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Optimal Ridge–Furrow Ratio for Maximum Drought Resilience of Sunflower in Semi-Arid Region of China

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Abstract: Ridge–furrow planting is often applied in semi-arid regions to reduce the drought risk on crop yield under rain-fed conditions. Sunflower (*Helianthus annuus* L.) is widely planted in northern China and how to reduce the drought risk on sunflower production remains a significant issue. A three-year field experiment with seven treatments (a flat plot without mulching, three plastic film-mulching treatments and three non-film-mulching treatments with different ridge–furrow ratios (1.0 m:1.0 m, 1.0 m:0.5 m and 0.5 m:1.0 m)) was conducted to study the effects of the ridge–furrow rainwater harvesting system on the rain-fed sunflower. The results showed that the sunflowers in the film-mulched treatment with the larger ridge–furrow ratio (1.0 m:0.5 m) (M1R2) had greater growth advantage under drought conditions. In the dry year, M1R2 improved the yield and water use efficiency by 11.9%–107.5% and 13.8%–120.6%, respectively, and reduced the blight grain rate by 21.5%–32.5% with less evapotranspiration (ET) compared to other treatments. Based on the historical climatological data, the guarantee rate of sunflower water requirement for M1R2 was about 75%, while the guarantee rates for the other two film-mulched treatments were only about 40% and 50%. Based on the effects of drought resilience and the characteristics of precipitation, M1R2 is recommended to be the relatively optimal treatment for sunflower production in regions with similar climatic conditions to Wuchuan County in northern China.

Keywords: ridge–furrow rainwater harvesting system; plant biomass; leaf area index; soil water storage

1. Introduction

Crop growth and production in the semi-arid regions of China are restricted severely by water availability due to limited surface or ground water resources and limited rainfall with uneven temporal and spatial distribution [1–4]. The rising air temperature and more frequent and intense precipitation extremes have been observed and predicted under climate change projections in the northwestern semi-arid region of China [5–7]. This region has become warmer and drier with less groundwater resources [8–10], and the increasing variation of precipitation has led to fluctuating grain productions [11]. The projected changes of climate conditions increase the risks in rain-fed agricultural production [12]. To adapt to the warming and drying climate, highly effective utilization of precipitation is crucial for agricultural production in semi-arid areas.

The ridge–furrow rainwater harvesting system (RFRHS) has been proved to be an effective method to save water and increase water-use efficiency (WUE). The RFRHS usually results in high yields and high soil moisture; previous results showed that it improved the WUE of maize [13] by 9.2%, wheat [14] by 12%, potatoes [15] by 30% and alfalfa [16] by 70%. This is because that the RFRHS can change the

micro-topography and thus cause the rain water redistribution in the field [17,18], and a mulched ridge can reduce evaporation and enhance soil temperature in the early growing season [19]. Due to its water retention and increments in yield, the RFRHS has been an important farming management measure for improving water use efficiency (WUE) and alleviating water shortages and has been widely used in the Loess Plateau and northwestern China [20–22].

The previous studies have shown that the ridge–furrow ratio and mulches are two major factors that impact crop yield, evapotranspiration (ET) and WUE in RFRHS [23–26]. For example, the optimal ridge–furrow ratio of Alfalfa was 35–36 cm:60 cm [27]. However, few studies have focused on the effects of RFRHS on oil seed crops like sunflower, not to mention optimal ridge–furrow ratio. As an important cash crop, sunflower is widely cultivated in semi-arid regions of northern China and is the second major oil seed crop in China. It is significant to study whether and how the RFRHS could efficiently improve the yield of the sunflower in semi-arid regions. In addition, previous studies mainly discussed the optimal RFRHS derived from a statistical approach [28–30]. The reduction of planting density caused by a wide ridge of RFRHS and whether the reduction would result in a decrease of total crop yield in some years were not discussed. However, decreasing planting density properly is necessary for increasing the drought resilience of crops in semi-arid regions during dry years.

The objective of this study was to examine the effects of ridge–furrow ratio in RFRHS on the sunflower growth and yield and to recommend the optimal ridge–furrow ratio for ensuring and stabilizing the sunflower yield in the semi-arid region, China.

2. Materials and Methods

2.1. Study Region

This study was conducted at the Scientific Experimental Station of Agro-environment (41°08′22.8″ N, 111°17′43.6″ E) in Wuchuan County, Inner Mongolia, which lies in the semi-arid region of northern China with typical temperate continental climate conditions [31]. Its elevation above sea level is 1589 m. The average annual precipitation is about 348 mm and 85.7% of which occurs from May to September with an uneven temporal–spatial distribution [32,33], and the average growth-period rainfall during 1961–2015 was 294.7 mm (Figure 1). The rainfall during the growth period (May–September) from 2013 to 2015 was 414.9 mm, 366.1 mm and 307.5 mm, respectively. In 2015, there was a severe drought in August, when the sunflower was in the flowering and maturity stage which are the critical stages of sunflower growth. Therefore, we defined 2015 as a dry year, and accordingly defined 2013 and 2014 as rainy years in this study. The soil type is chestnut soil (Haplic Krastazem, FAO) with a pH of 8.5, organic C of 10.3 g·kg^{−1}, N of 0.79 g·kg^{−1}, P of 0.45 g·kg^{−1}, and K (total potassium) of 2.45 g·kg^{−1}.

Figure 1. Monthly mean temperature (°C) and rainfall (mm) in May–September in 2013, 2014, 2015, and the long-term (1961–2010) averages at the experimental station.

2.2. Experimental Design

This study focused on the ridge–furrow rainwater-harvesting system (RFRHS) in a sunflower field. A field experiment with seven treatment combinations was conducted in 2013–2015 (Figure 2), including control check (CK, a flat plot without mulching), plastic film-mulched with three ridge–furrow ratios treatments (M1R1 (1.0 m:1.0 m), M1R2 (1.0 m:0.5 m) and M1R0.5 (0.5 m:1.0 m)), and non-film-mulched with three ridge–furrow ratios treatments (M0R1 (1.0 m:1.0 m), M0R2 (1.0 m:0.5 m) and M0R0.5 (0.5 m:1.0 m)).

