



# Ridge and furrow configuration improved grain yield by optimizing the soil hydrothermal environment and maize canopy traits in Northwest China

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## Abstract

**Background and aims** Ridge and furrow technology is widely used to increase yields in Northwest China, where the focus is primarily on ridge cropping or furrow planting. However, the effects of ridge and furrow configuration (planting both on ridges and in furrows) on soil water and temperature, maize canopy structure and grain yield are still not clear.

**Methods** A 2-year (2015–2016) field experiment was conducted to investigate the regulatory effects of different planting systems [conventional flat planting (CK), ridge and furrow configuration with two rows of plants in both ridges and furrows ( $R_2F_2$ ), and with three rows in ridges and two rows in furrows ( $R_3F_2$ )] on soil water and temperature, canopy traits, grain yield and resource use efficiency.

**Results** Soil hydrothermal environment and canopy structure were improved under ridge and furrow configuration, but did not cause excessive water consumption. Compared with CK, ridge and furrow configuration showed a greater advantage in water and temperature allocation, which increased leaf area index (LAI), photosynthetic capacity per plant and dry matter accumulation in furrows. Additionally, ridge and furrow systems represented a higher canopy light transmission rate to bottom layers, which contributed 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 improved by 26.2% and 20.1%, and radiation use efficiency improved by 28.2% and 17.8%, respectively.

**Conclusions** Ridge and furrow configuration optimized canopy structure and soil hydrothermal environment, ultimately increasing grain yield and resource use efficiency.

**Keywords** Ridge and furrow configuration · Maize yield · Canopy structure · Soil environment · Resource use efficiency

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## 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), especially in some water-deficient regions, such as Northwest China. Environmental factors such as soil hydrothermal (water and temperature) and photosynthetically active radiation significantly affect crop yield (Zheng et al. 2022). Making full use of limited resources and improving their use efficiency are major challenges to obtaining higher crop productivity.

Ridge and furrow technology (cropping plants on ridges or in furrows) has been proven to effectively alleviate stress resistance during the maize growth period, which plays an important role in ensuring maize growth and grain yield (Gu et al. 2019; Li et al. 2013). Ridge cropping improves the farmland microclimate, which is conducive to the reproduction and growth of microorganisms in surface soil, and improves the soil water holding capacity and water use efficiency (Hatfield et al. 1998). Compared with traditional flat cropping, ridge cropping can enhance the resistance of spring maize to high temperature stress during grain filling, to improve photosynthetic capacity and yield (Tao et al. 2013). Ridge cropping is more suitable for areas with frequent extreme weather, e.g. North Plain China. Compared with flat cropping, ridge-furrow with film mulching planting (film mulching on ridges and planting in furrows) improved rainfall and photosynthetic utilization efficiency, increased yield by 25% and water productivity by 20% (Liu et al. 2010). However, it increases the material cost and environmental risk (white pollution). Additionally, the effect of yield-increasing and efficient resource use was affected by the size of ridges and furrows (Liu et al. 2020a, b; Luo et al. 2021). Photosynthetic capacity determines yield formation, and canopy structure is the driving factor affecting light energy capture and photosynthetic efficiency. Ridge cropping can effectively improve the canopy structure and photosynthetic effective radiation of waterlogged summer maize and increase yield by 39% (Ren et al. 2016). The ridge and furrow planting pattern (one row on ridge and two rows in furrow) optimizes crop light transmittance in the furrow and improves photosynthetic capacity per plant during grain filling, which result in an increase of 25.2% yield (Liu et al. 2018). Photosynthesis is also affected by soil water and heat status. Ridge and furrow planting improves leaf growth and photosynthetic

rates by collecting rainfall, which contributes to obtaining higher yields. However, the increase in soil temperature on ridges promotes plant growth, accelerates leaf senescence, and may further reduce per leaf photosynthesis and carbon fixation (Ding et al. 2020). In general, the coordination between crop photosynthetic capacity and soil hydrothermal conditions under ridge and furrow planting has not been fully evaluated.

A shortage of water resources is the main challenge threatening agricultural sustainability in Northwest China. The typical cropping system in this area is wheat/maize rotation, which is a high water-consumption system (Li et al. 2017; Lu et al. 2021). Therefore, people have explored new alternative planting systems to meet the needs of water saving and high yield, such as the spring maize system. The results showed that the growth season of spring maize was highly matched with the distribution of precipitation, and the production potential of light, temperature and water was better than that of summer maize (Zhao et al. 2008). Previous studies on ridge cropping or furrow planting are mainly aimed at improving the soil water and temperature environment for crop growth (Li et al. 2020a, b; Ren et al. 2008). In contrast, the three-dimensional ridge and furrow configuration (planting both on ridges and in furrows) optimizes the allocation and utilization of resources on ridges and in furrows by changing the niche of individual plants. However, studies on the effect of ridge and furrow configuration to maize canopy structure and the distribution of soil water and temperature are scarce. Therefore, we hypothesized that the ridge and furrow configuration could (1) elucidate the spatiotemporal dynamics of soil moisture and temperature; (2) optimize canopy distribution and leaf senescence; and (3) obtain higher maize yield and resource use efficiency in northwest region of China.

## Materials and methods

### Site description

This experiment was conducted during 2015 and 2016 at the Experimental Station of the 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. The annual

average rainfall was 550 mm, with over 60% occurring from June to September. The total rainfall during the growing season (April–September) was 412.2 and 425.5 mm in 2015 and 2016, respectively (Fig. 1). The annual mean temperature was 12.9 °C and the mean pan evaporation was 993.2 mm. The total yearly sunshine duration was 2196 h, and the period without frost was 220 d. The soil was Eum-Orthosols (Chinese Soil Taxonomy). The soil bulk density was 1.30 g cm<sup>-3</sup> in the top 20 cm, 1.35 g cm<sup>-3</sup> in a depth of 20–40 cm, and 1.42 g cm<sup>-3</sup> at a depth of 40–160 cm. The average field water holding capacity was 0.24 m m<sup>-3</sup> and the permanent wilting coefficient was 0.09 m m<sup>-3</sup>. The topsoil chemical properties (0–20 cm) were measured: soil organic matter 12.22 g kg<sup>-1</sup>; available phosphorus 22.34 mg kg<sup>-1</sup>; and available potassium 87.37 mg kg<sup>-1</sup>. Prior to the experiment, spring maize was sown in the site.

