Ridge and Furrow Configuration Optimized Soil Hydrothermal Environment, Maize Canopy Traits and Improved Grain Yield in Northwest China

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Research Article

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Abstract

Ridge and furrow planting system is widely used for yield-increasing in Northwest area of China. However, the effect of optimized ridge and furrow configuration (planting both on ridges and in furrows) to soil hydrothermal environment, maize canopy structure and grain yield are still not clear. Therefore, a 2-year (2015—2016) field experiment was conducted to investigate the regulatory effects of different planting systems [conventional flat planting without ridge (CK), ridge-furrow planting system with two row plants in both ridge and furrow (R_2F_2), and with three rows in a ridge and two rows in a furrow (R_3F_2)] on maize growth, grain yield and resource utilization. The results showed that soil hydrothermal environment and canopy structure were improved under the optimized ridge and furrow configuration, but not caused excessive water consumption. Compared with CK, the ridge and furrow configuration showed a greater advantage in virtue of coordinating water and temperature allocation, which increased LAI, photosynthetic capacity per plant and dry matter accumulation for plants in furrows. In addition, ridge and furrow systems represented a higher canopy light transmission rate of bottom layers, which contribute to more light interception capacity for plants. In comparison with CK, grain yield of R_2F_2 and R_3F_2 significantly improved by 20.5% and 12.4%, water use efficiency by 26.2% and 20.1%, radiation use efficiency by 28.2% and 17.8%, respectively. Overall, the optimized ridge and furrow configuration (R_2F_2) brought an improvement of soil hydrothermal environment, optimize canopy structure, and ultimately obtained an increase of grain yield.

Highlights

The planting pattern (crops growing on the ridge and in the furrow) is investigated.

The furrow configuration improves the soil hydrothermal environment in the furrow.

Change of individual niche optimizes canopy light distribution and RUE.

Optimized furrow configuration increases yield and WUE.

1. Introduction

Total global food demand is expected to double by 2050 (Tilman et al., 2011), with limited or no increases in planted area and irrigation water. Meeting the demand for increased food production requires increasing the productivity of existing cropping systems (Godfray et al., 2010), so it is particularly important to increase food production per unit area with low water consumption (Perry et al., 2009), especially in some water-deficient regions, such as Northwest China.

In recent years, the effects of warming (Song et al., 2013), rain harvesting (Ren et al., 2008) and moisture conservation (Wang et al., 2009) of furrow and ridge planting systems have significantly promoted vegetative growth of crops, and ultimately improved yields (Liu et al., 2014; Zhang et al., 2019), which are widely used. in semi-arid agricultural areas at home and abroad. The ridge-furrow configuration is built by shaping the soil surface with alternate ridges and furrows along the contour (in a "trapezoid" shape). First of all, the ridge and furrow technology realized the effective regulation of rainfall in time and space. The ridge is conducive to the infiltration and transfer of water, and the water in the ditch is superimposed, which can effectively accumulate natural precipitation and improve the efficiency of rainfall utilization. When there is a lot of rainfall, the water will infiltrate vertically and move laterally at the same time, and the water in the furrow can seep laterally to the bottom of the ridge. Some simulation experiments (Wang et al., 2011; Chen et al., 2011; Zhang et al., 2012, 2013a, b) about soil water infiltration have been proved that the lateral infiltrated water could meet crops growth needs on the ridges. The water in the furrow mainly moves laterally to the row position, minimizing the downward movement of water. In addition, the yield-increasing effect of the furrow planting system was affected by the furrow-to-furrow ratio and mulching material (Liu et al., 2020).

Canopy structure is a key factor affecting the light distribution and photosynthetic characteristics of crop populations (Liu et at., 2018; Zhang et al., 2022). Improving the photosynthetic efficiency and material production capacity of crop populations mainly lies in improving the light transmittance of the canopy and enhancing the photosynthetic performance of the population. Therefore, the canopy structure is often affected by adjusting the plant type and leaf orientation in production. Ridging in the field, planting crops on the ridges and furrows, changing the vertical spatial difference of crops, improving the light transmittance of the crop canopy, improving the effective interception of light, and helping to improve the utilization rate of light energy and group productivity.