The experiments were in a randomized complete block design with three replicates for each treatment each year. Each plot was 8 m long and 6 m wide. The height of ridge was approximately 0.25 m, and the ridge surface was arched with a slope angle of approximately 40° (Figure 2). Sunflowers were planted in the furrows with the same row spacing (0.5 m) and plant distance in a row (0.5 m).

Figure 2. The different experimental ridge–furrow ratio treatments and the measuring points of soil moisture.

Fertilizer was applied to all the experiment plots before sowing with ammonium dihydrogen phosphate ($75 \text{ kg} \cdot \text{ha}^{-1}$), urea ($90 \text{ kg} \cdot \text{ha}^{-1}$) and potassium chloride ($60 \text{ kg} \cdot \text{ha}^{-1}$), and no extra fertilizer was applied during the sunflower growth period. Sunflowers were sown in mid-May and harvested at the end of September each year. During the experiment, there was only one tillage before sowing and the stubble was retained in winter each year.

The soil moisture (10–100 cm) in every 10 cm layer was measured by a neutron probe (CPN-503DR). The oven drying method was used to measure the 0–10 cm soil moisture and calibrate the 10–100 cm soil moisture. The locations of measuring points were shown in Figure 2. The soil moisture in the ridges of M1R0.5 and M0R0.5 were not measured because the ridges were too narrow to setup the instrument. In order to protect the film on the ridge (M1R1 and M1R2), the 0–10 cm soil moisture was not measured in these treatments.

Dry biomass and leaf area were measured biweekly from the seedling stage. Three adjacent plants of each plot were measured as samples each time. Dry biomass was measured with the oven drying method (105°C for 30 min, then 80°C for 8h) and represented as dry-matter mass per plant (g/plant) in each plot. The plant leaf area was measured with the LI3000C when sampling. For yield measurement, 1/3 plants in each plot were collected at harvest time each year. The crop yield, hundred-grain weight,

and blight grain rate were measured after drying. The crop yield data in 2013 were missing because all the sunflowers suffered wind damage.

2.3. Calculation Method

The total soil water storage (SWS, mm) at each measured point was calculated as Equation (1) [31]:

$$SWS = \sum_{i=1}^n (0.1\rho_i\theta_i h_i), \quad (1)$$

where n is the number of soil layers, $\rho_i\theta_i$ and h_i are the soil bulk density ($\text{g}\cdot\text{cm}^{-3}$), gravimetric soil water content (%), and soil layer thickness (cm) in the soil layer i , respectively.

The leaf area index (LAI) is calculated as the equation below:

$$\text{LAI} = \frac{\text{leaf area (m}^2\text{)}}{\text{area per plant (m}^2\text{)}}. \quad (2)$$

We calculated the evapotranspiration (ET, mm) of the film-mulched treatments by Equation (3), and calculated the ET of the no-mulched treatments and CK by Equation (5) [26]:

$$ET = P_f \times \frac{N_2}{N_1 + N_2} + SW_0 - SW_1, \quad (3)$$

$$P_f = P + E_r \frac{N_1}{N_2} P, \quad (4)$$

$$ET = P + SW_0 - SW_1, \quad (5)$$

where P_f is the precipitation in the planted furrows (mm); P is precipitation during the growth period (mm); N_1 and N_2 are the ridge width (m) and the furrow width (m) respectively; SW_0 and SW_1 are soil water storages (mm) when sowing and harvesting, respectively; E_r is the runoff coefficient.

Water use efficiency (WUE, $\text{kg}\cdot\text{mm}^{-1}\cdot\text{ha}^{-1}$) is the ratio of the unit area yield (Y , $\text{kg}\cdot\text{ha}^{-1}$) to the ET (mm) [34]:

$$WUE = Y/ET. \quad (6)$$

The precipitation guarantee rate is an important index of the yield guarantee rate of water requirement. Sorting the historic annual precipitation in descending order, the precipitation guarantee rate could be calculated as Equation (7) [35].

$$P_{gr} = N \cdot 100\% / (n + 1) \quad (7)$$

where P_{gr} is the precipitation guarantee rate, N is the sequence number of the annual precipitation in descending order; n is the sample size of the annual precipitation sequence.

2.4. Statistical Analyses

Analyses of variance was conducted using SPSS17.0 to compare the effects of RFRHS. Least significant differences (LSD) were used to detect the mean differences between the treatments. In all cases, $p < 0.05$ was used to determine the significance.

3. Results

3.1. The Effects of Different Treatments on Plant Growth

The variations in average plant biomass per area (Ba) and plot leaf area index (LAI) during the growth period are shown in Tables 1 and 2. As shown in Table 1, Ba in the film-mulched treatments were greater than that in non-mulched treatments and the CK. Among the three film-mulched treatments, the Ba of M1R0.5 increased by 31%~70% compared to the CK, better than that of M1R1 and M1R2 in 2013 and 2014 (rainy years). However, in 2015, the Ba of M1R2 was greater than that of M1R1 and M1R0.5 in August (82–112 days after sowing) when a severe drought happened.

Table 1. The average plant biomass per area (Ba, g·m⁻²) under the different rainwater harvesting treatments during 2013–2015.

