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Plastic-Covered Ridge-Furrow Planting Combined with Supplemental Irrigation Based on Measuring Soil Moisture Promotes Wheat Grain Yield and Irrigation Water Use Efficiency in Irrigated Fields on the Loess Plateau, China

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Abstract: The purpose of this study was to investigate whether combining plastic-covered ridge and furrow planting (RF) and supplemental irrigation based on measuring soil moisture (SIMSM) can increase the grain yield and water use efficiency (WUE) of wheat (*Triticum aestivum* L.) in irrigated fields of Loess Plateau, China. In 2016–2018, the experiment was conducted at Doukou experimental farm (34°36′ N, 108°52′ E) with two plant systems (RF and traditional planting (TF)) and three irrigation treatments (S1 and S2: SIMSM with a target relative soil water content of 85% and 100%, respectively). The results suggest that under the TF system, SIMSM decreased the grain yield and nitrogen utilization. The reason for this may be the local low precipitation. However, the combination of RF and S2 significantly increased the WUE, protein and wet gluten concentration in the grain. In addition, the grain yield of the RF plus S2 treatment was not significantly different than that of the traditional irrigation method. These results suggest that combining RF and SIMSM with a target relative soil water content of 100% is beneficial to the synergistic improvement of the wheat yield, the wheat quality, and the water and fertilizer use efficiency in irrigated fields on the Loess Plateau.

Keywords: plastic-covered ridge and furrow planting; supplemental irrigation based on measuring soil moisture; wheat; grain yield; water use efficiency

1. Introduction

The Loess Plateau is the main dryland area in China. However, low rainfall is the main limiting factor for crop production here. The grain production potential in this area has declined by 60–70% due to the factor mentioned earlier [1]. Therefore, increasing grain yields within the context of a limited water supply is important for achieving an adequate food supply for local people.

The Guanzhong Plain which is the southern portion of the Loess Plateau, has a semi-humid and drought prone climate. As compared to other regions, this area has a mild climate, and receives a relatively high annual rainfall. It facilitates irrigation to a certain extent [2]. This plain is the main high yielding crop production area in the Loess Plateau. Increasing the grain yield in this area can effectively alleviate the grain crisis in other areas which are arid and crop production is limited by climatic conditions [3]. Thus, the yield of the Guanzhong Plain plays a vital role in maintaining the grain production in the Loess Plateau and even for grain security in arid Northwest China.

The Guanzhong Plain is an important wheat (*Triticum aestivum* L.) production region of China where water availability is the main limiting factor for high-yielding wheat production. The prime reason for this is that over 70% of the annual precipitation is received during a period of four months (June to September) which does not coincide with the growing period of winter wheat [4]. It makes irrigation the most important agronomic measure for achieving high yield in wheat. However, dense urbanization and the consequent priority for domestic use limits the availability of water for irrigation in this region [5]. Further, the common method of irrigation used is surface irrigation which accounts for huge wastage of water resulting in low water use efficiency (WUE) [6]. This situation has aggravated regional water deficiency and has rendered high-yield wheat production unsustainable [7]. This calls for techniques to increase existing WUE by reducing wastage and producing more for per unit of water used. Only then can it sustain a high yield of wheat production in the region.

In recent years, supplemental irrigation based on measuring soil moisture (SIMSM), has shown to reduce the quantity of irrigation water used and to increase the WUE of wheat at Huang-Huai-Hai Plain in China [7–9]. SIMSM is based on the water demand characteristics of wheat and the target relative water content of the soil during its key growth stages, which affects water requirements [10]. Based on the relative water content of the target soil, the amount of irrigation calculated is required to supplement the amount of water available during critical crop growth stages. This substantially improves the yield and WUE [7]. A previous study suggested that SIMSM significantly promoted the utilization of the soil water-holding capacity of the middle soil layer and improved the efficiency of solar energy utilization of wheat, leading to both high yields and reduced water usage [10–13]. However, there is little information on use of SIMSM in the irrigated fields of the Loess Plateau.

In the rainfed regions of the Loess Plateau, rainfall is the only source of water for wheat production. Therefore, the effective use of rainwater is necessary in this region [14]. One of the important rainwater harvesting systems, namely plastic-covered ridge and furrow planting (RF) has been widely used in recent years in the rainfed region of the Loess Plateau [15]. A previous study by Li et al. [16] suggested that the RF system can concentrate the limited rainfall within the planting furrow and rooting zone of plants. Moreover, plastic cover on RF greatly reduces unnecessary evaporation of water from the surface of the land [17]. Thus, this approach has significantly increased soil moisture, crop yield, and crop WUE [18]. Ali et al. [14] reported that RF can significantly increase the WUE of wheat under suitable irrigation conditions. These studies suggest that RF is an effective measure for efficient water use and could notably save irrigation water.

From these studies, the RF and SIMSM both significantly improve the WUE of crops. However, questions of whether these two systems have an interaction effect and if combining these two systems has an additive effect that can further reduce irrigation water use and increase the WUE of wheat in irrigated fields in a sub-humid region have not been answered clearly. In the present study, the combination of land configuration and irrigation methods have been used as treatments in an irrigated system. Land configuration includes flat bed and RF; however, irrigation methods used included traditional and SIMSM methods. The objective of the present study is to investigate the interaction effects of RF and SIMSM on the grain yield and WUE of winter wheat in the sub-humid region in China under irrigated conditions. The ultimate goal is to assess whether RF and SIMSM can be used for winter wheat production in an irrigated system in the Loess Plateau of China.

2. Materials and Methods

2.1. Experimental Design

The present study was conducted at the Doukou Experimental Farm of Northwest A&F University, Shaanxi Province, China (34°36′ N, 108°52′ E), during 2016–2018. The experimental site is at an elevation of 510 m above the mean sea level. The annual mean temperature was 13.2 °C, and the annual mean precipitation was 548.7 mm, 70% of which was received during a period of four months (June to September). The soil in the top 1.2 m was Eum-Orthrosols (Chinese soil taxonomy). The soil bulk density, organic matter content, available nitrogen (N), phosphorus (P), and potassium (K) at a topsoil depth of 0–20 cm were 1.05 g cm^{-3}, 14.60 g kg^{-1}, 99.40 mg kg^{-1}, 20.24 mg kg^{-1}, and 243.20 mg kg^{-1}, respectively (before fertilization). Precipitation during the wheat growing period was 130.7 mm and 73.1 mm in 2016–2017 and 2017–2018, respectively (Figure 1).

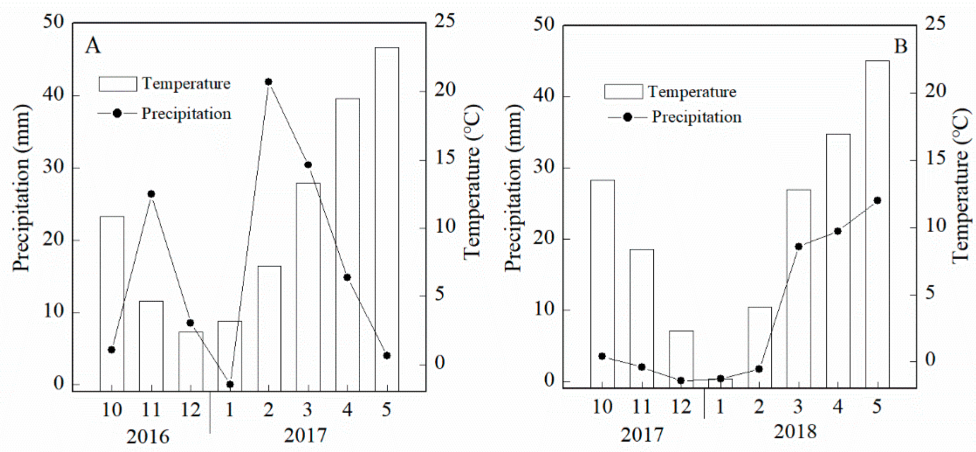

Figure 1. The average precipitation and temperature during the wheat growing seasons in experimental fields: (**A**) 2016–2017, (**B**) 2017–2018.