### Experimental design and treatments

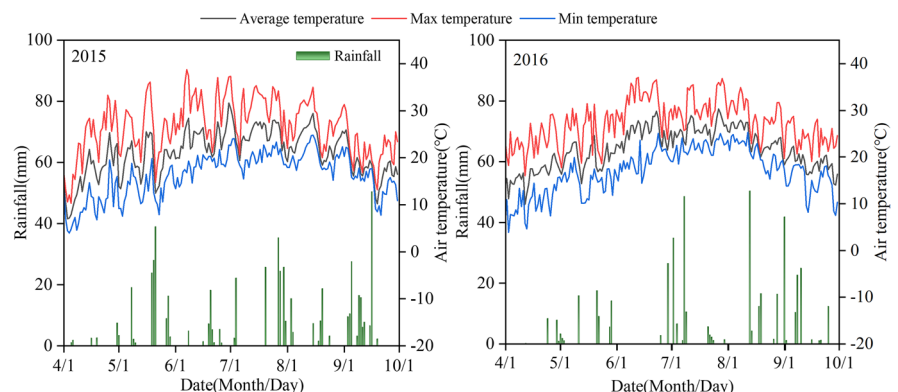
Traditional flat cropping treatment (CK) was used as a control. Two types of ridge and furrow combinations were implemented and included: R<sub>3</sub>F<sub>2</sub> consisting of three rows of maize planted on ridges and two rows in furrows, the planting area of maize on ridges and in furrows accounted for 60% and 40%, respectively; and for R<sub>2</sub>F<sub>2</sub>, which consisted of two rows of maize planted on ridges and two rows in furrows, the planting area on ridges and in furrows accounted for 50% and 50%, respectively. The plant and row spacing of maize were 30 and 50 cm, respectively in the three planting patterns. Each experimental plot was 32 m<sup>2</sup> (8 m×4 m), with three replicates adopted in a randomized block design. The ridge and furrow

configuration consisted of alternating south-north-oriented ridges and furrows, and the height of the ridge was 15 cm. A schematic diagram of the system with crop configuration is shown in Fig. 2. The maize cultivar “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 and 18 September 2016, respectively. The plant density in all three treatments was 67,500 plants ha<sup>-1</sup>. 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<sup>-1</sup>, 150 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 78.5 K<sub>2</sub>O ha<sup>-1</sup> 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<sup>-1</sup> at the jointing stage. Other field management measures followed the local tradition.

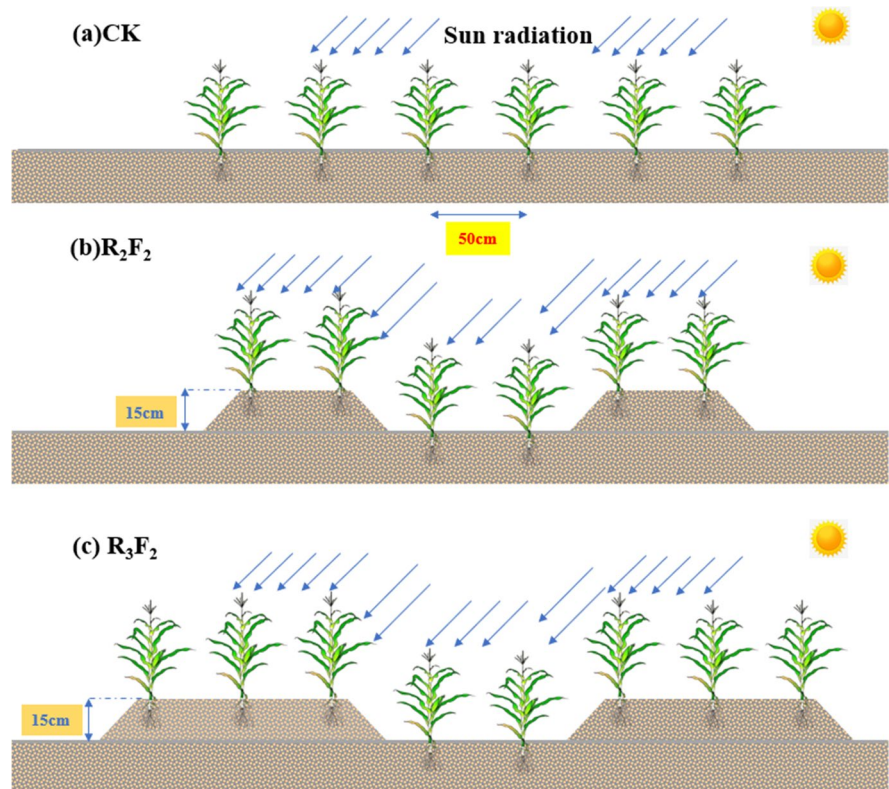
### Soil water measurements

The soil water content (SWC) was measured at all experimental plots by the gravimetric method during the sowing (S), jointing (V6), tasseling (VT), and physiological maturity (R6) stages. Soil samples were collected using an auger (54 mm diameter) every 10 cm within 0–40 cm, and every 20 cm within 60 to 160 cm soil depth. In ridge and furrow configuration (R<sub>2</sub>F<sub>2</sub> and R<sub>3</sub>F<sub>2</sub>), SWC was measured as the average value of samples that were taken on ridges, sides and furrows according to horizontal height. In conventional flattening planting (CK), SWC was measured between two plants. SWC was calculated by the oven-drying method (105 °C over

**Fig. 1** Daily rainfall and daily air temperature during 2015 and 2016 maize growing seasons, in the Institute of Water Saving Agriculture in Arid Regions, Northwest A&F University, China



**Fig. 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



12 h). Soil water storage (SWS) was determined by summing the SWS at the 0–160 cm soil profile.

$$SWS = SWC_i \times B_i \times D_i \times 10$$

where  $SWC_i$  is the soil water content (%),  $B_i$  is the bulk density ( $g\ cm^{-3}$ ),  $D_i$  is the soil profile (cm), and  $i$  refers to different soil profiles: 0–10, 10–20, 20–30, 30–40, 40–60...and 100–160 cm.