Growth Stage	Elongation Stage				Squaring Stage				Flowering and Filling Stage			
2013 days after sowing	46				58				90			
M1R1	52	ab			265	a	625	ab	922	bc		
M0R1	49	abc			189	b	593	ab	795	cd		
M1R2	44	bc			234	ab	577	ab	909	bc		
M0R2	36	c			193	b	516	b	674	d		
M1R0.5	59	a			276	a	754	a	1178	a		
M0R0.5	46	ac			252	a	705	a	1067	ab		
CK	48	abc			198	a	573	ab	893	bc		
2014 days after sowing	37				51				65			
M1R1	7.6	b	80	bc	343	ab	538	ab	832	ab	896	bc
M0R1	6.7	b	63	c	218	cd	454	bc	550	c	722	cd
M1R2	6.9	b	71	c	313	abc	593	ab	936	a	1021	ac
M0R2	6.5	b	48	c	160	d	309	c	505	c	618	d
M1R0.5	13.3	a	110	a	385	a	700	a	1012	a	1182	a
M0R0.5	9.5	ab	104	ab	297	abc	472	bc	603	bc	652	cd
CK	6.0	b	77	bc	272	bc	516	b	630	bc	696	cd
2015 days after sowing	35				50				65			
M1R1	2.9	b	31	ab	138	a	428	a	672	ab	691	ab
M0R1	2.1	c	13	c	75	b	232	b	305	c	380	c
M1R2	2.7	b	28	b	142	a	474	a	756	a	733	a
M0R2	1.5	d	12	c	57	b	198	b	286	c	344	c
M1R0.5	3.7	a	38	a	162	a	466	a	592	b	576	b
M0R0.5	2.3	c	16	c	75	b	222	b	328	c	349	c
CK	2.3	c	15	c	74	b	257	b	346	c	298	c

Note: values within a column and in one year with different letters were significantly different ($p < 0.05$).

For all treatments, the LAI at the same development stage in 2013 were greater than those in 2014 and then greater than those in 2015 (Table 2). There were no significant differences in LAI among all treatments in 2013. In 2014 and 2015, the film-mulched treatments improved LAI greatly relatively to non-mulched treatments and the CK. In the pre-growth stage, the LAI of M1R0.5 was greater than that of M1R1 and M1R2, but in the filling stage, the LAI of M1R2 was the largest. The LAI of M1R2 increased by 168%~197% compared to the CK in 2014 and 2015, which means that M1R2 could improve the crop yield compare to the CK.

Table 2. The leaf area index (LAI) under the different rainwater harvesting treatments in 2013–2015.

Growth Stage	Elongation Stage				Squaring Stage				Flowering and Filling Stage			
2013 days after sowing	46				58				90			
M1R1	0.45	ab			1.87	a	2.41	ab	2.56	a		
M0R1	0.41	abc			1.51	a	2.22	abc	2.33	a		
M1R2	0.37	bc			1.93	a	2.41	bc	2.61	a		
M0R2	0.33	c			1.65	a	1.95	c	2.18	a		
M1R0.5	0.50	a			1.97	a	2.46	a	2.69	a		
M0R0.5	0.42	abc			1.76	a	2.27	abc	2.42	a		
CK	0.41	abc			1.77	a	2.40	abc	2.52	a		
2014 days after sowing	37				51				80			
M1R1	0.09	b	0.73	ab	1.44	ab	1.50	ab	1.28	ab	0.72	a
M0R1	0.06	b	0.59	ab	0.87	cd	1.17	bc	0.84	c	0.39	bc
M1R2	0.07	b	0.64	ab	1.30	ab	1.54	ab	1.46	a	0.83	a
M0R2	0.07	b	0.40	b	0.74	d	0.88	c	0.78	c	0.38	bc
M1R0.5	0.14	a	0.93	a	1.55	a	1.88	a	1.58	a	0.62	ab
M0R0.5	0.09	b	0.90	a	1.23	ab	1.29	bc	0.89	c	0.36	bc
CK	0.10	ab	0.67	ab	1.16	bc	1.33	b	0.98	bc	0.31	c
2015 days after sowing	35				50				82			
M1R1	0.03	b	0.21	b	0.65	a	1.10	a	0.89	a	0.60	ab
M0R1	0.02	c	0.09	c	0.31	b	0.61	b	0.42	b	0.31	bc
M1R2	0.03	b	0.20	b	0.65	a	1.09	a	1.00	a	0.67	a
M0R2	0.01	d	0.09	c	0.28	b	0.56	b	0.42	b	0.23	c
M1R0.5	0.04	a	0.27	a	0.69	a	1.09	a	0.88	a	0.35	bc
M0R0.5	0.02	c	0.12	c	0.36	b	0.59	b	0.42	b	0.26	c
CK	0.02	c	0.11	c	0.34	b	0.68	b	0.50	b	0.23	c

Note: values within a column and in one year with different letters were significantly different ($p < 0.05$).

3.2. The Effects of Different Treatments on Sunflower Yield

The actual sunflower yield ($\text{kg}\cdot\text{ha}^{-1}$) and yield components are shown in Table 3. The sunflower yields in film-mulched treatments were improved greatly compared with the CK. Yields in non-mulched treatments were not improved significantly compared with the CK. The average crop yield in the film-mulched treatments and non-mulched treatments were $3007 \text{ kg}\cdot\text{ha}^{-1}$ and $2155 \text{ kg}\cdot\text{ha}^{-1}$ in 2014, and were $1638 \text{ kg}\cdot\text{ha}^{-1}$ and $1125 \text{ kg}\cdot\text{ha}^{-1}$ in 2015, respectively. The crop yield of the film-mulched treatments M1R1, M1R2 and M1R0.5 were 18.9%–31.9%, 45.1%–56.9% and 37.2%–49.6% greater than that of the non-mulched treatments with the same ridge–furrow ratio.

Table 3. The actual yield of sunflower ($\text{kg}\cdot\text{ha}^{-1}$) under the different rainwater harvesting treatments in 2013–2015.

Treatments	Yield ($\text{kg}\cdot\text{ha}^{-1}$)	Variation Compared to CK (%)	100-Grain Weight (g)	Variation Compared to CK (%)	Blighted Grain Rate (%)
2013					
M1R1	—	—	17.1 ± 1.0 a	0.9	15.2
M0R1	—	—	16.8 ± 1.4 a	−1.2	16.1
M1R2	—	—	18.4 ± 0.8 a	8.5	17.8
M0R2	—	—	16.8 ± 0.3 a	−0.7	22.3
M1R0.5	—	—	16.8 ± 0.2 a	−0.9	15.6
M0R0.5	—	—	16.8 ± 2.0 a	−0.9	20.6
CK	—	—	17.0 ± 1.3 a	—	15.8

Table 3. Cont.