Maize (*Zea mays* L.) is one of the most common crops in Northwestern China. In this area, annual rainfall ranges from 200 mm to 750 mm, with 60% of rainfall (frequent and heavy rainstorm) falling between June and September, which led to the expansion of the scale and severity of soil erosion. Some cultivating system such as rainwater concentration practices (planting only on ridges or in furrows) have been conducted to obtain higher maize yield and WUE (Ren et al., 2008; Liu et al. 2020). The three-dimensional ridge and furrow configuration optimizes the allocation and utilization of resources on the ridge and within the furrow by changing the niche of individual plants. However, the research on the distribution of maize canopy and utilization of light, temperature and water resources under different ridge and furrow configurations was scarce. This paper described three planting patterns: conventional flatting planting pattern without ridge (CK), the ridge and furrow planting system with two rows plants in ridge and two rows in furrow (R_2F_2), three rows in ridge and two rows in furrow (R_3F_2). In the optimized ridge and furrow system, we hypothesized that: (1) elucidate spatio-temporal dynamics of soil moisture and temperature; (2) optimize canopy distribution and leaf senescence; (3) obtain higher maize yield and resource use efficiency in Northwest region of China.

2. Materials And Methods

2.1. Site description

This experiment was conducted during 2015 and 2016 at the Experimental Station in Institute of Water Saving Agriculture in Arid Regions (34°20'N, 108°04'E, 466.7 m a.s.l), Northwest A&F University, Shaanxi Province, Northwest China. Annual average rainfall was 550 mm with over 60% occurring in June to September. The total rainfall during the growing season (April-September) was 412.2 mm and 425.5 mm in 2015 and 2016, respectively (Fig. 1). The annual mean temperature was 12.9°C and mean pan evaporation was 993.2 mm. The total yearly sunshine duration was 2196 h and no frost period was 220 d. The soil was Eum-Orthrosols (Chinese soil Taxonomy). The soil bulk density was 1.30 g cm^{-3} in top of 20 cm, 1.35 g cm^{-3} between 20 and 40 cm, and 1.42 g cm^{-3} between 40 and 120 cm, respectively. The average field water holding capacity were 0.24 m m^{-3} and permanent wilting coefficient was 0.09 m m^{-3}. The topsoil chemical properties (0–20 cm) were measured: soil organic matter 12.22 g kg^{-1}; available phosphorus 22.34 mg kg^{-1}; available potassium 87.37 mg kg^{-1}. Prior to the experiment, spring maize was sown in the site.

2.2. Experiment design and treatments

Taking the traditional flat cropping treatment (CK) as a control, two kinds of ridge and furrow combinations planting patterns were set: (R_3F_2: three rows of maize was planted on the ridge and two rows in furrow; R_2F_2: two rows of maize was planted on the ridge and two rows in furrow). The plant and row spacing of maize was 30 cm and 50 cm, respectively in three planting patterns. Each experimental plot was 32 m^2 (8 m×4 m), with three replicates adopted in a randomized block design. The ridge and furrow system consisted of alternating south-north-oriented ridges and furrows, and the height of ridge was 15 cm. A schematic diagram of the system with crop configuration was indicated in Fig. 2. The maize cultivars “Zhengdan 958” was sown on 20 April 2015 and 22 April 2016, using a hand hole-sowing machine, and was harvested on 15 September 2015, 18 September 2016, respectively. The plant density in all these three treatments was 67,500 plants ha^{-1}. Prior to planting, the ridges were banked up with soil on the spot and the furrows were leveled. In accordance with local agronomic practices, chemical fertilizer was applied at a rate of 125 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1} and 78.5 K_2O ha^{-1} as starter fertilizer, and topdressing fertilizer application (The fertilizer was applied in furrows and on ridges by side-dressing nitrogen fertilizer) was taken at a rate of 100 kg N ha^{-1} at jointing stage. Other field management measures followed the local tradition.

2.3. Sampling and measurements

2.3.1 Soil environment

2.3.1.2 Soil moisture

Soil moisture (SM) was measured at all experimental plots by the gravimetric method during sowing (S), jointing (V6), tasseling (VT), and physiological maturity (R6) stages in 2015 and 2016. Soil samples were collected using an auger (54 mm diameter) every 10 cm for 0–40 cm, and every 20 cm from 60 to 160 cm soil depth, respectively. In ridge and furrow system (R_2F_2 and R_3F_2), SM was measured as the mean of samples which were taken from the ridge, side and in furrow. In the conventional flatting planting (CK), SM was measured between two plants. SM was calculated by the oven-drying method (105°C over 12 h). Soil water storage (SWS) was determined by summing the SWS at 0 – 120 cm soil profiles.

$$SWS = SMi \times Bi \times Di \times 10$$

where SMi is the soil moisture (%), Bi is bulk density (g cm^{-3}), Di is soil profile (cm), and i referred to different soil profiles: 0–10, 10–20, 20–30, 30–40, 40–60…and 100–160 cm.

In this areas, groundwater infiltration and recharge can be considered negligible. Therefore, the evapotranspiration (ET) can be calculated as follow:

$$ET = R + \triangle S$$

where R (mm) is the rainfall at the growth period;$\triangle Si$ (mm) is reduction of soil water storage from sowing to maturity stage. In this paper, ET refers to water consumption. The crop water use efficiency (WUE) was calculated as follows:

$$WUE = Y/ET$$

where Y is maize grain yield (kg ha^{-1}), and ET is total water consumption over the growing season.