In this area, groundwater infiltration and recharge can be considered negligible. Therefore, the evapotranspiration (ET) and crop water use efficiency (WUE) can be calculated as follows:

$$ET = R + \Delta S$$

$$WUE = Y/ET$$

where  $R$  (mm) is the rainfall during the growth period and  $\Delta S_i$  (mm) is the reduction in soil water storage from the sowing to maturity stage. In this paper, ET refers to water consumption.  $Y$  is the grain yield ( $kg\ ha^{-1}$ ).

#### Soil temperature

Soil temperature was recorded in the 5 and 15 cm soil profiles using mercury-in-glass geothermometers (Ren et al. 2008). In ridge and furrow configurations ( $R_2F_2$  and  $R_3F_2$ ), soil temperature was measured as the average value of samples that were taken on the ridges, sides and furrows according to horizontal height in each plot. Soil temperature was measured between two plants in flat planting. Soil temperature was observed at 08:00, 10:00, 12:00, 14:00, 16:00 and 18:00 at 10 day intervals between sowing and harvesting during the two trial years. The mean daily topsoil temperature (at 5 and 15 cm) was calculated as the mean of the three daily readings.

#### Leaf area index

The leaf area index (LAI) in each plot was measured at the jointing, tasseling and filling stages.

Five maize plants were selected to record green leaf area both on ridges and in furrows respectively (Liu et al. 2018). The LAI was calculated by dividing total green leaf area (leaf length  $\times$  maximum width  $\times$  0.75) by the plant density (Duan et al. 2021). Population LAI was the sum of maize LAI on ridges and in furrows.

#### Dry matter accumulation and grain yield

The dry matter per plant was measured at the jointing, tasseling, filling and maturity stages. Maize plants were kept at 105 °C for 30 min and then oven-dried at 75 °C for over 48 h to obtain dry matter weight ( $\text{g plant}^{-1}$ ). Five maize plants were selected both on ridges and in furrows to determine dry matter accumulation per plant. Population dry matter accumulation was the sum of dry matter accumulation on ridges and in furrows. Maize yield and its components (kernel number per ear and 100-kernel weight) were estimated by harvesting, threshing, and air-drying the grain from  $3.0 \times 3.0 \text{ m}^2$  subsampling plots that were placed randomly in ridges, furrows and flat-cropped maize. The grain yield was considered the standard yield (grain water content of 14%). The source–sink ratio (SSR) was calculated as the ratio of post-anthesis dry matter accumulation per plant to kernel number per plant (Chen et al. 2016).

#### Maize canopy and radiation use efficiency

During the tasseling stage (VT) and physiological maturity stage (R6) of maize, the weather was sunny. From 10:00 to 12:00 in the morning, the LP-80 canopy meter was used to measure the canopy photosynthetically active radiation (PAR,  $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) of the ear layer and the bottom layer, which was repeated three times for each plot. The light transmittance rate and radiation use efficiency (RUE,  $\text{g MJ}^{-1}$ ) were as follows (Zheng et al. 2022):

$$\begin{aligned} \text{Light transmittance rate} &= I_t/I_0 \\ K &= (-1/\text{LAI}) \times \ln(I_t/I_0) \\ \text{IPAR} &= Q_a \times [1 - \exp(-K \times \text{LAI})] \\ \text{RUE} &= \text{DMA}/\text{IPAR} \end{aligned}$$

where  $I_t$  is the photosynthetically active radiation at different canopy heights, and  $I_0$  is the photosynthetically active radiation at the top of canopy.  $K$  is the extinction coefficient, IPAR ( $\text{MJ m}^{-2}$ ) is canopy

intercepted photosynthetically active radiation,  $Q_a$  ( $\text{MJ m}^{-2}$ ) is the total intercepted radiation, and DMA is the dry matter accumulation.

#### 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 the 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 analyses were performed using IBM SPSS Statistics 22.0.