Two planting systems, RF and traditional planting (TF), were used in the experiment. For each planting pattern, three irrigation treatments were established: (1) SIMSM-85, with a target relative soil water content of 85%; (2) SIMSM-100, with a target relative soil water content of 100%; and (3) traditional irrigation, in which in each round of irrigation, the irrigation amount is 100 mm, as this is the amount traditionally used by local farmers. The irrigation was given at the wintering and jointing stages of crop growth. The experiment was laid in completely randomized design with six treatments and replicated three times. The plot area was 12 m^2 (3 m × 4 m), with spacing of 1 m between the plots.

The SIMSM method employed was mainly based on previous studies [10–13]. For SIMSM, the water content of the soil to a depth of 0–40 cm was determined using a TDR 100 soil moisture meter (FieldScout TDR 100, 6440FS, Spectrum Technologies, Aurora, CO, USA). Each plot had ten replications to measure the soil moisture. The mass water content of the soil to a depth of 0–40 cm was obtained by measuring the bulk density and the field water-holding capacity. The amount of irrigation water (IR) was then calculated according to Ekren's method [19].

$$\mathrm{IR} = 10 \times \mathrm{a} \times \mathrm{H} \times \mathrm{FC} \times (\theta_{tr} - \theta_n) \quad (1)$$

In the equation, a is the soil bulk density from 0–40 cm (g cm^{-3}); H is the depth of the soil layer (in this paper, 40 cm); FC is the field capacity; θ_{tr} (%) is the target relative soil water content (in this paper, 85% and 100% for the treatments SIMSM 1 and SIMSM 2, respectively); and θ_n (%) is the water content of the soil on a weight-basis before irrigation.

The amount of irrigation was measured using a water meter (LXS-25Y; Nanchang Water Industry Group Co., Nanchang, Jiangxi, China). The amount of irrigation given in each treatment is listed in Table 1.

For RF, land was configured into ridge and furrows each measuring 30 cm and plastic film (with a thickness of 0.012 mm) was mulched on the ridges (Figure 2). These were formed manually in an alternate manner. The height of the ridges (or the depth of the furrows) was 15 cm. Rotary tillage was used during land preparation and 225 kg hm^{-2} N (urea) and 120 kg hm^{-2} P_2O_5 (ordinary superphosphate) were applied as basal doses.

The wheat was planted in the furrows, with two plant rows per furrow. The row spacing for RF and TF was 0.30 m in all cases. The wheat cultivar Xinong 979 was sown at the seed rate of

150 kg hm^{-2} on 18 October in the first year of experimentation (2016) and 16 October in the next year (2017). The crop was harvested on 31 May and 29 May in the years 2017 and 2018, respectively.

Table 1. Seasonal amount of irrigation given in each treatment during the two wheat growth stages (mm).

Planting	Irrigation	2016–2017			2017–2018		
		Wintering	Jointing	Total	Wintering	Jointing	Total
RF	S1	0.0	0.0	0.0	0.0	0.0	0.0
	S2	0.0	7.8	7.8	5.1	6.7	11.8
	CK	100.0	100.0	200.0	100.0	100.0	200.0
TF	S1	3.2	2.9	6.1	10.7	5.5	16.2
	S2	27.0	26.7	53.7	34.6	39.3	73.9
	CK	100.0	100.0	200.0	100.0	100.0	200.0

RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation.

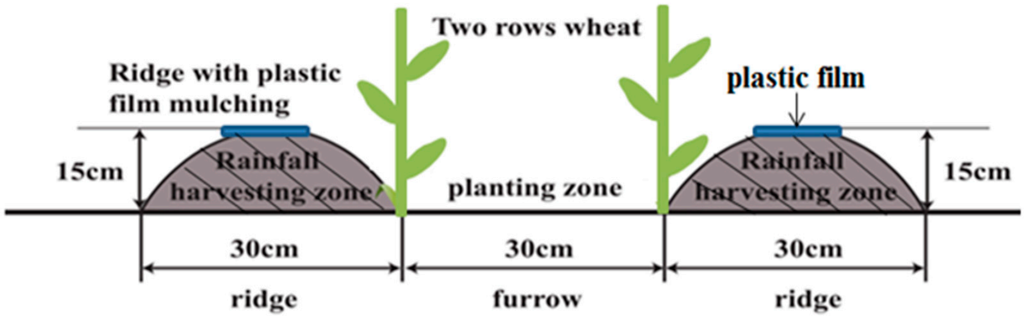

Figure 2. Schematic diagram for the plastic-covered ridge and furrow planting system (RF).

2.2. *Measurements and Data Analysis*

2.2.1. Plant Growth, Grain Yield, and Quality

The number of tillers and stems was recorded at the growth stages of seedling, wintering, jointing, anthesis, and maturity, in two rows of 1 m length per plot. At the same stages, the aboveground total biomass was determined after oven drying at 80 °C to a constant weight.

At maturity, the plants in 2 m^2 of each plot were harvested. The grain yield and grain yield components, namely, the spike number per unit area, the spikelet number per spike, and the grain weight were measured. The grain samples were dried naturally for quality analysis using a near-infrared analyzer (DA7250; Perten, Stockholm, Sweden).

The root dry weight was measured at the state of maturity. Root drills (with a diameter of 9 cm) were used to take root samples in and between wheat rows in each plot. Then, 2 m of sampling depth was taken at an interval of 20 cm. The roots were removed by manual selection and rinsing, dried in the oven at 60 °C to a constant weight, and finally weighed with a balance of 1/10,000; the results were used to calculate the dry weight density of the roots.

2.2.2. Soil Moisture and Temperatures

The soil moisture of the 0–20 cm deep soil layer was measured at approximately 15-day intervals. At sowing to maturity, it was determined for a total depth of 0–200 cm. The soil moisture reported for RF was the average value of that in a ridge and a furrow. The soil sampling was done at 20 cm increments. The soil moisture was measured based on the methodology described by Li et al. [20]. Each plot had three replications to measure the soil moisture. The soil was sampled using a soil ferric auger, and the gravimetric (g g^{-1}) soil water content was measured by drying the soil at 105 °C to a constant weight. The soil temperatures of the 5 cm deep soil layer were measured using mercury-in-glass thermometers with bent stems; they were recorded daily at 8:00, 14:00, and 20:00. The results were then used to calculate the average soil temperature. Each plot had three replications for measured the soil temperature.