2.3.1.2 Soil temperature

Soil temperature was recorded in 5 cm and 15 cm soil profile using mercury-in-glass geothermometers. In ridge and furrow planting system (R_2F_2 and R_3F_2), soil temperature was measured as the mean of soil sample which were taken from the ridges and furrows in each plot. Soil temperature was measured between two plants in flatting planting. Soil temperature was observed at 08:00, 10:00, 12: 00, 14:00, 16:00 and 18:00 at 10 days intervals between sowing and harvesting under two trial years. Mean daily topsoil temperature (5 cm and 15 cm) was calculated to the mean of the three daily readings.

2.3.3. Leaf area index

The leaf area index (LAI) in each plot was measured at jointing, tasseling and filling stage, respectively. Five maize plants were selected from each plot ridge and furrow respectively to record green leaf area. The calculation formula is as follows:

Leaf area of a single leaf = length×width×0.75

Leaf area index = sum of leaf area per unit land area/unit land area

Population leaf area index (R_3F_2) = ridge leaf area index×3/5 + furrow leaf area index×2/5

Population leaf area index (R_2F_2) = ridge leaf area index×1/2 + furrow leaf area index×1/2

2.3.4. Dry matter accumulation

Dry matter per plant was measured at jointing, tasseling, filling and maturity. Maize plants were kept at 105°C for 30 min, then oven-dried at 75°C for over 48 h to obtain dry matter weight (g $plant^{-1}$). Five maize plants were selected both on ridges and in furrows to determine dry matter accumulation per plant.

Population dry matter accumulation (R_3F_2) = ridge dry matter accumulation×3/5 + furrow dry matter accumulation×2/5

Population dry matter accumulation (R_2F_2) = ridge dry matter accumulation×1/2 + furrow dry matter accumulation×1/2

2.3.2. maize canopy

During tasseling stage (VT) and physiological maturity stage (R6) of maize, the weather is sunny. From 10:00 to 12:00 in the morning, use the LP-80 canopy meter to measure the canopy photosynthetically active radiation (PAR, $mol \cdot m^{-2} \cdot s^{-1}$) of the ear layer and the bottom layer respectively, repeated three times for each plot .

Light transmittance rate = It/I0;

where It is the photosynthetically active radiation at different canopy heights, and I0 is the photosynthetically active radiation at the top of the canopy.

Radiation use efficiency (RUE, g MJ^{-1}) and other related indicators

Total intercepted radiation Qa (MJ m^{-2}) and dry matter accumulation (DMA), extinction coefficient (K), canopy intercepted photosynthetically active radiation (IPAR, MJ m^{-2}) and:

$K=(-1/LAI)\times\ln(It/I0)$

$IPAR = Qa\times[1-\exp(-K\times LAI)]$

$RUE = DMA/IPAR$

2.3.5. Grain yield

Maize yield and its components (kernel number per ear and 100-kernel weight) was estimated by harvesting, threshing, and air-dried the grain from 3.0×3.0 m^2 sub-sampling plots placed randomly in ridges, furrows and flat-cropped maize respectively. The calculation method of population yield in ridge and furrow system referred to dry matter yield. The grain yields were considered as the standard yield (grain water content of 14%).

2.4. Statistical analysis

All test data and charts were processed by Excel 2016 and Origin 2018. The significance of differences in maize growth, yield formation, dry matter accumulation, and other parameters under three planting systems were tested by variance analysis, and the means were tested for least significant differences (LSD) at the 0.05 level. All statistical analysis was analyzed by the IBM SPSS Statistics 22.0.

3. Results

3.1. Soil moisture

The ridge and furrow configuration significantly affected the distribution of soil moisture (SM) on the ridge and within the furrow (Fig. 3). The SM within the furrow (0–40 cm layer) was significantly higher than that on the ridge and CK. The soil water contents of R_2F_2 and R_3F_2 were % and % higher than that of CK at the jointing and tasseling stages, respectively. There was no significant difference was found between three treatments at the physiological maturity (V6) stage. In the 2015 and 2016 growing seasons, the average SM in 0—160 cm soil depth of R_2F_2 and R_3F_2 obviously increased by 5.1% and 7.8% ($P < 0.05$), respectively.

3.2. Soil temperature

The surface soil temperature (0–15 cm) showed the trend of increasing first and then decreasing during the whole growing season, reaching the maximum value at tasseling period (Fig. 4). The average topsoil temperature in ridge and furrow pattern was higher than that in CK during two maize growth seasons, 2.8°C and 2.3°C in 2015 and 2016, respectively. Compare with CK, R_2F_2 and R_3F_2 treatments improved average temperature by 2.1°C and 1.2°C from sowing to jointing stage (0—60 d), respectively; by 0.6°C and 0.47°C from jointing to tasseling stage (60—90 d), respectively. However, there was non-significant difference among three planting patterns during tasseling to maturity stage (90—140 d).