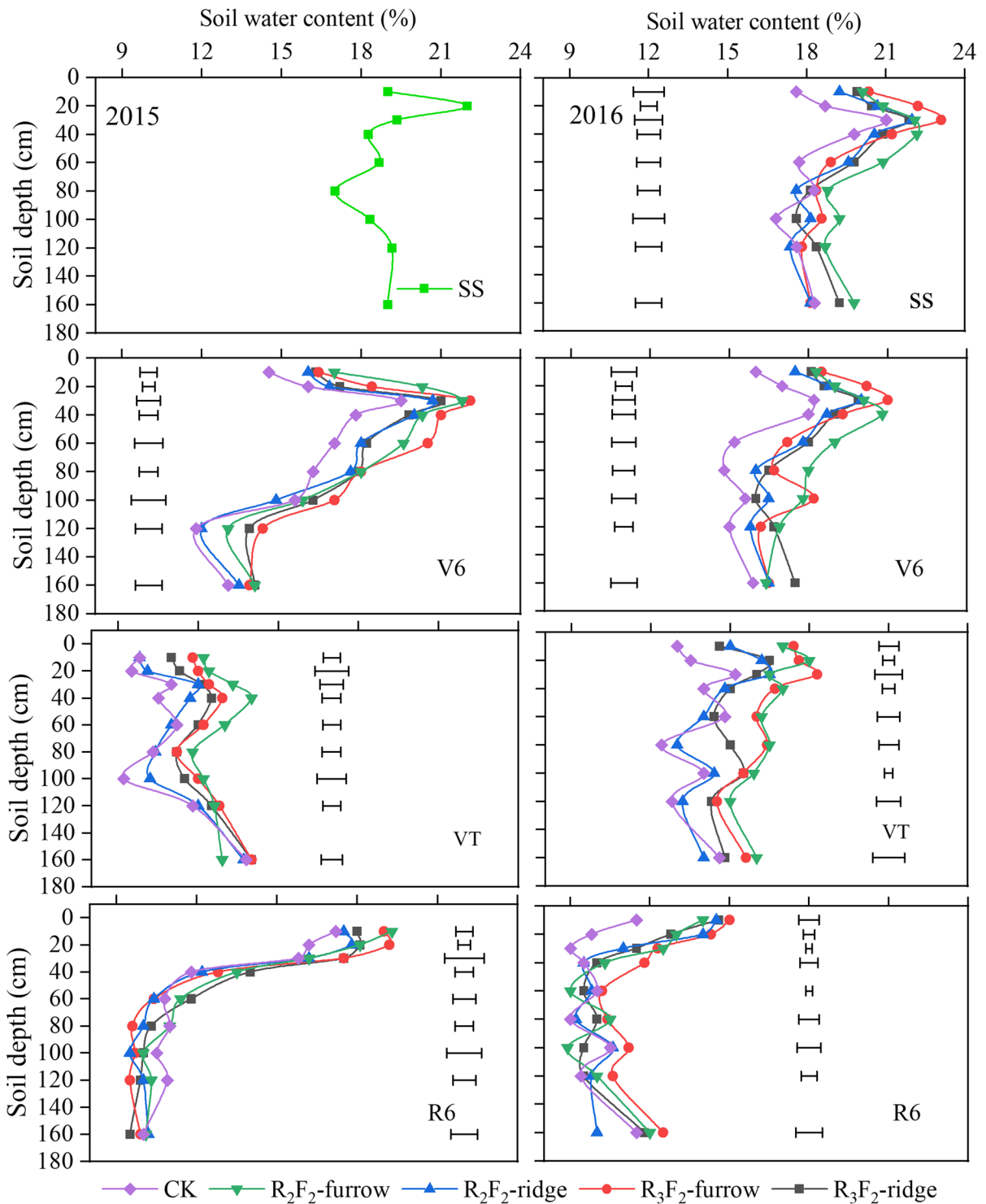
## Results

### Soil water

The ridge and furrow configuration significantly affected the distribution of soil water content (SWC) on ridges and in furrows (Fig. 3). The SWC in the furrow (0–40 cm layer) was significantly higher than that on the ridge and CK. SWC of  $R_2F_2$  and  $R_3F_2$  was 6.8% and 5.4% higher than that of CK at the jointing and tasseling stages, respectively. No significant difference was found between them at physiological maturity (V6) stage. In 2015 and 2016 growing seasons, the average SWC in 0–160 cm soil depths of  $R_2F_2$  and  $R_3F_2$  increased by 5.1% and 7.8% ( $P < 0.05$ ), respectively.

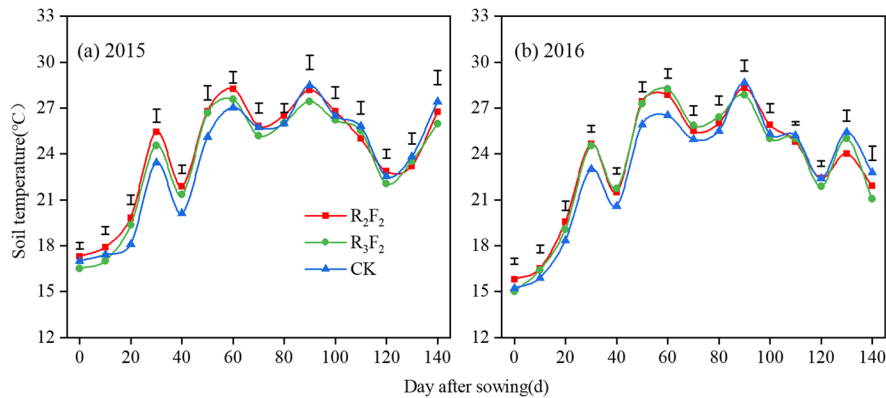
### Soil temperature

The surface soil temperature (0–15 cm) showed a trend of increasing initially and then decreasing during the remaining growing season, reaching the maximum value at the tasseling period (Fig. 4). The average topsoil temperature in the ridge and furrow configuration was higher than that in CK during two maize growth seasons, 2.8 °C and 2.3 °C in 2015 and 2016, respectively. Compared with CK, the  $R_2F_2$  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, and by 0.6 °C and 0.47 °C from the jointing to tasseling stage (60–90 d), respectively. However, there was a nonsignificant



**Fig. 3** Effects of ridge and furrow configuration on dynamic of soil moisture at various growth stages during 2015 and 2016 growing seasons. Note: SS, V6, VT and R6 represent sowing, jointing, tasseling and physiological maturity stage. CK represents the conventional flat

ting 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



**Fig. 4** Effect of ridge and furrow configuration on soil temperature 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. The bars showed the least significant difference at 5% level

difference among the three planting patterns during the tasseling to maturity stage (90–140 d).