2.2.3. Water Use Efficiency (WUE)

The WUE was calculated as the value obtained by dividing the grain yield of wheat by seasonal evapotranspiration. The specific method described by Li et al. was used for this [20]. Seasonal evapotranspiration for each plot was determined by the formula ET = P + SWC + I, where P is the total seasonal precipitation (mm), SWC is the soil moisture change, and I is the total amount of irrigation. The experimental field had fairly good water-holding capacity and therefore little drainage was observed beyond 200 cm depth of soil during the growing season. The irrigation WUE (IWUE) and precipitation WUE (PWUE) were calculated by dividing the winter wheat yield by the total amount of irrigation and total seasonal precipitation during the wheat growth period, respectively.

2.2.4. Nitrogen Use Efficiency (NUE)

At maturity, the total N concentration in the aboveground tissue was determined by H_2SO_4-H_2O_2 digestion and analysis of the digestate by the automatic Kjeldahl method (FOSS8400, Foss, Hilleroed, Switzerland). The N accumulation (NA) was calculated as the product of N concentration and aboveground biomass. The N uptake efficiency (NUE) was calculated as the ratio of N uptake by the aboveground crop at maturity to the amount of N fertilizer applied. The N fertilizer productivity (NFP) was calculated as the ratio of the grain yield to the amount of N fertilizer applied. NUE was calculated as the ratio of the grain yield to the total N uptake [7].

2.2.5. Nitrate Nitrogen (NO_3^--N)

Soil NO_3^--N concentration was determined at maturity at a soil depth of 0–100 cm. The soil was sampled in 20 cm increments. The soil NO_3^--N concentration was measured using the methodology described by Li et al. [18].

2.3. Statistical Analyses

The SPSS 16.0 statistical software package was used for analysis of data. Means of data for each treatment were calculated by averaging the values for each plot. The general linear model was selected and the differences between means were evaluated by Tukey's test at $p = 0.05$.

3. Results

3.1. Soil Moisture and Temperature

In the present study, the RF system and irrigation both significantly affected the soil moisture of 0–20 cm soil layer which increased with irrigation (Figure 3A,B). In both the years of experimentation (2016–2017 and 2017–2018) for the same level of irrigation the mean soil moisture of the 0–20 cm soil layer under the RF was 7.0–14.1% higher than that under the TF. However, by increasing the amount of irrigation, the difference in soil moisture between the RF and TF decreased. The average soil moisture of the 0–20 cm soil layer in RFS1, RFS2, and RFCK was 12.4–14.1%, 10.1–13.0%, and 7.0–8.8% higher than in TFS1, TFS2, and TFCK, respectively. At maturity, the soil moisture of the 0–200 cm soil layer was measured. The soil moisture of the 0–200 cm soil layer in the RF system (the average value of three irrigation levels) was 5.03% and 3.86% higher than that in the TF system in the year 2016–2017 and 2017–2018, respectively (Figure 3C,D). Further, the difference in the soil moisture of the 2 m soil layer between RF and TF also decreased with increasing irrigation. The soil moisture in the 2 m soil layer in RFS1, RFS2, and RFCK was 6.0–7.9%, 3.9–6.2%, and 1.0–1.8% higher than in TFS1, TFS2, and TFCK, respectively.

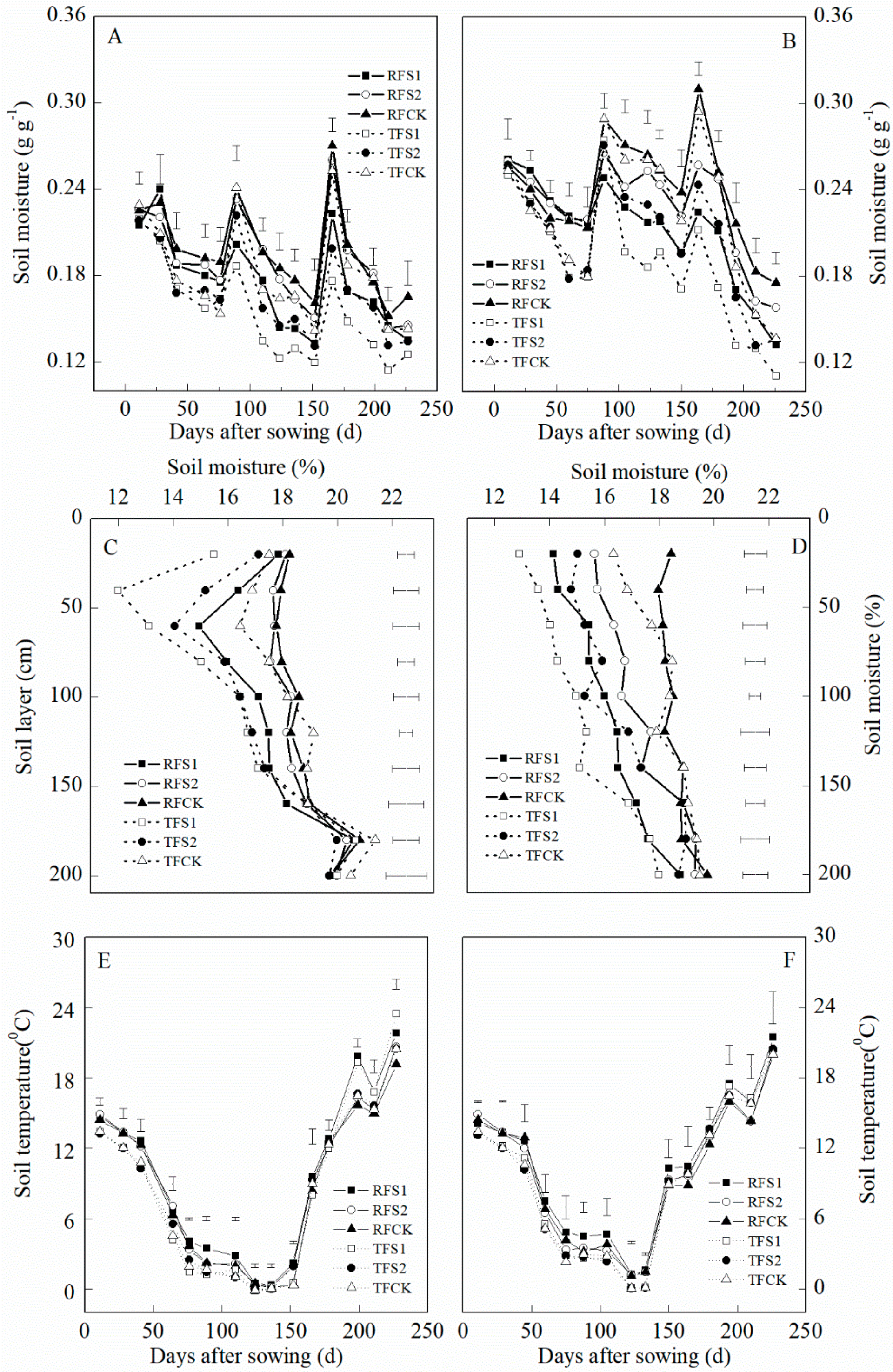

Figure 3. Effects of planting method and irrigation on the soil moisture and soil temperature. (**A**,**B**): soil moisture of 0–20 cm soil layer during the growing period of wheat in 2016–2017 and 2017–2018, respectively. (**C**,**D**): soil moisture of 0–200 cm soil layer at maturity in 2016–2017 and 2017–2018, respectively. (**E**,**F**): soil temperature of 5 cm soil layer during the wheat growth period in 2016–2017 and 2017–2018, respectively. RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation. Horizontal bars represent the honestly significant difference at $p = 0.05$.