The diurnal variation of soil temperature at different depths is shown in Fig. 5. At 30 d and 60 d after sowing, the daily soil temperature at 5 cm and 10 cm layers showed a trend of first increasing and then decreasing, with the expression in furrow > on ridge > CK. Compared with CK, R_2F_2 and R_3F_2 at 5 cm layers increased by 1.9 and 1.4°C, increased by 0.9 and 0.5°C at 10 cm layers respectively. Soil temperature (15 cm layer) also showed a trend of increasing first and then decreasing, but there was no significant difference among the treatments. At 90 d after sowing, the warming effect of ridge and furrow configuration weakened.

3.3. Maize canopy structure and photosynthesis traits

3.3.1. Leaf area index

Ridge and furrow planting systems notably influenced leaf area per plant of maize after tasseling (VT) stage. The average leaf area per plant in furrows of R_3F_2 and R_2F_2 were significantly higher 13.2% and 15.6% than conventional flatting (CK), while no significant differences were found between them ($P > 0.05$). Additionally, there was non-significant differences between ridges (R_3F_2 and R_2F_2) and CK. Sum up, ridge and furrow planting systems significantly improved population leaf area index (LAI) of maize during different growing stages (Fig. 6). Compared with CK, the two year-average LAI of in R_2F_2 and R_3F_2 increased 18.1% and 11.6%, respectively ($P < 0.05$). The results showed that optimized ridge-furrow configuration (R_2F_2) improved maize population leaf area index due to more green leaf area per plant in furrow.

3.3.2. Canopy light transmittance rate

The canopy light transmittance rate (LTR) of ear layer and bottom layer under ridge-furrow planting patterns were obviously higher than that of CK (Table 1). At tasseling (VT) stage was as follows: R_2F_2 > R_3F_2, while there was no significant difference between each other at physiological maturity (V6) stage. On an average for two years, the LTR of R_2F_2 treatment increased by 10.0% and 27.2% at VT stage, and increased by 6.1% and 23.8% at R6 stage, respectively ($P < 0.05$). The results declared that ridge and furrow structure improved the light transmittance rate within the canopy.

Table 1
Effects of different planting systems on canopy light transmittance rate (LTR) of maize during 2015 and 2016 growing seasons.

Year	Planting pattern	Canopy transmittance rate			
		Ear layer		Bottom layer	
		VT	R6	VT	R6
2015	R_3F_2	11.9 ± 0.15b	41.4 ± 0.2b	8.4 ± 0.1b	23.1 ± 0.5a
	R_2F_2	12.6 ± 0.1a	43.7 ± 0.3a	9.3 ± 0.2a	25.5 ± 0.3a
	CK	11.2 ± 0.2b	32.1 ± 0.6c	7.3 ± 0.3c	19.2 ± 0.2b
2016	R_3F_2	14.3 ± 0.36b	31.4 ± 0.6a	8.7 ± 0.2b	20.4 ± 0.3b
	R_2F_2	16.3 ± 0.6a	32.9 ± 0.4a	9.1 ± 0.4a	22.5 ± 0.4a
	CK	12.2 ± 0.6c	29.1 ± 0.5b	6.7 ± 0.5c	15.4 ± 0.6c
Average	R_3F_2	13.1 ± 0.4b	36.4 ± 1.8a	8.5 ± 0.3b	22.7 ± 1.3a
	R_2F_2	14.5 ± 0.3a	38.3 ± 1.5a	9.2 ± 0.2a	24.0 ± 1.5a
	CK	11.7 ± 0.6c	32.6 ± 2.1b	7.5 ± 0.6c	17.3 ± 1.8b

Note: CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. VT and R6 represent tasseling and physiological maturity, respectively. Different lower-case letters in a column denote significant differences among treatments at $P < 0.05$. Data represent means ± SE (n = 3).

3.3.3. Net photosynthetic rate

The ridge and furrow three-dimensional planting system significantly increased the net photosynthetic rate (Pn) of ear leaves (Fig. 7). During the two-year experiment, the highest value of Pn was reached at V6 stage, and each treatment showed plants in furrows > on ridges > CK, obtained an increase of 15.9—21.8% ($P < 0.05$). In comparison with CK, the plants in furrow maintained a relatively higher Pn from V6 to R6 stage, but there was no significant difference was found between R_3F_2 and R_2F_2 treatments.