Treatments	Yield (kg·ha ⁻¹)		Variation Compared to CK (%)	100-Grain Weight (g)	Variation Compared to CK (%)	Blighted Grain Rate (%)
2014						
M1R1	2742 ± 101	bc	22.9	18.1 ± 0.3 ab	58.3	19.5 *
M0R1	2005 ± 423	d	−10.1	13.8 ± 1.2 cd	20.8	22.8
M1R2	2971 ± 26	ab	33.1	19.4 ± 1.5 a	70.2	20.0 *
M0R2	2047 ± 181	d	−8.3	14.8 ± 2.4 bc	29.3	25.6
M1R0.5	3310 ± 154	a	48.3	15.4 ± 1.3 bc	34.7	21.6
M0R0.5	2413 ± 84	bcd	8.1	13.4 ± 0.4 cd	17.5	22.9
CK	2231 ± 233	cd	—	11.4 ± 1.0 d	—	26.9
2015						
M1R1	1628 ± 195	ab	85.4	15.1 ± 0.9 ab	50.9	29.7
M0R1	1234 ± 369	abc	40.6	12.7 ± 1.1 cd	26.8	30.8
M1R2	1822 ± 252	a	107.5	16.3 ± 0.6 a	62.8	23.3 *
M0R2	1161 ± 324	abc	32.2	14.8 ± 0.5 bc	47.3	33.2
M1R0.5	1465 ± 28	abc	66.9	12.7 ± 0.8 bc	27.2	32.8
M0R0.5	979 ± 12	bc	11.5	10.6 ± 1.3 cd	5.8	34.5
CK	878 ± 380	c	—	10.0 ± 0.8 d	—	31.3

Note: Values within a column and in one year with different letters were significantly different ($p < 0.05$). * means this value was significantly different compared to CK ($p < 0.05$).

Among the three film-mulched treatments, the yield of the treatment M1R0.5 was the greatest in 2014 (a rainy year) while the yield of the treatment M1R2 was the greatest in 2015 (a dry year). According to Table 3, the 100-grain weight of the treatment M1R2 was the greatest followed by the treatment M1R1. The differences of the 100-grain weight between all treatments were not significant in 2013 (a rainy year), but M1R2 improved 100-grain weight significantly compared to other treatments except M1R1 in 2014 and 2015. Meanwhile, M1R2 reduced the blight grain rate by approximately 34.5% and 37.9% compared to CK in 2015. In general, the RFRHS showed better positive impacts on sunflower yield in dry year (2015) compared with the rainy years (2013 and 2014) (Table 3).

3.3. The Effects of Different Treatments on Soil Water Storage (SWS)

The average SWS in 2014 was the highest (134 mm) and the average SWS in 2015 was the least (117 mm) (Figure 3). Comparing the variation trends of SWS (10–100 cm) in different treatments, the SWS in the film-mulched treatment with the greatest ridge–furrow ratio (M1R2) was the highest, while the SWS in the non-mulched treatment with the greatest ridge–furrow ratio (M0R2) was lowest. The SWS in M1R2 increased by 10.4%–13.8% compared to the CK in 2013–2015. The SWS in M0R2 reduced by 2.9%–7.0% compared to the CK in 2013–2015. The SWS in film-mulched treatments were 0.4%–13.8% higher than CK in 2013–2015. Before the squaring stage, the significant increases were 24 mm and 17 mm for M1R2 in 2014 and 2015, and the increase was 18 mm for M1R1 in 2014. According to the SWS on sowing day in 2014 and 2015, it could also imply that the film-mulched treatment with a wider ridge (M1R2) stored more water in soil before sowing when the plastic film was mulched during the fallow period (Figure 3).

Compared to the CK, the furrow-SWS in the film-mulched treatments increased (Figure 4a,b) and the ridge-SWS in them decreased in the upper 50 cm soil layer (Figure 4c). The furrow-SWS of the film-mulched treatments performed as M1R2 > M1R1 > M1R0.5. The differences of SWS in each layer between treatments were not significant in 2013, but in 2014 and 2015, the furrow-SWS in M1R2 were significantly increased by 33 mm and 22 mm compared to the furrow-SWS in the CK, respectively, while the differences between the other treatments were not significant.

Figure 3. Soil water content (10–100 cm) (mm) in different treatments during the growth period in 2013–2015. Error bars are the LSD at $p = 0.05$.

Figure 4. Profile of soil moisture in the upper 0–100 cm layer at increments in 10 cm at different observation points in all treatments. The observation points included (a) the point in the middle of the furrow, (b) the point at the ridge–furrow junction and (c) the point in the middle of the ridge. Error bars are the least significant differences (LSD) at $p = 0.05$.

3.4. The Effects of Different Treatments on ET and WUE

In general, ET in the film-mulched treatments decreased significantly comparing with the non-mulched treatments (Table 4). There were no significant differences in ET between the CK and

other treatments in 2013. In 2014, the ET in M1R1, M0R1 and M0R2 were greater than the CK, while the ET in M1R0.5 was less compared to the CK. In 2015, the ET in all the film-mulched treatments decreased compared with the CK. The WUE was determined by the ratio of yield to ET. Table 4 also showed that the WUE in the film-mulched treatments M1R1, M1R2, and M1R0.5 were improved by 36.7%–39.5%, 45.1%–56.9% and 37.2%–49.6%, respectively, compared with non-mulched treatments with the same ridge–furrow ratio. The WUE in M1R1, M1R2 and M1R0.5 increased by 18.9%–92.6%, 31.6%–120.6% and 55.4%–71.0% compared with CK in 2014–2015, respectively. In 2014, a relatively rainy year, M1R0.5 had higher (18.1%–84.0%) WUE than other treatments. However, in the dry year (2015), M1R2 had the greatest WUE which improved WUE by 13.8%–120.6% compared with other treatments.