The soil temperature in the 5 cm soil layer decreased with increasing level of irrigation (Figure 3E,F). Further, in the RF system the soil temperature was relatively higher in the 5 cm soil layer in the early growth period of wheat. However, it decreased later.

3.2. Plant Growth

Methods of planting and irrigation significantly affected the tiller and stem numbers and the aboveground biomass of wheat (Figure 4). They increased with the increase in levels of irrigation. In addition, the RF system also affected the tiller and stem numbers and the aboveground biomass, but its effects were related to the irrigation level. At the stage of maturity, the tiller and stem numbers of RFS1, RFS2, and RFCK were 12.81%, 6.60%, and 3.62% higher than those of TFS1, TFS2, and TFCK, respectively (averaged over the two years). The values of aboveground biomass at maturity in the treatments RFS1, RFS2, and RFCK were 22.25%, 17.74%, and 8.84% higher than those of TFS1, TFS2, and TFCK, respectively (averaged over the two years).

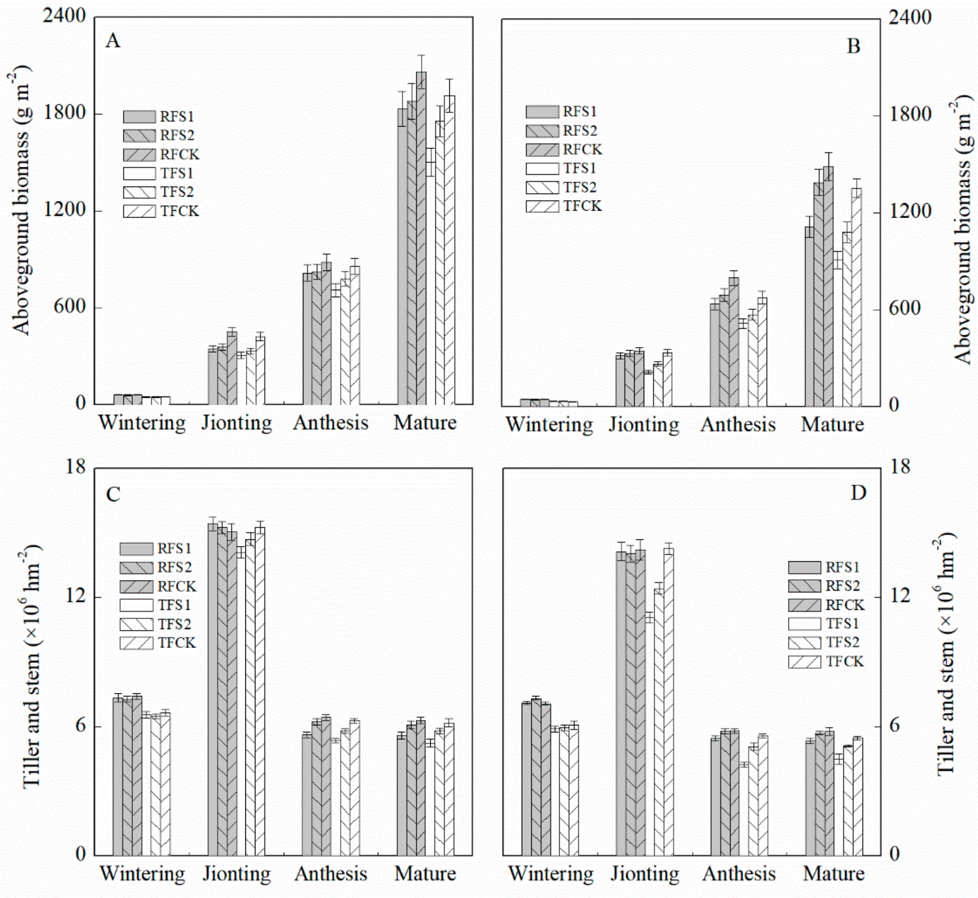

Figure 4. Effects of planting and irrigation on the aboveground biomass ((**A**): 2016–2017, (**B**): 2017–2018) and the tiller and stem number ((**C**): 2016–2017, (**D**): 2017–2018) during the wheat growth period. RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation. Vertical bars represent ± the standard deviation of the mean (n = 3).

The planting methods and irrigation treatments notably affected the root growth. SIMSM significantly ($p < 0.05$) decreased the root biomass in the 2 m soil layer, and it was significantly ($p < 0.05$) lower in the S1 system than that of the S2 system (Figure 5A,B). RF method of planting significantly ($p < 0.05$) increased the root biomass in the 2 m soil layer under the SIMSM system. However, it had no significant ($p > 0.05$) effect on the root biomass in the traditional irrigation system (200 mm irrigation amount).

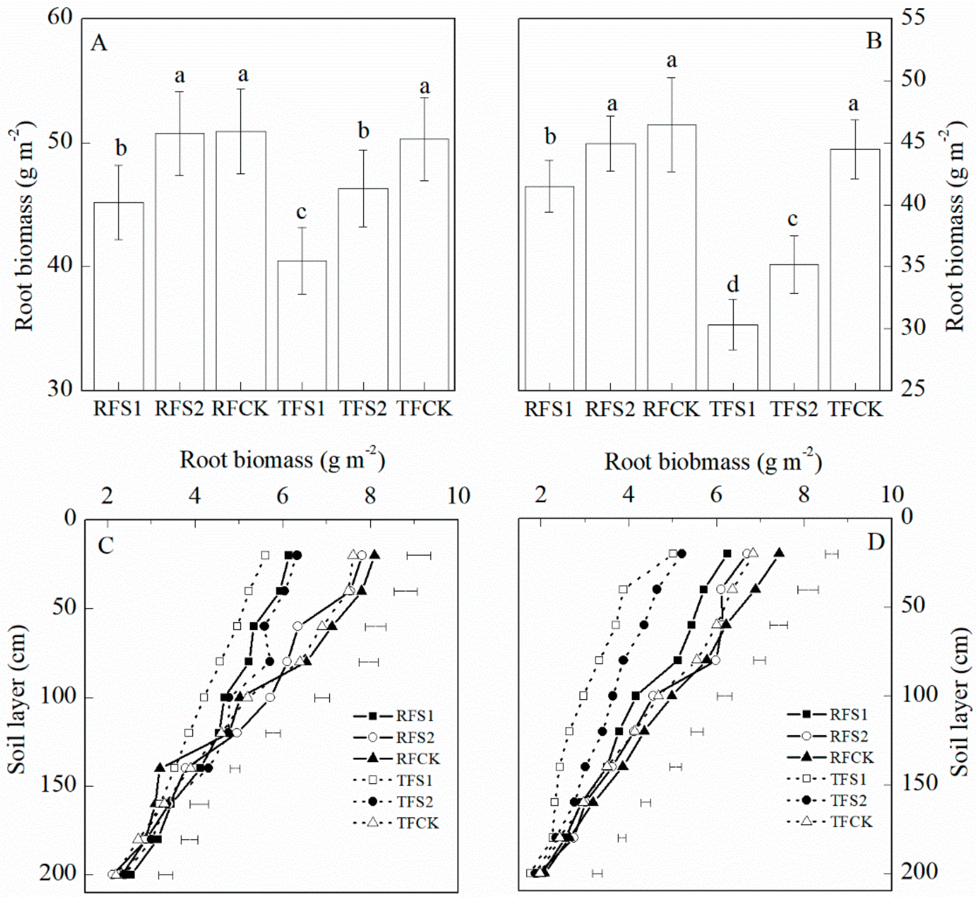

Figure 5. Effects of planting and irrigation on the root biomass at the stage of maturity. (**A**,**B**) The total root biomass under 0–200 cm soil layer, in 2016–2017 and 2017–2018, respectively. (**C**,**D**) The root biomass in 20 cm increments in the 0–200 cm soil layer, in 2016–2017 and 2017–2018, respectively. In (**A**,**B**), vertical bars represent ± the standard deviation of the mean ($n = 3$). Values followed by different letters are significantly different at $p = 0.05$. In (**C**,**D**), horizontal bars represent the honestly significant difference at $p = 0.05$. RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation.