The diurnal variation in soil temperature at different depths is shown in Fig. 5. At 30 d and 60 d after sowing, the daily soil temperature at the 5 and 10 cm layers showed a trend of first increasing and then decreasing, with the expression of furrow > on ridge > CK. Compared with those of CK,  $R_2F_2$  and  $R_3F_2$  in the 5 cm layers increased by 1.9 and 1.4 °C and increased by 0.9 and 0.5 °C at the 10 cm depth layers, respectively. Soil temperature (15 cm soil depth) 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 the ridge and furrow configuration weakened.

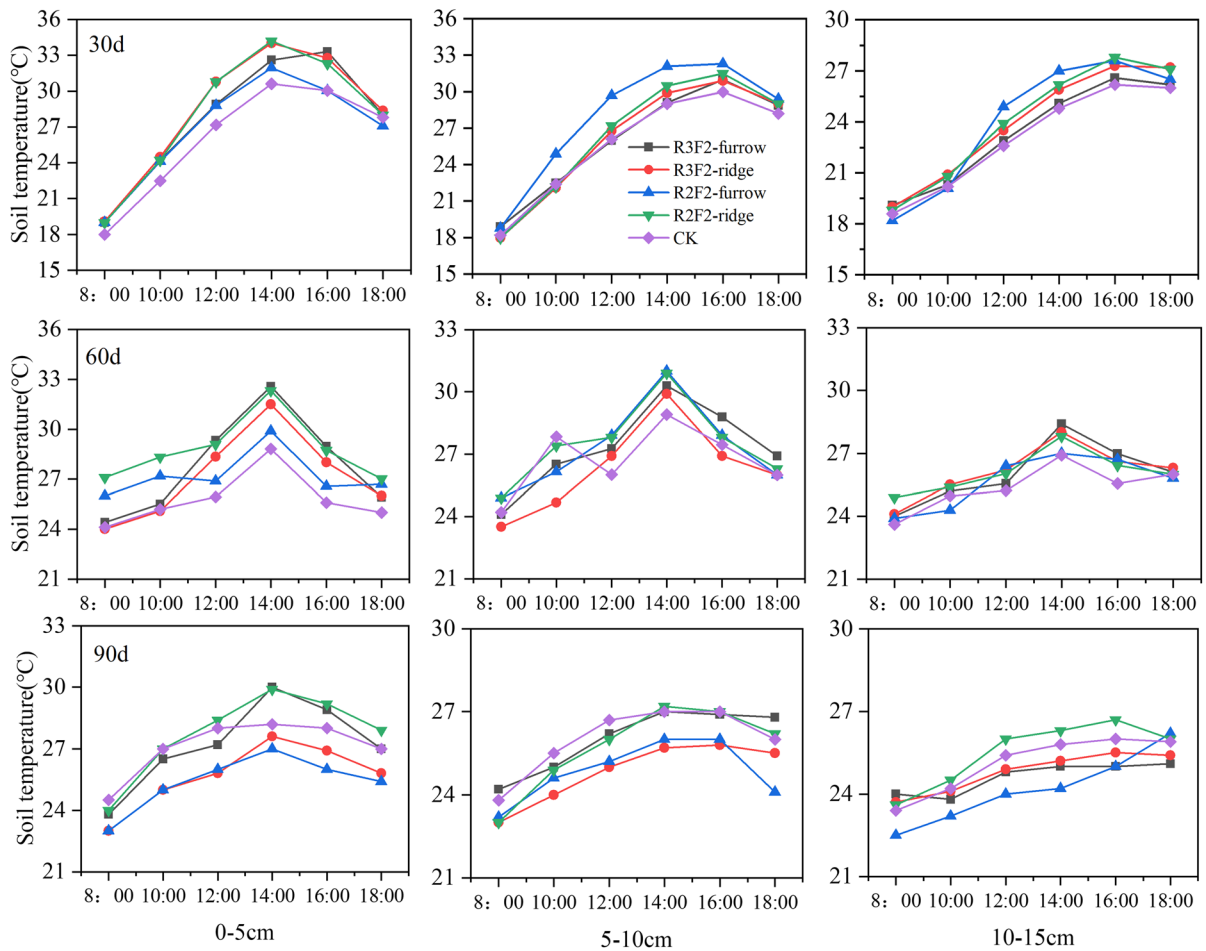
#### Maize canopy structure and photosynthesis traits

The ridge and furrow configuration notably influenced leaf area per maize plant after tasseling stage. The average leaf area per plant in the furrows of  $R_3F_2$  and  $R_2F_2$  was significantly higher (13.2% and 15.6%, respectively) than that under CK, while no significant differences were found between them ( $P > 0.05$ ). Additionally, there were nonsignificant differences between ridges ( $R_3F_2$  and  $R_2F_2$ ) and CK. In summary, ridge and furrow configuration significantly improved the population LAI of maize

during different growing stages (Fig. 6). Compared with CK, the two-year average LAI in  $R_2F_2$  and  $R_3F_2$  increased by 18.1% and 11.6%, respectively ( $P < 0.05$ ). The results showed that the optimized ridge-furrow configuration ( $R_2F_2$ ) improved the maize population leaf area index due to more green leaf area per plant in the furrow.

The canopy light transmittance rate (LTR) of the ear layer and bottom layer under the ridge and furrow configuration was higher than that of CK (Table 1). At the tasseling (VT) stage,  $R_2F_2 > R_3F_2$ , while there was no significant difference between them at the physiological maturity (V6) stage. On average, for two years, the LTR of  $R_2F_2$  treatment increased by 10.0% and 27.2% at the 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.

The ridge and furrow configuration 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 the 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 the furrow maintained a relatively higher Pn from the V6 to R6 stages, but there was no significant difference was found between  $R_3F_2$  and  $R_2F_2$  treatments.