Table 4. The evapotranspiration (ET) and water-use efficiency (WUE) of sunflower under the different rainwater harvesting treatments in 2013–2015.

Treatments	Precipitation (mm)	ΔW (mm)	ET (mm)	WUE ($\text{kg}\cdot\text{mm}^{-1}\cdot\text{ha}^{-1}$)
2013				
M1R1	414.9	75.1	463.9	—
M0R1	414.9	59.5	474.4	—
M1R2	414.9	57.6	444.8	—
M0R2	414.9	64.2	479.1	—
M1R0.5	414.9	68.8	469.9	—
M0R0.5	414.9	91.0	505.9	—
CK	414.9	60.4	475.3	—
2014				
M1R1	366.1	24.1	371.9 *	7.4 *
M0R1	366.1	16.9	383.0 **	5.2
M1R2	366.1	22.4	364.1	8.2 **
M0R2	366.1	15.9	382.0 **	5.4
M1R0.5	366.1	−10.3	343.6 **	9.6 **
M0R0.5	366.1	−10.4	355.7	6.8
CK	366.1	−6.2	360.0	6.2
2015				
M1R1	307.5	−10.5	281.7 **	5.8 *
M0R1	307.5	−10.1	297.4	4.2
M1R2	307.5	−12.0	275.0 **	6.6 **
M0R2	307.5	−12.1	295.4	3.9
M1R0.5	307.5	−12.3	284.9 *	5.1*
M0R0.5	307.5	−12.9	294.6	3.3
CK	307.5	−14.2	293.3	3.0

Note: * means this value was significantly different from it in the CK ($p < 0.05$), and ** means the different was very significant ($p < 0.01$).

4. Discussion

4.1. The Film-Mulched Treatments Can Improve the Growth of Sunflower Significantly Due to the Higher SWS

The film-mulched treatments improved Y, Ba, LAI and WUE compared with the CK, while the non-mulching treatments did not. This was because film mulching resulted in more runoff to furrow [36], increased soil moisture storage and reduced the evaporation [37,38]. This finding is in accordance with the studies on maize, potatoes and wheat in Shaanxi Province and Gansu Province [33,39–41]. In this study, the film-mulched treatments with a wider ridge (M1R1 and M1R2) increased SWS (Figures 3 and 4) compared to non-mulching treatments and CK, while M1R0.5 did not. A wider ridge with larger drainage area can accumulate and redistribute more rainfall into the furrow, therefore it reduces ineffective evaporation more and has a lower planting density [22]. In this experiment, the plastic film mulching during the fallow period resulted in higher SWS in the film-mulched treatments before sowing. It improved the plant growing condition and even the crop yield. This result was also in accordance with previous research [42].

4.2. The Output of Sunflower Is Determined by Precipitation and Ridge–Furrow Ratio

The film-mulched treatments with larger ridge–furrow ratio boosted growth of single plant, which resulted in greater 100-grain weight (Table 3). As the SWS was higher in M1R2 than other treatments (Figure 3), the single plant growth in M1R2 was boosted the most. In general, the B_a , LAI and crop yield of the film-mulched treatments were higher than the non-mulched treatments with the same ridge–furrow ratio. These results were similar to the results of the studies on maize [43,44], potato [45] and alfalfa [46]. However, the effect of treatments on the plant growth at plot scale were different in years with varied rainfall. In contrast to the above previous studies, treatments with a wider film-mulched ridge did not have greater yields than those with smaller ridges in rainy years. The treatment M1R0.5 had the better performance in rainy years (2013 and 2014), while the treatment M1R2 performed better in the dry year (2015) (Tables 1–3). It means that the growth advantages of the film-mulched treatments were greater in dry years comparing to the CK, especially the growth advantages in the treatments with larger ridge–furrow ratio. The main reason for this was the wider ridge reduced the planting area, and the increment due to the increase of crop production per plant cannot offset the decrease due to the reduction of plant area in rainy years. This result illustrates that the optimal ridge furrow ratio may be different with different precipitation patterns.

In this experiment, a large ridge–furrow ratio meant a small cultivated density, and the varied effects of RFRHS under different precipitation patterns led to the inter-annual changes in sunflower growth and production (Table 3). In 2013, there was comparatively enough rainfall for the water requirement of sunflower (Figure 1). This may result in the non-significant differences between the treatments in 2013 (Tables 1–3). In 2014, the single-plant growing advantage in treatment with wider ridge could not counteract the yield reduction caused by a smaller cultivated area in rainy years. Thus, the sunflower yield and WUE in M1R0.5 were higher than M1R2 (Tables 3 and 4). In August 2015, the rainfall was not enough to satisfy the normal plant growth (Figure 1), and the film-mulched treatment M1R2 with the widest ridge maintained more available soil water and produced the largest crop yield and highest WUE (Tables 3 and 4). It meant that the effect of RFRHS with larger ridge–furrow ratio on the sunflower yield was more effective in dry year. This result was consistent with the review of Bouma et al. [47] which point out that RFRHS is especially effective in low rainfall years. For sunflower at the study region, an appropriate small ridge–furrow ratio film-mulched treatment could have greater crop yield and WUE in rainy years, but a larger ridge–furrow ratio film-mulched treatment is recommended in dry years. Thus, the appropriate ridge–furrow ratio should be determined by considering both the influence of production increasing and the precipitation characteristics.

4.3. The Optimum Ridge–Furrow Ratio for Stable Sunflower Yield

Plant growth and production were closely dependent on precipitation at different growth stages [48]. According to previous studies, the average water requirements of sunflower in the growing season was approximately 400 mm, and the water requirement in seeding stage (mid-to-late May), elongation stage (early June to early July), squaring stage (July), flowering and filling stage (August) and ripening stage (September) was approximately 28 mm, 58 mm, 152 mm, 120 mm and 50 mm, respectively [49]. According to the precipitation guarantee rate, the accumulated frequency of precipitation (Figure 5), the water requirement in crucial stages (squaring stage, flowering and filling stage) could not be met in most years in this and similar semi-arid regions. There is severe drought risk in the study region. Maximizing the resilience of drought is crucial for ensuring the stability of the crop yields at this region. Under dry conditions, the film-mulched RFRHS could improve the effective precipitation markedly [50]. Therefore, the implementation of film-mulched RFRHS is recommended.