The effects of irrigation and RF on root biomass were dependent on soil depth (Figure 5C,D). They had no significant ($p > 0.05$) effect on root biomass in the 160–200 cm soil layer. In the case of irrigation treatments, the values of root biomass in the 0–80 cm soil layer of the S1 and S2 treatments were 25.74% (24.73%) and 11.18% (15.74%) lower than those of the traditional irrigation (CK; the average of RF and TF) in 2016–2017 and 2017–2018, respectively. However, in the 100–140 cm soil layer they were less by only 6.51% (13.64%) and 6.06% (9.37%) in 2016–2017 and 2017–2018, respectively. The effect of RF followed a similar trend. The root biomass values in the 0–80 cm soil layer of the RF system were 10.89% and 28.44% higher than those of TF in 2016–2017 and 2017–2018, respectively.

However, in the 100–140 cm soil layer they were higher by only 4.75% and 13.90% in 2016–2017 and 2017–2018, respectively.

3.3. Grain Yield and Quality

Overall, RF improved grain yield as compared to TF, and the SIMSM reported lower yield as compared to the traditional method of irrigation (Table 2). A similar trend was observed in the case of yield components; namely, spikes per unit area, spikelets per spike, and 1000-kernel weight. The interaction between the planting system and methods of irrigation was found to be significant on the grain yield. In the first year of experimentation (2016–2017), the RF system produced a significantly higher grain yield than the TF system under the SIMSM system, but it had no significant effect on the grain yield under the traditional irrigation system. However, the RF system significantly increased grain yields under both SIMSM and the traditional irrigation system in the year 2017–2018. Under the TF method of planting, there was a significant decrease in the grain yield under SIMSM system during the two years. However, under the RF system, the grain yield of the S2 treatment was not significantly different from that of the CK treatment.

Table 2. Effect of two planting systems (RF and TF) and three irrigation levels (S1, S2, and CK) on the grain yield of wheat.

Year	Planting	Irrigation	No. of Spikes ($\times 10^6$ ha^{-1})	No. of Spikelets per Spike	1000-Kernel Weight (g)	Grain Yield (t·ha^{-1})
2016–2017	RF	S1	5.59 ed	37.58 c	40.33 bcd	7.13 b
		S2	6.08 ab	40.24 ab	42.51 ab	7.84 a
		CK	6.29 a	41.96 a	43.31 a	8.06 a
	TF	S1	5.26 ef	33.22 d	35.67 e	5.54 de
		S2	5.81 b	39.09 bc	41.41 abcd	7.04 b
		CK	6.18 a	41.43 a	42.40 ab	7.89 a
2017–2018	RF	S1	5.33 de	29.18 e	39.71 cd	5.13 e
		S2	5.70 bc	32.56 d	41.42 abcd	5.84 cd
		CK	5.78 bc	34.28 d	41.56 abcd	6.02 c
	TF	S1	4.49 g	21.62 f	39.10 d	3.44 f
		S2	5.11 f	27.16 e	40.13 bcd	4.90 e
		CK	5.48 cde	32.73 d	41.83 abc	5.73 cd
	F-Value	Year (Y)	**	**	ns	**
		Planting (P)	**	**	*	**
		Irrigation (I)	**	**	**	**
		Y × P	**	ns	ns	ns
		Y × I	ns	ns	ns	**
		P × I	*	ns	ns	**
		Y × P × I	ns	ns	ns	**

Values within a column followed by different letters are significantly different at $p = 0.05$. * and **: F-values significant at the $p = 0.05$ and 0.01 level, respectively. RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation. The irrigation was given at the wintering and jointing stages of crop growth, respectively.

SIMSM significantly improved the grain protein and wet gluten concentrations of the wheat under both systems of planting (Table 3). However, RF had no significant ($p > 0.05$) effect on grain protein and wet gluten concentrations. In addition, the treatments had no significant ($p > 0.05$) effect on the absorption, volume weight, and flour yield of wheat grain.

Table 3. Effect of two planting systems (RF and TF) and three irrigation levels (S1, S2, and CK) on the grain quality of wheat.

Year	Planting	Irrigation	Protein	Wet Gluten	Absorption	Volume Weight	Flour Yield
			%	%	%	$g{\cdot}L^{-1}$	%
2016–2017	RF	S1	14.13 a	31.25 abc	64.80 a	789.71 a	71.05 a
		S2	13.55 bc	30.78 bc	64.00 a	800.61 a	72.54 a
		CK	13.12 d	27.73 d	64.73 a	803.69 a	72.33 a
	TF	S1	13.99 a	31.21 abc	64.57 a	802.18 a	71.57 a
		S2	13.63 b	30.27 c	65.23 a	796.15 a	72.33 a
		CK	13.12 d	26.81 d	63.43 a	803.60 a	73.35 a
2017–2018	RF	S1	14.03 a	32.28 a	63.79 a	794.06 a	71.02 a
		S2	13.94 a	32.25 a	65.12 a	802.43 a	72.34 a
		CK	13.24 cd	27.61 d	64.63 a	806.36 a	70.93 a
	TF	S1	14.15 a	32.06 ab	63.12 a	796.23 a	71.25 a
		S2	13.95 a	31.94 ab	64.03 a	803.24 a	72.35 a
		CK	13.22 d	28.10 d	62.75 a	794.52 a	70.46 a
	F-Value		**	**	ns	ns	ns
			ns	ns	ns	ns	ns
			**	**	ns	ns	ns
			ns	ns	ns	ns	ns
			**	ns	ns	ns	ns
			ns	ns	ns	ns	ns
			ns	ns	ns	ns	ns

Values within a column followed by different letters are significantly different at $p = 0.05$. **: F-values significant at the $p = 0.01$ level. RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation. The irrigation was given at the wintering and jointing stages of crop growth, respectively.

3.4. Water and Nitrogen Use Efficiency

Effect of RF system of planting on water use efficiency was influenced by the employed irrigation method. Under the traditional irrigation system, RF had no significant ($p > 0.05$) effect on the WUE, PWUE, and IWUE (Figure 6) compared to the TF. However, under the SIMSM system, RF had a significant ($p < 0.05$) increase in values of these in comparison with TF. SIMSM significantly ($p < 0.05$) increased the valued of WUE and IWUE but decreased that of PWUE under both systems of planting (RF and TF systems).