**Fig. 5** Effects of ridge and furrow configuration 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

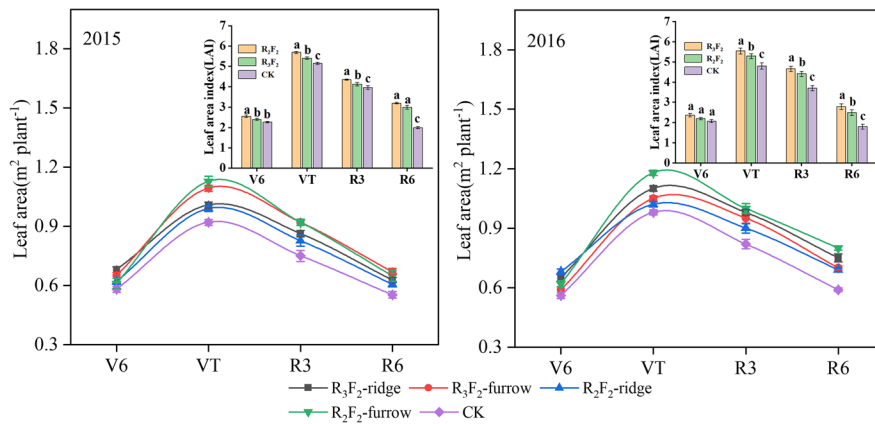
#### Dry matter accumulation and source–sink ratio

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

#### Grain yield and resource use efficiency

The ridge and furrow configuration markedly increased the 100-grain weight in furrows and ultimately resulted in an improvement in grain yield (Table 2). Compared with CK,  $R_2F_2$  and  $R_3F_2$  resulted in an increase in the two-year average grain yield by 20.5% and 12.4%, respectively. Ridge and furrow configuration brought an obvious increase of radiation use efficiency (RUE) and water use efficiency (WUE). The  $R_2F_2$  and  $R_3F_2$  treatments increased





**Fig. 6** Effects of ridge and furrow configuration 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<sub>2</sub>F<sub>2</sub> represents the planting system with two rows plants in each ridge and furrow, respectively; R<sub>3</sub>F<sub>2</sub>

represents the planting pattern with three rows in a ridge and two rows in a furrow, respectively. V6, VT, R3 and R6 represent the jointing, tasseling, filling and physiological maturity stages, respectively. Data represent means ± SE (n = 3)

**Table 1** Effects of ridge and furrow configuration 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 <sub>3</sub> F <sub>2</sub>	11.9 ± 0.15b	41.4 ± 0.2b	8.4 ± 0.1b	23.1 ± 0.5a
	R <sub>2</sub> F <sub>2</sub>	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 <sub>3</sub> F <sub>2</sub>	14.3 ± 0.36b	31.4 ± 0.6a	8.7 ± 0.2b	20.4 ± 0.3b
	R <sub>2</sub> F <sub>2</sub>	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 <sub>3</sub> F <sub>2</sub>	13.1 ± 0.4b	36.4 ± 1.8a	8.5 ± 0.3b	22.7 ± 1.3a
	R <sub>2</sub> F <sub>2</sub>	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

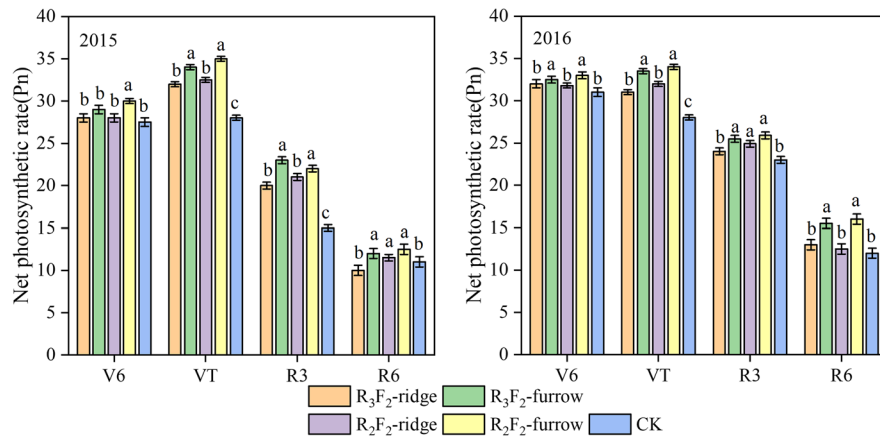
Note: CK represents the conventional flatting without ridge; R<sub>2</sub>F<sub>2</sub> represents the planting system with two rows plants in each ridge and furrow, respectively; R<sub>3</sub>F<sub>2</sub> represents the planting pattern with three rows in a ridge and two rows, respectively. VT and 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)

RUE by 28.2% and 17.8%, and WUE increased by 26.2% and 20.1%, respectively.

Correlation analysis

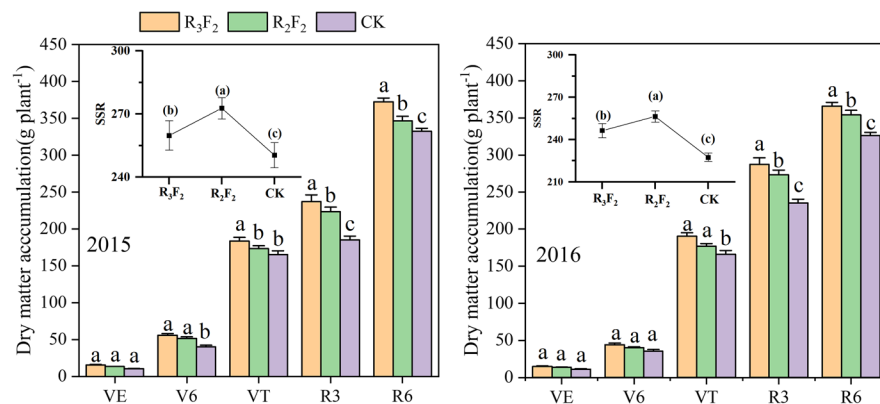
Correlation analysis (Fig. 9) showed that grain yield was positively correlated with population Pn, canopy light transmittance of the bottom layer, LAI

and soil temperature at 0–15 cm depth (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 the 0–5 cm and 0–15 cm soil layers.