3.4. Dry matter accumulation and source-sink ratio

The ridge and furrow planting system significantly increased aboveground dry matter yield ($P < 0.05$), Compared to CK, obtained an improvement of 12.1% and 6.4% in R_2F_2 and R_3F_2 at maturity (R6) stage, respectively (Fig. 8). Ridge and furrow planting systems obviously brought an increase of source and sink ratio (SSR). In comparison with CK, the R_2F_2 and R_3F_2 increased SSR by 10.7% and 5.9%, respectively.

3.5. Grain yield, yield components and resource use efficiency

Ridge and furrow planting system remarkably increased 100-grain weight in furrows and ultimately obtained an improvement of grain yield (Table 2). Compare with CK, R_2F_2 and R_3F_2 obviously improved two year-average grain yield by 20.5% and 12.4%, respectively. Ridge and furrow planting system brought an obvious increase of radiation use efficiency (RUE) and water use efficiency (WUE). The R_2F_2 and R_3F_2 treatment increased RUE by 28.2% and 17.8%, WUE increased by 26.2% and 20.1%, respectively.

Table 2

Effects of planting systems on grain yield, its components, water use efficiency (WUE), and radiation use efficiency (RUE) of maize in 2015 and 2016 growing seasons.

Year	Treatments	Kernel number per spike	100-grain weight (g)	Yield ($kg\ ha^{-1}$)		ET (mm)	WUE ($kg\ ha^{-1}\ mm^{-1}$)	RUE ($g\ MJ^{-1}$)
2015	R_3F_2-ridge	616 ± 10b	32.8 ± 0.1b	8825 ± 85c	9400 ± 243b	385.6 ± 5.4a	23.9 ± 2.2b	0.93 ± 0.02a
	R_3F_2-furrow	620 ± 12b	33.5 ± 0.4ab	10262 ± 101b				
	R_2F_2-ridge	654 ± 11a	32.5 ± 0.2b	10082 ± 95b	10274 ± 105a	381.1 ± 3.6a	26.0 ± 2.5a	0.97 ± 0.03a
	R_2F_2-furrow	648 ± 9a	34.4 ± 0.3a	10465 ± 102a				
	CK	610 ± 8b	30.5 ± 0.5c	8583 ± 90c	8583 ± 289c	374.6 ± 8.2a	20.3 ± 1.6c	0.75 ± 0.05b
2016	R_3F_2-ridge	608 ± 10b	29.6 ± 0.2c	8961 ± 115c	9137 ± 189b	362.5 ± 4.3a	22.8 ± 2.1a	0.91 ± 0.02b
	R_3F_2-furrow	618 ± 12b	32.5 ± 0.4a	9401 ± 106b				
	R_2F_2-ridge	635 ± 10a	31.8 ± 0.2b	9328 ± 112b	9606 ± 234a	368.0 ± 5.4a	23.1 ± 1.5a	1.03 ± 0.05a
	R_2F_2-furrow	628 ± 8a	32.3 ± 0.5a	9883 ± 123a				
	CK	598 ± 10b	28.5 ± 0.3c	7921 ± 211d	7921 ± 204c	360.5 ± 4.9a	18.6 ± 1.8b	0.81 ± 0.06c
AVOVA								
	PP	*	**	**	**	ns	**	**
	Y	ns	ns	ns	ns	ns	*	ns
	PP×Y	ns	ns	ns	ns	ns	ns	ns

Note: PP represents planting patterns; Y represents year; CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. Different lower-case letters in a column denote significant differences among treatments at $P < 0.05$. Data represent means ± SE (n = 3).

3.6. Correlation analysis

Correlation analysis showed that grain yield was positively correlated with population net photosynthetic rate (Pn), canopy light transmittance of bottom layer, leaf area index (LAI) and 0–15 cm soil temperature (ST0-15), but had no significant correlation with water consumption (ET). The bottom light transmittance was significantly positively correlated with Pn. There was a significant positive correlation between LAI and soil temperature in 0-5cm and 0-15cm soil layers.

4. Discussion

4.1. Soil moisture and temperature

The ridge tillage and furrow planting pattern, of which the furrows served as water infiltration areas, and both of the ridges and furrows served as planting areas, has been proven useful in improving crop yield in semiarid regions (Ren et al., 2008; Wang et al., 2011). Ridge and furrow planting pattern can increase crop root-zone moisture by rainfall water to meet crop water demand and decreasing evaporation (Gu et al., 2019b). In the ridge and furrow system, the flow water on furrows infiltrates into ridge-furrow configuration by capillarity forces, and lateral infiltrated water meet the needs of the crops growth on the ridges. Meanwhile, ridge width affected the cumulative infiltration in field trials (Bargar et al., 1999; Liu et al., 2010; Zhang et al., 2015). The ridge with furrow planting pattern could significantly improve soil moisture during the early-middle growing periods, and soil moisture of R_2F_2 was higher than that of R_3F_2, which promoted the maize dry matter accumulation in late growth period. Furthermore, our study also indicated that increasing the ratio of furrow to ridge was a more effective method to improve soil moisture availability on the semi-arid region of China. It was well known that the evaporation rate was inversely proportional to the water depth, irrigation water infiltrated into deeper layer, which helped to inhibit evaporation and promoted plant growth.