SIMSM increased the soil NO_3^--N concentration in the upper soil layer while it decreased in the lower soil layer (Figure 7). RF significantly increased the soil NO_3^--N concentration in the 0–20 cm soil layer under the traditional irrigation system. However, it had no significant effect on the soil NO_3^--N concentration in the rest of the soil layers under the present study.

N accumulation in plants and NUE were found to increase with an increase in the amount of irrigation (Figure 8A–D). Under the SIMSM system, the value of these indices was significantly higher in the RF system than the TF system. However, it was not significant under the traditional irrigation system. When these indices were compared in different treatment combinations, the NFP of TFS1 was significantly lower than that of the other treatments in the year 2016–2017. In the last year of experimentation (2017–2018) the NFP of TFS1 was less than that of RFS1, and the NFP of TFS2 was less than those of RFS2, RFCK, and TFCK (Figure 8E,F).

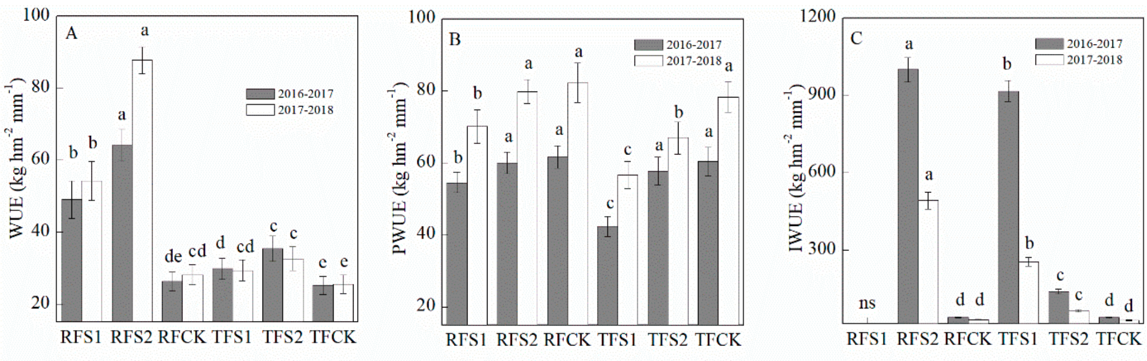

Figure 6. Effects of planting and irrigation on the water use efficiencies of wheat. A, B and C represent WUE, PWUE and IWUE, respectively. RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation. WUE: water use efficiency; IWUE: irrigation water use efficiency; PWUE: precipitation water use efficiency. Vertical bars represent ± the standard deviation of the mean (n = 3). Values followed by different lower letters are significantly different at p = 0.05 in the same year.

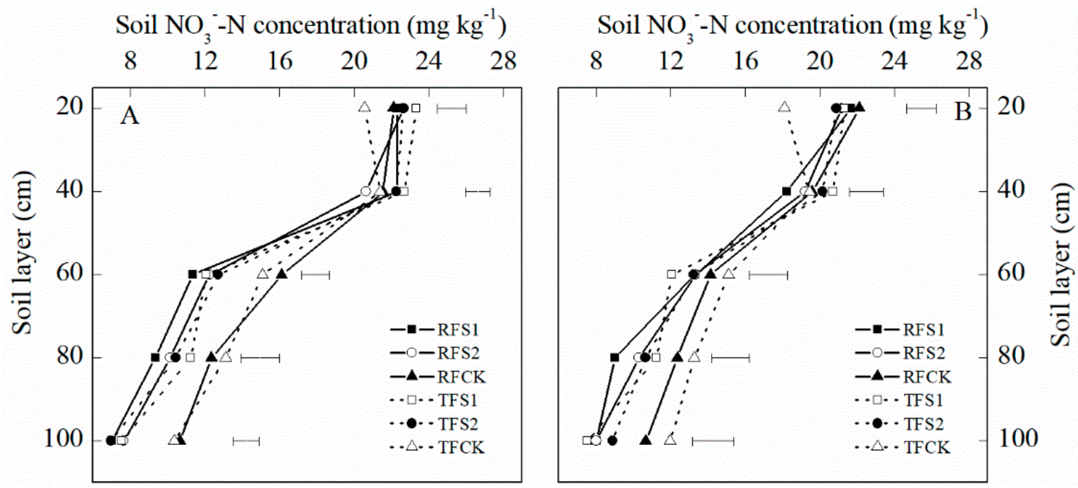

Figure 7. Effects of planting and irrigation on the soil NO_3^--N concentration in 0–100 cm soil layer in 2016–2017 (**A**) and 2017–2018 (**B**), respectively. RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation. Horizontal bars represent the honestly significant difference at p = 0.05.