Based on the water requirement at each stage, the accumulated frequency of enough precipitation in M1R1, M1R2 and M1R0.5 is about 50%, 75% and 40%, respectively. In this experiment, treatment M1R2 reduced water consumption, greatly improved the WUE in the dry year (Table 4) and improved the yield and the grain quality compared to the CK in the rainy year (2014) and the dry year (2015) (Table 1). In addition, the increase of B_a , LAI and yield in M1R2 in 2015 proved that the treatment M1R2

is more resilient to droughts similar to that in August, 2015. Thus, a large ridge–furrow ratio RFRHS would be more practical for agricultural production in this study region. M1R2 (the film-mulching treatment with the ridge–furrow ratio 1.0 m:0.5 m) could be recommended as a better sunflower rainwater-harvesting pattern in Wuchuan as well as similar climatic regions where the precipitation guarantee rate of 300 mm is below 75% during the sunflower growing season. If the climate in some semi-arid regions is relatively wet, a narrower film-mulching ridge should be considered for farmers. Specifically, when the growth-season precipitation guarantee rate of 320 mm is above 75%, M1R0.5 (the film-mulching treatment with the ridge–furrow ratio 1.0 m:0.5 m) could be recommended in these semi-arid regions.

Figure 5. The precipitation guarantee rate in July, August and the total year.

There were still some deficiencies and limitations in this study. The experiment was conducted under limited precipitation conditions, and the data collected by this experiment were not enough to establish statistical models about the relationship between precipitation and the ridge–furrow ratio. Further study is needed to investigate the quantitative relationship between ridge–furrow ratio and precipitation for the RFRHS extension under various precipitation conditions.

5. Conclusions

In this study, the results of the three-year field experiment confirmed that the rainwater harvesting system with film-mulching and with optimal ridge and furrow ratio is an effective way to improve drought resilience of crops, thus ensure yields in the semi-arid area in northern China. The film-mulched treatments increased the soil moisture, LAI, dry biomass and yield of sunflower. A small ridge–furrow ratio rainwater harvesting system with film-mulching is good for a relatively high yield in a rainy year, while a larger ridge–furrow ratio is recommended in a dry year. The appropriate ridge–furrow ratio should be determined by considering both the effect of production increasing and the precipitation characteristics in the study region. In this study, the film-mulched RFRHS with the ridge–furrow ratio 1.0 m:0.5 m (M1R2) ensured an adequate supply of moisture to maintain and even increase yield. In the regions like Wuchuan where the precipitation guarantee rate of 300 mm is below 75%, the RFRHS M1R2 could be recommended to be an optimal sunflower farming practice. However, when the growth-season precipitation guarantee rate of 320 mm is above 75%, M1R0.5 (the film-mulching treatment with the ridge–furrow ratio 1.0 m:0.5 m) is more proper in these semi-arid regions.

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References

- Li, X.; Gong, J.; Wei, X. In-situ rainwater harvesting and gravel mulch combination for corn production in the dry semi-arid region of China. *J. Arid Environ.* **2000**, *46*, 371–382. [[CrossRef](#)]
- Gong, D.; Shi, P.; Wang, J. Daily precipitation changes in the semi-arid region over northern China. *J. Arid Environ.* **2004**, *59*, 771–784. [[CrossRef](#)]
- Ren, X.; Chen, X.; Jia, Z. Effect of Rainfall Collecting with Ridge and Furrow on Soil Moisture and Root Growth of Corn in Semiarid Northwest China. *J. Agron. Crop Sci.* **2010**, *196*, 109–122. [[CrossRef](#)]
- Ren, X.; Zhang, P.; Chen, X.; Guo, J.; Jia, Z. Effect of Different Mulches under Rainfall Concentration System on Corn Production in the Semi-arid Areas of the Loess Plateau. *Sci. Rep.* **2016**, *6*, 19019. [[CrossRef](#)] [[PubMed](#)]
- IPCC. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; pp. 1–32.
- Wen, X.; Fang, G.; Qi, H.; Zhou, L.; Gao, Y. Changes of temperature and precipitation extremes in China: Past and future. *Theor. Appl. Climatol.* **2016**, *126*, 369–383. [[CrossRef](#)]
- Ju, H.; van der Velde, M.; Lin, E.; Xiong, W.; Li, Y. The impacts of climate change on agricultural production systems in China. *Clim. Chang.* **2013**, *120*, 313–324. [[CrossRef](#)]
- Deng, L.; Wang, W.; Cai, Y.; Hu, A.; Tan, L. Groundwater Diffuse Recharge and its Response to Climate Changes in Semi-Arid Northwestern China. *Terr. Atmos. Ocean. Sci.* **2015**, *26*, 451–461. [[CrossRef](#)]
- Feng, H.; Zhang, M. Global land moisture trends: Drier in dry and wetter in wet over land. *Sci. Rep.* **2015**, *5*, 18018. [[CrossRef](#)]
- Zhang, J.; An, P.; Pan, Z.; Hao, B.; Wang, L.; Dong, Z.; Pan, X.; Xue, Q. Adaptation to a Warming-Drying Trend Through Cropping System Adjustment over Three Decades: A Case Study in the Northern Agro-Pastoral Ecotone of China. *J. Meteorol. Res.* **2015**, *29*, 496–514. [[CrossRef](#)]
- Turner, N.C.; Molyneux, N.; Yang, S.; Xiong, Y.; Siddique, K.H.M. Climate change in south-west Australia and north-west China: Challenges and opportunities for crop production. *Crop Pasture Sci.* **2011**, *62*, 445–456. [[CrossRef](#)]
- Lobell, D.B.; Burke, M.B.; Tebaldi, C.; Mastrandrea, M.D.; Falcon, W.P.; Naylor, R.L. Prioritizing climate change adaptation needs for food security in 2030. *Science* **2008**, *319*, 607–610. [[CrossRef](#)] [[PubMed](#)]
- Eldoma, I.M.; Li, M.; Zhang, F.; Li, F. Alternate or equal ridge–furrow pattern: Which is better for maize production in the rain-fed semi-arid Loess Plateau of China? *Field Crop. Res.* **2016**, *191*, 131–138. [[CrossRef](#)]
- Chakraborty, D.; Nagarajan, S.; Aggarwal, P.; Gupta, V.K.; Tomar, R.K.; Garg, R.N.; Sahoo, R.N.; Sarkar, A.; Chopra, U.K.; Sarma Sundara, K.S.; et al. Effect of mulching on soil and plant water status, and the growth and yield of wheat (*triticum aestivum* L.) in a semi-arid environment. *Agric. Water Manag.* **2008**, *95*, 1323–1334. [[CrossRef](#)]
- Zhao, H.; Wang, R.; Ma, B.; Xiong, Y.; Qiang, S.; Wang, C.; Liu, C.; Li, F. Ridge-furrow with full plastic film mulching improves water use efficiency and tuber yields of potato in a semiarid rainfed ecosystem. *Field Crop. Res.* **2014**, *161*, 137–148. [[CrossRef](#)]
- Gu, Y.J.; Han, C.L.; Fan, J.W.; Shi, X.P.; Kong, M.; Shi, X.Y.; Siddique, K.H.M.; Zhao, Y.Y.; Li, F.M. Alfalfa forage yield, soil water and p availability in response to plastic film mulch and p fertilization in a semiarid environment. *Field Crop. Res.* **2018**, *215*, 94–103. [[CrossRef](#)]
- Carter, D.C.; Miller, S. Three years' experience with an on-farm macro-catchment water harvesting system in Botswana. *Agric. Water Manag.* **1991**, *19*, 191–203. [[CrossRef](#)]