**Fig. 7** Effects of ridge and furrow configuration on net photosynthetic rate (Pn) of maize during 2015 and 2016 growing seasons. Note: CK represents the conventional flatting without ridge; R<sub>2</sub>F<sub>2</sub> represents the planting system with two rows plants in each ridge and furrow, respectively; R<sub>3</sub>F<sub>2</sub> represents

the planting pattern with three rows in a ridge and two rows in a furrow, respectively. V6, VT, R3 and R6 represent the jointing, tasseling, filling and physiological maturity, respectively. Data represent means  $\pm$  SE (n = 3)



**Fig. 8** Effects of ridge and furrow configuration on dry matter accumulation (DMA) and source-sink ratio (SSR) during 2015 and 2016 growing seasons. Note: CK represents the conventional flatting without ridge; R<sub>2</sub>F<sub>2</sub> represents the planting system with two rows plants in each ridge and furrow, respectively; R<sub>3</sub>F<sub>2</sub> represents the planting pattern with three rows in a

ridge and two rows in a furrow, respectively. VE, V6, VT, R3 and R6 represent the seedling, jointing, tasseling, filling and physiological maturity stages, respectively. Different lower-case letters in a column denote significant differences among treatments at  $P < 0.05$ . Data represent means  $\pm$  SE (n = 3)

## Discussion

The ridge and furrow configuration is a new planting pattern, of which the furrows serve as water infiltration areas, and both the ridges and furrows served as planting areas. Ridge and furrow configuration improved soil temperature and water allocation to meet maize water requirements on ridges and in furrows, thus promoting maize plant germination and

emergence (Li et al. 2013, 2017). In ridge and furrow configuration systems, the flow water in furrows infiltrates the ridge-furrow configuration by capillarity forces, and laterally infiltrated water meets the needs of crop growth on ridges. In our study, the ridge and furrow configuration could significantly improve topsoil water content in furrows because of water transfer by capillary action and vapor transfer from deep soil (Zhang et al. 2019), and R<sub>2</sub>F<sub>2</sub> was

**Table 2** Effects of ridge and furrow configuration on grain yield, its components, water use efficiency (WUE), and radiation use efficiency (RUE) of maize during 2015 and 2016 growing seasons

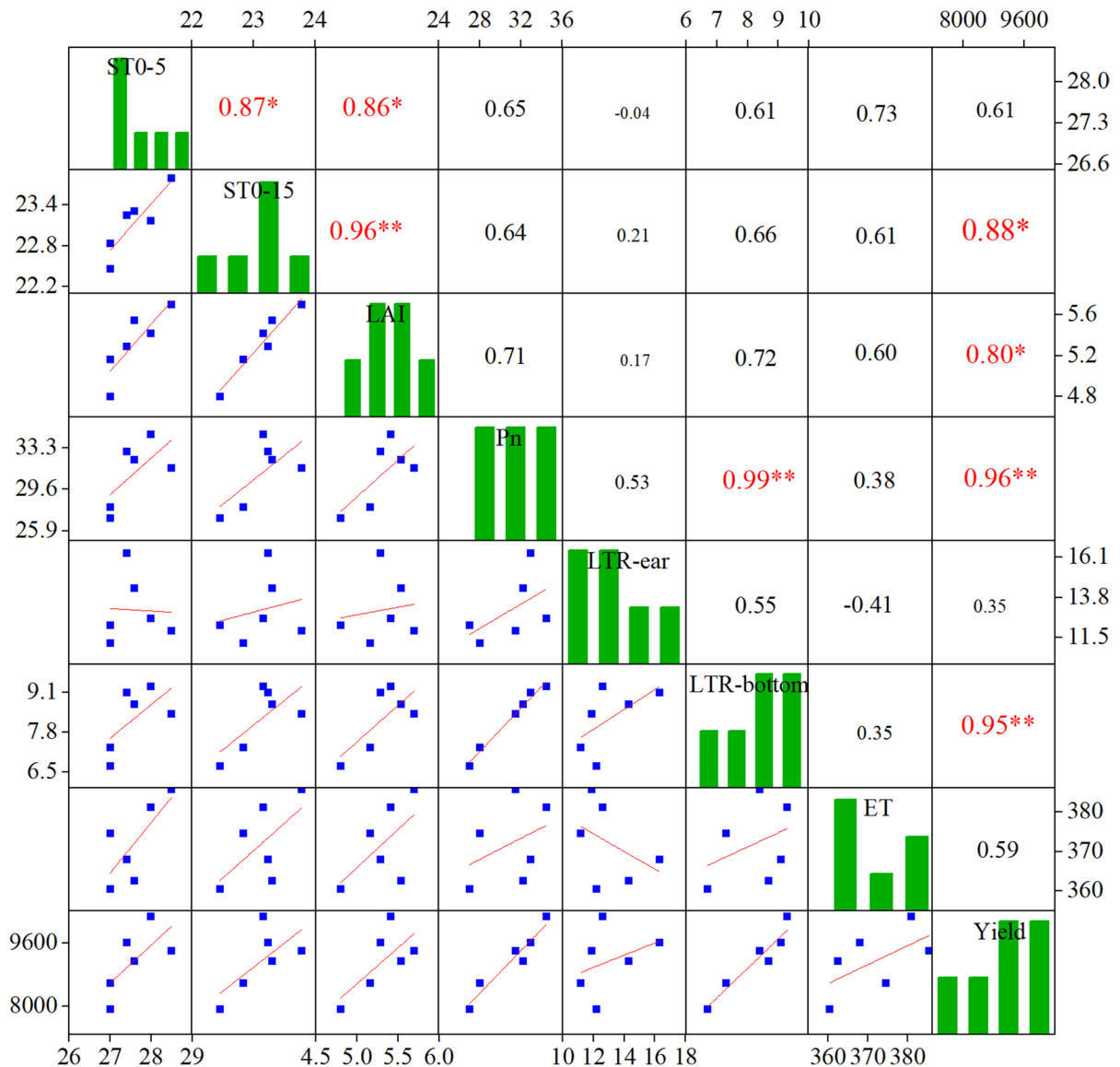
Year	Treatments	Kernel number per spike	100-grain weight (g)	Yield		ET (mm)	WUE (kg ha <sup>-1</sup> mm <sup>-1</sup> )	RUE (g MJ <sup>-1</sup> )
				(kg ha <sup>-1</sup> )	(kg ha <sup>-1</sup> )			
2015	R <sub>3</sub> F <sub>2</sub> -ridge	616 ± 10b	32.8 ± 0.1b	8825 ± 85c	9400 ± 243b	385.6 ± 5.4a	23.9 ± 2.2b	0.93 ± 0.02a
	R <sub>3</sub> F <sub>2</sub> -furrow	620 ± 12b	33.5 ± 0.4ab	10,262 ± 101b				
	R <sub>2</sub> F <sub>2</sub> -ridge	654 ± 11a	32.5 ± 0.2b	10,082 ± 95b	10,274 ± 105a	381.1 ± 3.6a	26.0 ± 2.5a	0.97 ± 0.03a
	R <sub>2</sub> F <sub>2</sub> -furrow	648 ± 9a	34.4 ± 0.3a	10,465 ± 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 <sub>3</sub> F <sub>2</sub> -ridge	608 ± 10b	29.6 ± 0.2c	8961 ± 115c	9137 ± 189b	362.5 ± 4.3a	22.8 ± 2.1a	0.91 ± 0.02b
	R <sub>3</sub> F <sub>2</sub> -furrow	618 ± 12b	32.5 ± 0.4a	9401 ± 106b				
	R <sub>2</sub> F <sub>2</sub> -ridge	635 ± 10a	31.8 ± 0.2b	9328 ± 112b	9606 ± 234a	368.0 ± 5.4a	23.1 ± 1.5a	1.03 ± 0.05a
	R <sub>2</sub> F <sub>2</sub> -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
ANOVA								
	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<sub>2</sub>F<sub>2</sub> represents the planting system with two rows plants in each ridge and furrow, respectively; R<sub>3</sub>F<sub>2</sub> 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)

