N), and potassium sulfate (contained 52% K_2O). The sowing dates were 8 October, and the harvest dates were June 11. Seedling density was controlled to 180 plants m^{-2} at 4-leaf stage. Other field managements were as same as those for high yield production.

Soil Moisture Content

Soils between 0 and 200 cm in depth were collected using a drill, and divided into 10 samples with 20 cm per sample. Each soil layer sample was dried in an aluminum box before determination of moisture content. The soil moisture content (%)= (fresh weight of soil sample –dry weight of soil sample) / dry weight of soil sample × 100.

Field Water Consumption Amount

The calculation was based on soil moisture content.

$$ET_{1-2} = 10 \sum_{i=1}^{n} \gamma_i H_i \left(\theta_{i1} - \theta_{i2} \right) + M + P + K \quad [8].$$

Where, ET_{1-2} is water consumption amount (mm) during a phase; i is the number of soil layer; n is the total number of soil layer; γ_i is the dry bulk density of the i^{th} soil layer(g cm^{-3}); H_i is the thickness of the i^{th} soil layer (cm); θ_{i1} and θ_{i2} are soil moisture contents of the i^{th} soil layer at the start and end of the phase, respectively; M is the irrigation amount in the phase (mm); P is the available precipitation (mm); and K is the supplemental amount from groundwater in the phase (mm). When the groundwater is below 2.5 m from the surface, the K value can be negligible. In this study, it was given to “0” for the groundwater level was below 5 m from the surface.

Grain Yield

At maturity, plants from 2 m^2 area were harvested for each plot. Grain yield was determined based on grain moisture content of 12.5%.

WUEs and Irrigation Benefit

Total WUE, irrigation WUE (WUE_I), precipitation WUE (WUE_P) and soil WUE (WUE_S) were calculated with the following formulas: $WUE = Y/ET$ [10], $WUE_I = Y/I$, $WUE_P = Y/P$, and $WUE_S = Y/\Delta S$ [11-13]. Irrigation benefit was determined as $IB = \Delta Y/I$ [14]. Where, Y is the grain yield (kg ha^{-1}); P is the available precipitation (mm); ΔS is the soil water consumption amount (mm); ΔY is the grain yield increment after irrigation (kg ha^{-1});

Table 1: Relative Soil Moisture Contents in Various Treatments of Water Supply (%)

Treatment	Relative Soil Moisture Content Designed		
	Sowing	Jointing	Anthesis
W0	85	80	70
W1	85	85	70
W2	85	85	75
W3	85	90	80

Data were the averages in 0 ~ 140 cm soil layers.

ET is the field water consumption amount during the growing season (mm); and I is the actual irrigation amount (mm).

Data Analysis

Observed data were managed in Microsoft Excel 2010. Statistical analysis was carried out using SPSS 19 (SPSS, Chicago, USA) packages.

RESULTS

Relative Soil Moisture Content at 0–140 cm Soil Layer after Supplemental Irrigation

In growing seasons, the actual relative soil moisture contents approached the designed contents with acceptable errors (hereinafter as regulative errors). For instance, the regulative errors of 4 treatments were 2.45% at sowing stage, 0.05%–2.67% at jointing stage, and 0.36%–2.99% at anthesis stage (Table **2**). This indicated that the designed soil moisture was obtained using the method of supplemental irrigation based on testing soil moisture.

Effects of Different Treatments on Grain Yield and WUEs

The grain yield and WUE of W0 treatment was lower during growth season (Table **3**). With the total irrigation amount increasing, the grain yield, WUE, WUE_I, WUE_p, WUE_s and IB decreased significantly. W1 was the best irrigation treatment with high yield and water saving. The grain yield, irrigation amount, WUE, WUE_I and IB were 8185.75 kg ha^{-1}, 15.32 mm, 21.86 kg ·ha^{-1} · mm-1, 65.32 kg ha^{-1}· mm-1 and 78.17 kg ha^{-1} mm^{-1}, respectively.

Correlation Analysis of Soil Moisture Content in Different Soil Layers before Watering

The average soil moisture content of 0-60 cm, 0-80 cm, 0-100 cm, 0-120 cm soil layers are significantly positive correlation with 0-140 cm soil layer (Table **4**). It shows that deep soil water content can be estimated by shallow soil moisture content, which is more conducive to estimate the deep soil water content through shallow soil and reduce the workload of supplemental irrigation based on testing soil moisture.

Table 2: Irrigation amount and Relative Soil Moisture Contents in Different Treatments

Treatment	Sowing Stage				Jointing Stage				Anthesis Stage			
	DRMC (%)	RMC (%)	RE (%)	I (mm)	DRMC (%)	RMC (%)	RE (%)	I (mm)	DRMC (%)	RMC (%)	RE (%)	I (mm)
W0	85	87.08	2.45	0	80	82.18	2.73	0	70	71.03	1.47	0
W1	85	87.08	2.45	0	85	85.04	0.05	15.32	70	72.09	2.99	0
W2	85	87.08	2.45	0	85	85.04	0.05	15.32	75	73.04	2.61	12.92
W3	85	87.08	2.45	0	90	87.60	2.67	27.42	80	79.71	0.36	38.81
Average			2.45				1.38				1.86	

Relative soil moisture contents were the averages at 0-140 cm soil layer.
DRMC: designed relative moisture content; RMC: relative misture content RE: regulative error; I: irrigation amount.