18. Yu, B.; Sombatpanit, S.; Rose, C.W.; Ciesiolka, C.; Coughlan, K.J. Characteristics and modeling of runoff hydrographs for different tillage treatments. *Soil Sci. Soc. Am. J.* **2000**, *64*, 1763–1770. [\[CrossRef\]](#)
19. Gan, Y.; Siddique, K.H.; Turner, N.C.; Li, X.G.; Niu, J.Y.; Yang, C.; Liu, L.; Qiang, C. Ridge–furrow mulching systems—An innovative technique for boosting crop productivity in semiarid rain-fed environments. *Adv. Agron.* **2013**, *118*, 429–476. [\[CrossRef\]](#)
20. Li, X.; Gong, J. Effects of different ridge: furrow ratios and supplemental irrigation on crop production in ridge and furrow rainfall harvesting system with mulches. *Agric. Water Manag.* **2002**, *54*, 243–254. [\[CrossRef\]](#)
21. Ye, J.; Liu, C. Suitability of Mulch and Ridge-furrow Techniques for Maize across the Precipitation Gradient on the Chinese Loess Plateau. *J. Agric. Sci.* **2012**, *4*, 182. [\[CrossRef\]](#)
22. Li, C.; Wen, X.; Wan, X.; Liu, Y.; Han, J.; Liao, Y.; Wu, W. Towards the highly effective use of precipitation by ridge-furrow with plastic film mulching instead of relying on irrigation resources in a dry semi-humid area. *Field Crop. Res.* **2016**, *188*, 62–73. [\[CrossRef\]](#)
23. Chen, X.; Wu, P.; Zhao, X.; Persaud, N. Effect of Different Mulches on Harvested Rainfall Use Efficiency for Corn (*Zea mays* L.) in Semi-Arid Regions of Northwest China. *Arid Land Res. Manag.* **2013**, *27*, 272–285. [\[CrossRef\]](#)
24. Wang, L.; Shangguan, Z. Water–use efficiency of dryland wheat in response to mulching and tillage practices on the Loess Plateau. *Sci. Rep.* **2015**, *5*, 12225. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Qin, S.; Yeboah, S.; Wang, D.; Zhang, J. Effects of ridge-furrow and plastic mulching planting patterns on microflora and potato tuber yield in continuous cropping soil. *Soil Use Manag.* **2016**, *32*, 465–473. [\[CrossRef\]](#)
26. Ren, X.; Cai, T.; Chen, X.; Zhang, P.; Jia, Z. Effect of rainfall concentration with different ridge widths on winter wheat production under semiarid climate. *Eur. J. Agron.* **2016**, *77*, 20–27. [\[CrossRef\]](#)
27. Wang, Q.; Song, X.; Li, F.; Hu, G.; Liu, Q.; Zhang, E.; Wang, H.; Davies, R. Optimum ridge–furrow ratio and suitable ridge-mulching material for Alfalfa production in rainwater harvesting in semi-arid regions of China. *Field Crop. Res.* **2015**, *180*, 186–196. [\[CrossRef\]](#)
28. Mo, F.; Zhou, H.; Wang, J.; Zhao, H.; Zhang, H.; Wu, S.; Chen, Y.; Yang, T.; Deng, H.; Asfa, B.; et al. Development and application of micro-field rain-harvesting technologies. *Trans. Chin. Soc. Agric. Eng.* **2013**, *8*, 1–17. [\[CrossRef\]](#)
29. Gammoh, I.A. An improved wide furrow micro-catchment for large-scale implementation of water-harvesting systems in arid areas. *J. Arid Environ.* **2013**, *88*, 50–56. [\[CrossRef\]](#)
30. Wang, Q.; Ren, X.; Song, X.; Hu, G.; Zhang, E.; Wang, H.; Maureen, M.V. The optimum ridge–furrow ratio and suitable ridge-covering material in rainwater harvesting for oats production in semiarid regions of China. *Field Crop. Res.* **2015**, *172*, 106–118. [\[CrossRef\]](#)
31. Hu, Q.; Pan, F.; Pan, X.; Zhang, D.; Yang, N.; Pan, Z.; Zhao, P.; Tuo, D. Effects of a ridge-furrow micro-field rainwater-harvesting system on potato yield in a semi-arid region. *Field Crop. Res.* **2014**, *166*, 92–101. [\[CrossRef\]](#)
32. Gong, D.; Shi, P. Variability of summer rainfall over northern China and its association with thermal condition at early stage underlying surface. *J. Nat. Resour.* **2001**, *16*, 211–215, (In Chinese with English Abstract). [\[CrossRef\]](#)
33. Wang, C.; Tian, X.; Li, S. Effects of ridge-mulching with plastic sheets for rainwater-harvesting cultivation on WUE and yield of winter wheat. *Agric. Sci. China* **2004**, *3*, 14–23.
34. Huang, Y.; Chen, L.; Fu, B.; Huang, Z.; Gong, J. The wheat yields and water-use efficiency in the Loess Plateau: Straw mulch and irrigation effects. *Agric. Water Manag.* **2005**, *72*, 209–222. [\[CrossRef\]](#)
35. Pan, X.; Long, B.; Wei, Y. Analysis on the Rainfall Regular and Potential of Collecting and Utilizing Rain in Loess Plateau of Inner Mongolia. *J. Arid Land Resour. Environ.* **2014**, *21*, 65–71. [\[CrossRef\]](#)
36. Wang, Q.; Zhang, E.; Li, F.; Li, F. Runoff efficiency and the technique of micro-water harvesting with ridges and furrows, for potato production in semi-arid areas. *Water Resour. Manag.* **2008**, *22*, 1431–1443. [\[CrossRef\]](#)
37. Mo, F.; Wang, J.; Xiong, Y.; Ngululu, S.N.; Li, F. Ridge-furrow mulching system in semiarid Kenya: A promising solution to improve soil water availability and maize productivity. *Eur. J. Agron.* **2016**, *80*, 124–136. [\[CrossRef\]](#)
38. Ali, S.; Jan, A.; Zhang, P.; Khan, M.N.; Cai, T.; Wei, T.; Ren, X.; Jia, Q.; Han, Q.; Jia, Z. Effects of ridge-covering mulches on soil water storage and maize production under simulated rainfall in semiarid regions of China. *Agric. Water Manag.* **2016**, *178*, 1–11. [\[CrossRef\]](#)