The ridge and furrow system regulated the soil temperature, thus promoting maize plant germination and emergence (Li et al., 2013; Li et al., 2017). In our research, the general trend of soil temperature during maize growing seasons showed an increase (0—90 d after sowing) then a decrease (90—140 d after sowing), whereas the effect of RTFI system on soil temperature was greater in the early growth period and weakened with crop growth. The ridge and furrow patterns provided better soil water and heat resources during the early growth stages, possibly because the ridge and furrow pattern simultaneously inhibited water evaporation and heat losses (Ren et al., 2008; Li et al., 2020). Moreover, the warming effect of R_2F_2 was significantly better than that of R_3F_2 as the result of the proper ridge to furrow ratio to promote water-temperature regulation (Luo et al., 2021; Yu et al., 2018).

4.2. Maize canopy structure and physiological characteristics

Canopy structure is a key factor affecting the light distribution and photosynthetic characteristics of crop populations (Liu et al., 2018; Zhang et al., 2022). Improving the photosynthesis efficiency and material production capacity of crop groups mainly lied in improving the ventilation and light transmission capacity of the canopy. In our study, the planting mode of ridge and furrow configuration significantly improves the leaf area index and light efficiency of the plants in the furrow, and enhances the light transmittance of the bottom layer. The ridge and furrow configuration with its special canopy structure increased solar radiation and resources utilization efficiency (Gu et al., 2021; Zhang et al., 2019), ultimately promoted dry matter accumulation and yield. In addition, the performance of R_2F_2 was better than that of R_3F_2, indicating that the two rows plant on ridges could maximize the edge advantage of crops on ridge and improve the intraspecific nutrient competition (Li et al., 2020). Overall, R_2F_2 optimized the canopy light distribution, delayed leaf senescence in the canopy after flowering, enhanced the bottom light transmittance and post-flowering photosynthetic efficiency, and achieved higher grain yield and radiation utilization.

4.3. Grain yield and WUE

The ridge tillage and furrow system as a new planting pattern improved soil temperature and coordinated water allocation to meet maize water requirement on ridge and in furrow, which significantly improved leaf area index and dry matter accumulation, so as to obtain higher grain yield. Our research showed that the ridge and furrow pattern increased topsoil moisture because of water transfer by capillary action and vapor transfer from deep soil to the surface. A higher soil moisture in the upper layer could boost green leaves stoma opening to increase photosynthetic and chlorophyll content (Sunoj et al., 2016). It can explain why maize plants of R_2F_2 and R_3F_2 could keep a greater dry matter accumulation at post-tasseling period. Consistent with previous results (Dong et al., 2018; Liu et al., 2020; Wu et al., 2015), ridge and furrow systems significantly increased WUE, which mainly the result of the increase in yield did not result in excessive crop water consumption. Moreover, our study revealed that the effect of increasing maize yield for two rows on ridge was greater than those of with three rows, which may be due to the limited of water migration distance.

5. Conclusion

In Northwestern region of China, the optimized ridge and furrow configuration (R_2F_2, two rows maize both in ridge and in furrow) brought an improvement of soil water-temperature environment, promote maize canopy growth, and ultimately obtained a 20.5% increase of grain yield. This increase was mainly attributable to optimized maize canopy structure (higher post-flowering photosynthetic capacity and enhanced light energy interception) and source-sink relationships, resulting in higher dry matter weight and grain yield. Overall, the R_2F_2 treatment which could be regarded as a more suitable for maize yield-improving in Northwestern of China.

Declarations

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No conflict of interest exists in the submission of this manuscript. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and it is not under consideration for publication elsewhere in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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Figures

Figure 1

Daily rainfall and daily air temperature during the two maize growing seasons of 2015 and 2016, in the Institute of Water Saving Agriculture in Arid Regions, Northwest A&F University, China.