Table 3: Effects of Different Treatments on Grain Yield, Water Consumption amount, and WUE in Wheat

Treatment	Grain Yield (kgha^{-1})	Water Consumption Amount (mm)				Water Use Efficiency (kg ha^{-1} mm^{-1})				
		Total	I	P	SWCA	WUE	WUE_I	WUE_P	WUE_S	IB
W0	6988.25c	366.98c	0.00d	233.80	133.18a	19.04b	-	29.89c	52.47d	-
W1	8185.75a	374.44c	15.32c	233.80	125.32bc	21.86a	534.32a	35.01a	65.32a	78.17a
W2	7480.50b	391.96b	28.24b	233.80	129.92ab	19.08b	264.89b	32.00b	57.58c	17.43b
W3	7369.10b	407.79a	53.29a	233.80	120.70c	18.07b	138.28c	31.52bc	61.05b	7.15c

I: irrigation amount; P: precipitation; SWCA: soil water consumption amount; WUE: water use efficiency; WUE_I: irrigation water use efficiency; WUE_P: precipitation use efficiency; WUE_S: soil water use efficiency; IB: irrigation benefit. Different small letters in the same column meant significant difference at P<0.05.

Table 4: Correlation Analysis of Soil Moisture Content in Different Layers in Treatments

Growing Season	Soil Layer (cm)						
		0~20	0~40	0~60	0~80	0~100	0~120
first	0~140	0.0485	0.4398	0.8860*	0.9513*	0.9692*	0.9848*
second	0~140	0.1576	0.5253	0.7719*	0.8992*	0.9713*	0.9938*

Data are r^2.

DISCUSSION

Proper irrigation regimes for wheat production in North China Plain have been studies with numerous experiments, of which most were designed with fixed irrigation amounts. Li *et al*. suggested 3 irrigation systems: 75 mm of water before sowing, 75 mm of water each at sowing and jointing stages, and 75 mm of water each at sowing, jointing, and at anthesis stages [15]. The total irrigation amount was 75–225 mm, and the highest yield was 7423 kg ha^{-1}. Fang *et al*. and Dong *et al*. conducted irrigation under the condition of sufficient soil moisture at sowing stage and found 60 mm of water at jointing and anthesis stages each pushed the grain yield to 7000–7500 kg ha^{-1} [16,17]; and total irrigation amount could be reduced to 60–120 mm, without decreases of yield and WUE, if high-yield and high-WUE-type cultivars were used [17]. Wang *et al*. pointed out that no irrigation needed for winter wheat in wet years and once (at jointing stage) or twice irrigations (at jointing and heading stages) were recommended in normal precipitation and dry years, respectively, with water amount of 60–75 mm at each time [18]. In this study we improved the irrigation method by considering the original soil moisture content before irrigation. The quantity of irrigation water was estimated after measuring soil moisture content. The 3 irrigation regimes (W1, W2, and W3) conduced to final grain yields of 8185.75, 7480.50, and 7369.10 kg ha^{-1}respectively, and the supplemental water amounts were 15.32, 28.24, and 53.29 mm in growing season, indicating the obtainment of water-saving and high-yield cultivation by means of supplemental irrigation based on testing soil moisture.

WUE is a major theme in water-saving cultivation. A key issue is to promote the WUEs of both natural precipitation and irrigation [19]. In wheat field, water consumption amount is composed of precipitation, irrigation water, and soil water. Soil moisture content plays important roles in wheat growth and development, such as boosting adsorptions of water and nutrition by roots. Abundant soil moisture at sowing stage may increase WUE_S and decrease soil residual moisture at harvest. As a result, the storage capacity of soil reservoir is expanded to hold more water in flood seasons and regulate the soil reservoir [20]. Deficit irrigation at jointing and anthesis stages can promote root growth and increase WUE_S [21]. Under dry condition, N fertilizer has positive effects on WUE_S [22] and WUE_P [23]. Deficit irrigation is beneficial to promoting economic index and WUE, but the grain yield might be reduced in some cases [24]. A moderate water deficit can improve crop yield and WUE simultaneously [21]. In winter wheat, Zhang *et al*. [25] suggested an irrigation regime for normal precipitation condition, *i.e*., soil moisture controlled from revival to erecting stage and supplemental irrigation at jointing and heading–anthesis stages with 60–70 mm at each time. In this experiment, we noticed that the grain yield, WUE_I, WUE_P, and irrigation benefit showed decrease trends in growing seasons when more water was irrigated. The W1 regime showed the best effects on WUE, WUE_P, soil water consumption amount, and final yield, and had a great potential in wheat production in North China Plain. First of all, the method for quantifying irrigation water needs to be improved if this technique is applied in water-saving and high-yield cultivation.

CONCLUSIONS

In growing seasons, the relative soil moisture contents in wheat fields were regulated to 85% at sowing, 80% at jointing, and 70% at anthesis stage through supplemental irrigating with 15.32 mm. This regime is suggested as the optimal scheme due to its remarkable effects on high yield, WUE, WUE_I, WUE_P, and IB. The deep soil water content (0-140 cm) can be estimated by shallow soil moisture content (0-60 cm), which is more conducive to estimate the deep soil water content through shallow soil and reduce the workload of supplemental irrigation based on testing soil moisture.

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