39. Tian, Y.; Su, D.; Li, F.; Li, X. Effect of rainwater harvesting with ridge and furrow on yield of potato in semiarid areas. *Field Crop. Res.* **2003**, *84*, 385–391. [[CrossRef](#)]
40. Zegada-Lizarazu, W.; Berliner, P.R. Inter-row mulch increase the water use efficiency of furrow-irrigated maize in an arid environment. *J. Agron. Crop Sci.* **2011**, *197*, 237–248. [[CrossRef](#)]
41. Qin, S.; Zhang, J.; Dai, H.; Wang, D.; Li, D. Effect of ridge–furrow and plastic-mulching planting patterns on yield formation and water movement of potato in a semi-arid area. *Agric. Water Manag.* **2014**, *131*, 87–94. [[CrossRef](#)]
42. Gu, X.; Li, Y.; Du, Y. Continuous ridges with film mulching improve soil water content, root growth, seed yield and water use efficiency of winter oilseed rape. *Ind. Crop. Prod.* **2016**, *85*, 139–148. [[CrossRef](#)]
43. Zhou, L.; Jin, S.; Liu, C.; Xiong, Y.; Si, J.; Li, X.; Gan, Y.; Li, F. Ridge-furrow and plastic-mulching tillage enhances maize–soil interactions: Opportunities and challenges in a semiarid agroecosystem. *Field Crop. Res.* **2012**, *126*, 181–188. [[CrossRef](#)]
44. Ren, X.; Zhang, P.; Chen, X.; Jia, Z. Impacts of ridge-furrow rainfall concentration systems and mulches on corn growth and yield in the semiarid region of China. *J. Sci. Food Agric.* **2016**, *96*, 3882–3889. [[CrossRef](#)] [[PubMed](#)]
45. Wang, Q.; Zhang, E.H.; Li, F.M.; Li, F.R.; Xu, C.L. Runoff generation characters of mini-size water collection by ridges and furrow in semiarid area of Loess Plateau and related potato-planting techniques. *Chin. J. Ecol.* **2005**, *24*, 1283–1286, (In Chinese with English Abstract).
46. Jia, Y.; Li, F.; Wang, X.; Yang, S. Soil water and alfalfa yields as affected by alternating ridges and furrows in rainfall harvest in a semiarid environment. *Field Crop. Res.* **2006**, *97*, 167–175. [[CrossRef](#)]
47. Bouma, J.A.; Hegde, S.S.; Lasage, R. Assessing the returns to water harvesting: A meta-analysis. *Agric. Water Manag.* **2016**, *163*, 100–109. [[CrossRef](#)]
48. Shan, Y.; Wang, L.; Ma, Y.; Song, C. Effect of different water deficit on yield, water use efficiency and economic benefit of sunflower. *J. Northeast Agric. Univ.* **2010**, *7*, 70–73. (In Chinese with English Abstract) [[CrossRef](#)]
49. Duan, P.; Qin, L. Study on Water Requirement of Sunflower Under Different Precipitation Years in Changling County. *Chin. Agric. Sci. Bull.* **2014**, *30*, 135–139. [[CrossRef](#)]
50. Zhou, L.; Li, F.; Jin, S.; Song, Y. How two ridges and the furrow mulched with plastic film affect soil water, soil temperature and yield of maize on the semiarid Loess Plateau of China. *Field Crop. Res.* **2009**, *113*, 41–47. [[CrossRef](#)]

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