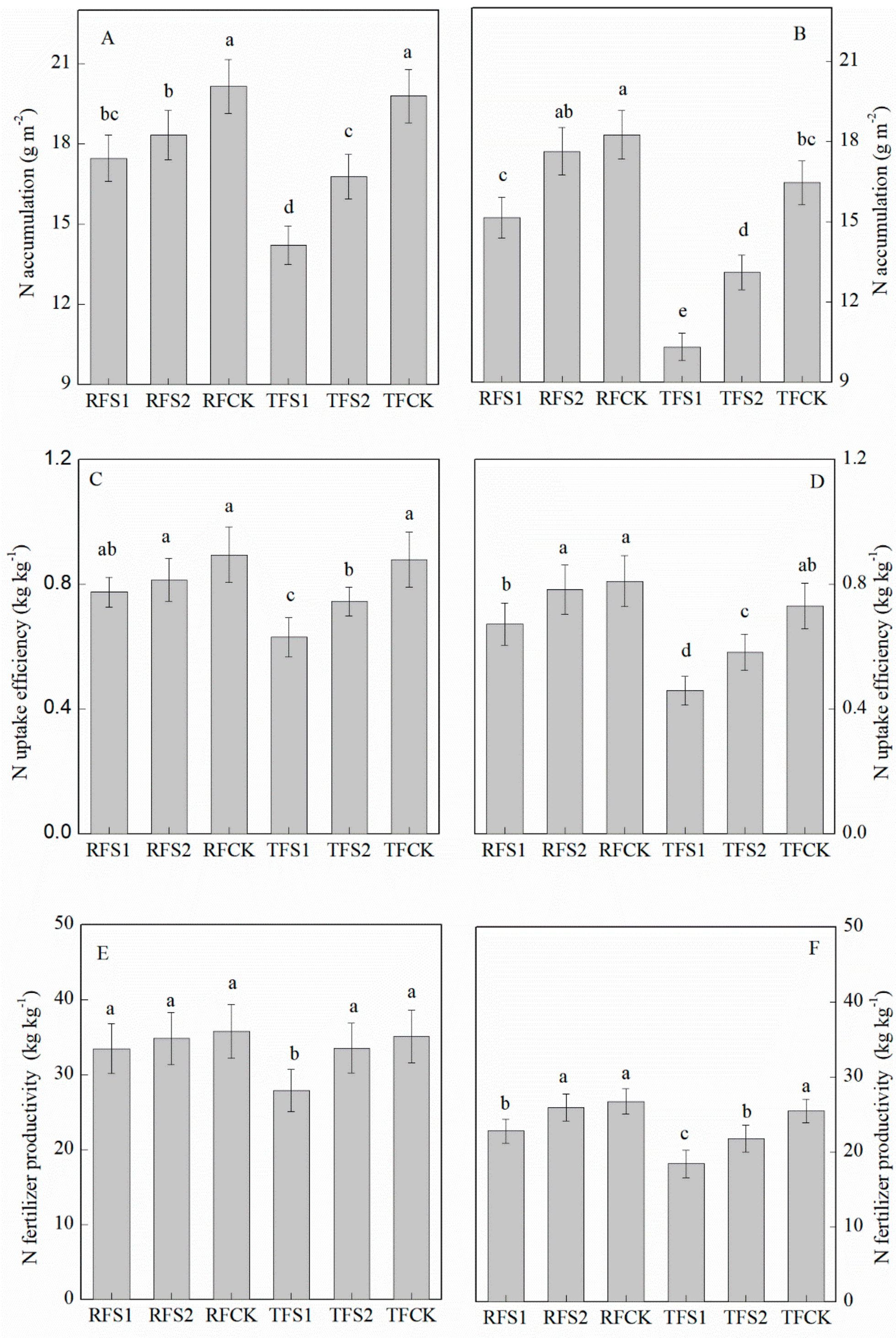

Figure 8. Effects of planting and irrigation on the nitrogen use efficiencies of wheat ((**A**,**C**,**E**): 2016–2017; (**B**,**D**,**F**): 2017–2018). RF: plastic-covered ridge and furrow planting; TF: traditional flatten planting; S1: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 85%; S2: supplemental irrigation based on measuring soil moisture and the target relative soil water content is 100%; CK: traditional irrigation. Vertical bars represent ± the standard deviation of the mean (n = 3). Values followed by different lowercase letters are significantly different at p = 0.05.

4. Discussion

Northern China is a major area of wheat production which faces inconsistent rainfall during growing period of wheat. Therefore, irrigation is essential to achieve high yields [21,22]. At present, the traditional irrigation for wheat is free flooding irrigation, which results in a low WUE and wastage of enormous amounts of irrigation water [5,23]. This scenario necessitates development of irrigation methods that can utilize water efficiently while maintaining high yields for local wheat production [24]. Previous studies have shown that SIMSM is an efficient water-saving irrigation measure. Zhang et al. [8] showed that SIMSM can significantly reduce the use of irrigation water (45.1 to 132.4 mm). Since wheat yields under SIMSM are not significantly different from those under conventional irrigation, they can effectively balance yield and water use targets. At present, the SIMSM technique has been included in the main agricultural promotion measures of the Ministry of Agriculture in China [9]. However, the areas in which SIMSM has been tested and promoted are mainly concentrated on the North China Plain, and its applicability in other regions is still in question. In previous studies, the amount of supplementary irrigation in SIMSM was determined by the soil moisture and target water content [25]. Guo et al. [7] reported that SIMSM could save water and increase yields more effectively when the target relative soil water content (target relative SWC) at 40 cm was 70%. However, the results of this study showed that under conventional flat-tillage conditions, the yields of S1 (with a target relative water content of 85%) were 29.78% ($p < 0.05$) and 39.97% ($p < 0.05$) lower than those of CK (conventional irrigation) in the years 2016–2017 and 2017–2018, respectively. These findings are inconsistent with the results of some previous research [7,8]. In this study, when the target water content was increased to 100% (S2 treatment), the wheat yield was still significantly lower than that of CK but higher than that of S1. Furthermore, the soil water content in the wheat growing season in this study was S1 < S2 < CK ($p < 0.05$). Therefore, the reduction in wheat yield of SIMSM in this study may be related to irrigation and soil water content. On the Loess Plateau, the precipitation during the wheat season is lower than that on the North China Plain, and the amounts of precipitation during the two wheat planting seasons in this study were only 130.69 mm and 73.14 mm. Due to the low rainfall and the small amount of SIMSM in northern China, the soil moisture in the wheat growing season was insufficient to meet the requirements for high yields, consequently resulting in low wheat yields. These results indicate that under the conventional flat-tillage conditions of the Loess Plateau irrigated farming area, SIMSM not only failed to increase but also significantly reduced wheat yield. This also shows that the application of the SIMSM technique needs to be adapted to local climatic conditions and cannot be applied arbitrarily.

RF is a widely used rainwater harvesting planting technique in the rainfed areas of the Loess Plateau. Ren et al. [1] showed that RF can significantly improve the soil water content by effectively concentrating limited rainfall at the plant roots, thereby promoting plant growth and increasing WUE. Daryanto et al. [26] found similar results. Ali et al. [14] reported that RF could significantly improve the utilization of irrigation water and yield of wheat. He observed that yield of wheat under the RF system of planting with supplementary irrigation of 75 mm was equivalent to TF with supplementary irrigation of 150 mm. This study also showed that under the traditional free flooding method of irrigation, there was no significant difference in wheat yield between two planting systems (RF and TF). However, the average soil water content in the 20 cm soil layer in the RFCK treatment was higher than that in the TFCK treatment in the wheat growing season, indicating that RF could significantly increase the surface soil water content by minimizing evaporation of water from the surface of land [27]. Under the condition of traditional free flooding irrigation, RF did not significantly increase the wheat yield, although it increased the soil moisture content and provided the wheat with sufficient water. Therefore, the application of RF has no yield advantage in when traditional free flooding irrigation method is used. Further, the additional cost of RF film incurred lowers its economic feasibility for adoption.

However, compared with traditional free flooding irrigation, RF fully harnesses its water accumulation effect when combined with SIMSM. Although the wheat yield under the S1 treatment was still significantly lower than that of the CK treatment under the RF system, the percentage decrease in wheat yield under S1 compared with CK in the two wheat production seasons was 11.54% and 14.78%, which were smaller than those of the TF system. Additionally, there was no significant difference in wheat yield between the RFS2 treatment and the CK treatment. Therefore, in the irrigated area of the Loess Plateau, the soil moisture content cannot meet the wheat growth requirements, even though the target relative water content was set to 85%, but the RF system efficiently uses precipitation due to its water accumulation effect. Consequently, the soil moisture conditions were significantly improved, and the production of the RFS1 treatment was significantly higher than that of the TFS1 treatment. When the target relative water content was set to 100%, the RF system not only fully exploited its water accumulation effect but also reduced soil water evaporation due to the plastic film mulch, enabling plants to utilize irrigation water efficiently [28]. Thus, a small amount of irrigation water can meet the needs to achieve high wheat yields and can effectively produce high yields while saving water. Although film mulching in the RF system increases the cost of wheat production, it significantly reduces the amount of irrigation and significantly increases the wheat yield. Therefore, the economic benefit of the RFS2 treatment was higher than that of the TFS2 treatment and was almost equal to that of the TFCK treatment (Table 4). In terms of economic efficiency, there was little difference between treatment combination RFS2 and TFCK. Considering the decrease in sources of water [24], coupled with the increase in the demand for industrial and domestic usage [5], the water availability for irrigation might decrease in the future in the Loess Plateau. Therefore, from the perspective of agricultural sustainability, the combination of RF and SIMSM might prove promising in irrigated areas on the Loess Plateau. In addition, the results of this study showed that SIMSM could significantly increase the content of protein and wet gluten in wheat seeds, which improved the quality of wheat. Taking into account the fact that the price and economic benefit of high-quality wheat are significantly higher than that of conventional wheat, this quality improvement increased the economic benefit of wheat production and achieved the combination of high yields and high quality. Some studies also believe that plastic film can cause white pollution, which limits the application of plastic film coverage in agriculture [26]. However, with the progress of science and technology, degradable plastic film, liquid plastic film, and other new eco-friendly plastic films are available which can be applied in production [29–32]. The application of these new types of plastic film reduces the environmental pollution caused by the degradation of plastic film cover and will play a good role in promoting the application of plastic film in agriculture.