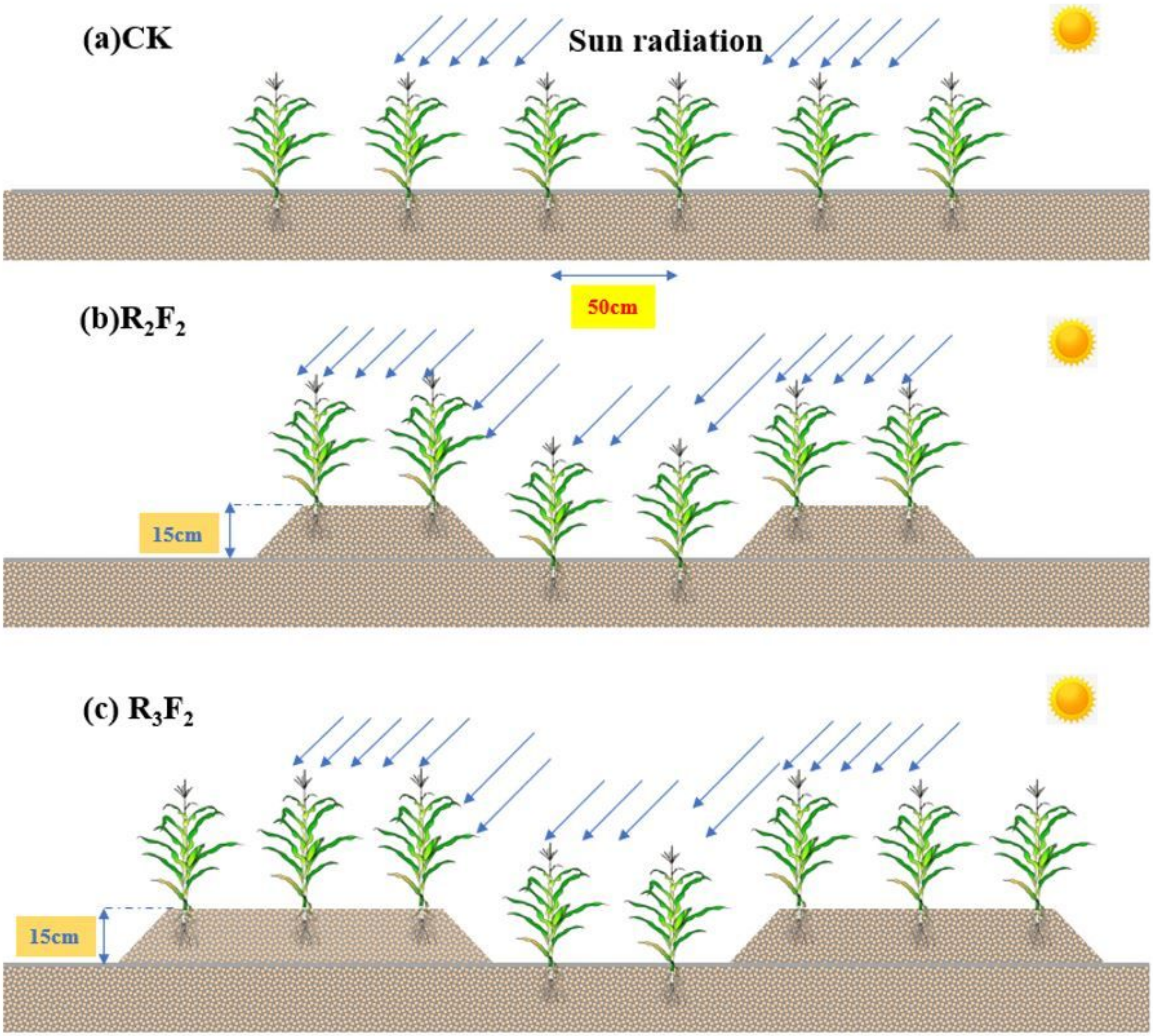

Figure 2

Schematic diagram of maize planting patterns.

Note: (a) CK, conventional flat planting without ridge; (b) R_2F_2, represents ridge and furrow planting system with two row plants in each ridge and furrow, and (c) R_3F_2, represents that with three rows in a ridge and two rows in a furrow. The ridge height of ridge and furrow planting patterns was 15 cm.

Figure 3

Dynamic of soil moisture at various growth stages under different planting patterns during the 2015 and 2016 growing seasons.

Note: SS, V6, VT and R6 represent sowing, jointing, tasseling and physiological maturity stage. CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. The bars showed the least significant difference at 5% level.

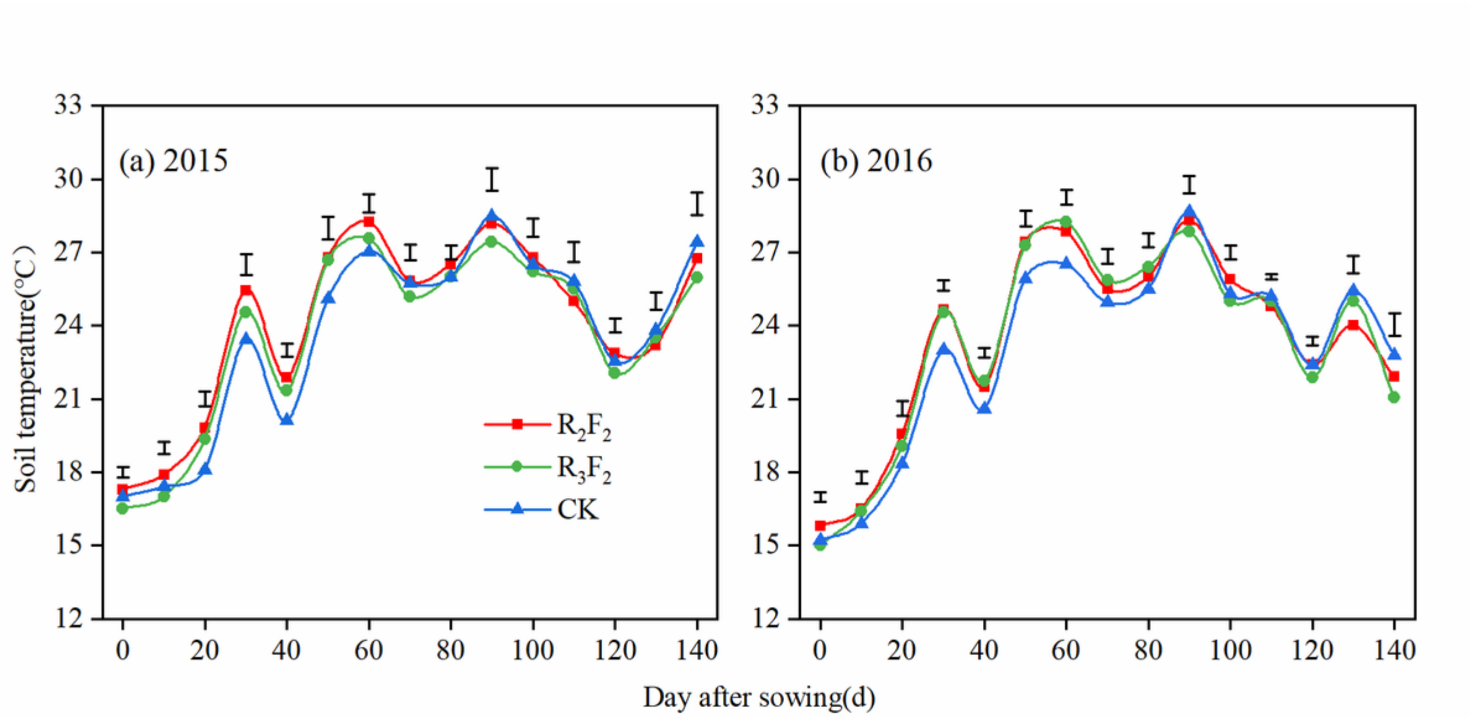

Figure 4

Effect of different planting patterns on soil temperature during the 2015 and 2016 growth season of maize.

Note: CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. The bars showed the least significant difference at 5% level.

Figure 5

Effects of different planting systems on diurnal variation of soil temperature at different depths (5, 10, 15 cm) during day after sowing 30d, 60d and 90d.

Note: CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively.

Figure 6

Effects of different ridge and furrow planting systems on leaf area per plant and leaf area index (LAI) of maize during 2015 and 2016 growing seasons.

Note: CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. V6, VT, R3 and R6 represent jointing, tasseling, filling and physiological maturity, respectively. Data represent means ± SE (n=3).

Figure 7

Effects of different ridge and furrow planting systems on net photosynthetic rate (Pn) of maize during 2015 and 2016 growing seasons.

Note: CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. V6, VT, R3 and R6 represent jointing, tasseling, filling and physiological maturity, respectively. Data represent means ± SE (n=3).

Figure 8

Effects of different ridge and furrow planting systems on dry matter accumulation (DMA) at different growth stages in 2015 and 2016.

Note: CK represents the conventional flatting without ridge; R_2F_2 represents the planting system with two rows plants in each ridge and furrow, respectively; R_3F_2 represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. VE, V6, VT, R3 and R6 represent seedling, jointing, tasseling, filling and physiological maturity, respectively. Different lower-case letters in a column denote significant differences among treatments at $P<0.05$. Data represent means ± SE (n=3).

Figure 9

Correlation analysis between yield and soil temperature, leaf area index, light transmittance, net photosynthetic rate and evapotranspiration.

Note: ST0-5 represents the soil temperature of 0-5 cm soil layer, ST0-15 represents the soil temperature of 0-15 cm soil layer, LAI represents the average leaf area index, Pn represents the net photosynthetic rate, LTR-ear represents canopy light transmittance of ear layer, LTR-bottom represents canopy light transmittance of bottom layer, ET represents evapotranspiration.