Table 4. Economic benefits of two planting systems and three irrigation levels.

Year	Planting	Irrigation	LC	IW	MC	AM	TIV	TOV	NI
			Yuan/ha	Yuan/ha	Yuan/ha	Yuan/ha	Yuan/ha	Yuan/ha	Yuan/ha
2016–2017	RF	S1	600	0	3000	3500	7100	14,260	7160
		S2	1200	78	3000	3500	7778	15,680	7902
		CK	1500	2000	3000	3500	10,000	16,120	6120
	TF	S1	1500	60	2000	2500	6060	11,080	5020
		S2	1500	538	2000	2500	6538	14,080	7542
		CK	1500	2000	2000	2500	8000	15,780	7780
2017–2018	RF	S1	600	0	3000	3500	7100	10,260	3160
		S2	1500	119	3000	3500	8119	11,680	3561
		CK	1500	2001	3000	3500	10,001	12,040	2039
	TF	S1	1500	161	2000	2500	6161	6880	719
		S2	1500	739	2000	2500	6739	9800	3061
		CK	1500	2000	2000	2500	8000	11,460	3460

LC: labor cost; IW: irrigation water; MC: mechanical cost; AM: agricultural materials, including fertilizers, pesticides, plastic mulch, and seeds; TIV: total investment; TOV: total output; NI: net investment.

Previous studies suggest that SIMSM can promote the accumulation of dry matter in plants and increase grain yield by significantly increasing plant photosynthesis and improving the transfer of non-structural carbohydrates to grains [10–13]. In addition, the results show that the accumulation of dry matter and the tiller and stem numbers of S1 and S2 plants were significantly lower than those of CK, which indicated that the SIMSM system limited the growth of the wheat plants in the irrigated areas of the Loess Plateau due to water limitations. The possible cause is that the SIMSM system reduced wheat production under normal conditions. Simultaneously, the results of this study showed that the dry matter accumulation and the number of tillers in wheat were significantly lower in the last year of experimentation (2017–2018) than those in the previous year (2016–2017). One of the possible causes is that the rainfall during the growth stage of winter wheat in the year 2017–2018 was lower than that in 2016–2017, which resulted in a further decrease in soil moisture. In addition, the occurrence of late spring cold conditions in the growing season of 2017–2018 was also an important factor attributing low yield. The late spring cold conditions occurred on 8 April 2018 and dropped the temperature to below 1 °C at 02:00 a.m. and below 0 °C between 03:00 a.m. and 7:40 a.m. The sudden drop in temperature caused a large number of spikelets and florets to degenerate or die, significantly reducing the number of spikes [33]. Moreover, the results of this study also show that the number of grains in 2017–2018 was 23.72% ($p < 0.05$) lower than that in 2016–2017. In addition to rainfall, these late spring cold conditions may be another major cause for this difference. Further, the results of this study showed that the number of spikes in S1 and S2 was 17.83% and 2.82% lower than the number of spikes in CK under TF conditions in 2016–2017. However, they were lowered by 33.94% and 17.02% in 2017–2018, indicating a significant decline. Liu et al. [34] showed that soil moisture significantly influenced the impact of late spring cold conditions on grain number and that soil drought aggravated the deterioration of wheat spikelets and florets caused by late spring cold conditions. This duo of stress may be an important reason for the huge decline in the number of grains in treatments S1 and S2 in the last year of experimentation as compared to the decline which occurred in the previous year in the aforementioned treatments of irrigation. Furthermore, the magnitude of the difference between the numbers of grains reported in different treatments of irrigation (S1, S2, and CK) was larger under the RF system than that in the TF system; however, the difference in the decline was less in the second quarter. The number of grains per spike in RFCK was lowered by 10.44% and 4.10% as compared to RFS1 and RFS2, respectively, in 2016–2017 and by 14.88% and 5.02%, respectively, in 2017–2018. The difference between the two seasons was not significant. This observation indicates that the RF system may help wheat resist the damage to developing spikelets induced by cold conditions in late spring. The reasons are as follows: on the one hand, RF increases the soil water content; on the other, it significantly increases soil temperature, which may have a vital role in protecting the root system [35] and alleviating the adverse effects of late spring cold conditions. In addition, previous studies have shown that RF can influence the growth process of plants [36]. Deng et al. [37] found that the effects on the development of wheat spikelets and florets are greatest during the interstitial period. However, the effect of RF on the growth process of plants may allow some wheat plants to avoid the influence of late spring cold conditions. Therefore, in the irrigated areas of the Loess Plateau, the application of only SIMSM may result in the risk of being damaged by the onset of late spring cold conditions, but it can be mitigated by using SIMSM and RF in combination. This combination is beneficial for improving stress resistance and achieving stable yields in wheat.

In addition to water, nutrients are also one of the major factors affecting crop production [38]. Improving the utilization rate of nitrogen fertilizer and promoting its absorption are of vital importance for the efficient production of wheat [39]. The results of this study show that the SIMSM system has a negative effect on NA, NUE, and NFP in both systems of planting (TF and RF). This impact may be due to reductions in the soil water content associated with SIMSM, which are not conducive for the absorption of nitrogen [7]. Additionally, this study found that SIMSM reduced the root biomass of plants, especially in the upper layer. Under the conditions of rotary tillage, the nitrogen fertilizer applied is mainly concentrated in the 0–40 cm soil layer [40]. The results also showed that the content of NO_3-N in the upper soil layer was significantly higher than that in the lower layer. The root system is the primary organ for nitrogen uptake. The SIMSM-induced inhibition of root growth for wheat, especially in the upper soil layer, reduced the nitrogen uptake capacity of the wheat resulting in decreased NA and NUE. Under the SIMSM system, RF had significantly higher values of NA, NUE, and NFP than TF. The reason being, RF significantly increased the soil water content, which was conducive for nitrogen uptake by roots. Moreover, under the SIMSM system, RF significantly promoted root development and increased root biomass, which increased the efficiency of not only water absorption but also uptake and utilization of nitrogen from the soil. As a result of these improvements, NUE and NFP increased.

5. Conclusions

Due to the low rainfall in the irrigated farming area of the Loess Plateau, SIMSM alone inhibited the growth of wheat under the traditional TF conditions, reduced the wheat production, and the value of indices used for measuring nitrogen use efficiency by crop, namely NUE and NFP. These impacts can negatively influence the objective to achieve high yield in wheat. However, it promoted the grain protein and wet gluten content of wheat. When the target relative water content is set at 100%, SIMSM in combination with RF can significantly reduce the amount of irrigation water used without imposing a yield penalty. Simultaneously, the WUE, grain protein, and wet gluten content of wheat are significantly increased. Thus, the collaborative use of RF and SIMSM (the target relative water content is set at 100%) can promote the high yield, high quality, and high efficiency of wheat production, and has good application prospects in the irrigated areas of the Loess Plateau where relatively low rainfall is received which consequently results in limited availability of irrigation water.

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