higher than that of R<sub>3</sub>F<sub>2</sub>. In our research, the effect of ridge and furrow system on soil temperature was greater in the early growing period and weakened with crop growth. The ridge and furrow patterns provided better soil temperature in furrow during the early growth stages, possibly because the ridge and furrow pattern simultaneously inhibited water evaporation and heat losses (Ren et al. 2008). Moreover, the warming effect of R<sub>2</sub>F<sub>2</sub> was significantly better than that of R<sub>3</sub>F<sub>2</sub>, indicating that increasing the ratio of furrow/ridge improves soil water and temperature availability (Zhang et al. 2022). Meanwhile, a higher soil moisture in the upper layer could boost green leaf stoma opening to increase photosynthetic and chlorophyll content (Sunoj et al. 2016). This could explain why ridge and configuration could maintain a greater dry matter accumulation during the post-tasseling period. Ridge and furrow configuration significantly increased grain yield as well as not excessive water consumption and resulted in a higher WUE (Dong et al. 2018; Liu et al. 2020a, b; Wu et al. 2015). Moreover, our study revealed that the effect of increasing maize yield for two rows on the ridges was greater

than those with three rows, which may be due to ridge width affecting the cumulative water infiltration (Bargar et al. 1999; Liu et al. 2010; Zhang et al. 2015).

Canopy structure is a key factor affecting the light transmittance and photosynthetic characteristics (Liu et al. 2018; Zheng et al. 2022). Compared with CK, R<sub>2</sub>F<sub>2</sub> and R<sub>3</sub>F<sub>2</sub> increased the light transmittance of the bottom layer at the tasseling stage, which improved the contribution of the lower leaves to photosynthetic product accumulation. R<sub>2</sub>F<sub>2</sub> and R<sub>3</sub>F<sub>2</sub> significantly improved the plant LAI and Pn in the furrow and delayed leaf senescence post tasseling stage. The source–sink relationship is closely related to yield formation (Chen et al. 2016). This study showed that the increase in the source sink ratio was due to the improvement of photosynthetic product assimilation after flowering by the ridge and furrow configuration system, and ultimately promoted dry matter accumulation and yield formation. Compared with CK, the ridge and furrow configuration enhanced a higher photosynthetic capacity per plant and longer duration of grain filling (Liu et al. 2018), resulting in an increase in grain yield and radiation use efficiency.



**Fig. 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 the canopy light transmittance of ear layer, LTR-bottom represents the canopy light transmittance of bottom layer, ET represents the evapotranspiration

The yield-increasing effect benefits from the increase of 100-grain weight of crops in furrow (Table 2). Furthermore, grain yield of  $R_2F_2$  was better than that of  $R_3F_2$ , indicating that the two rows of plants on ridges could maximize the edge advantage of crops on ridges and improve intraspecific nutrient and water competition (Li et al. 2020a, b). Some simulation experiments (Chen et al. 2011; Zhang et al. 2012, 2015) about soil

water infiltration have proven that lateral infiltrated water (irrigation) could meet crop growth needs on ridges and in furrows. In the future, we should study the effects of ridge and furrow configuration on the physiological characteristics of maize and its regulatory mechanism, e.g. carbon and nitrogen metabolism and root distribution. Additionally, the further effect of increasing production and saving water provided

by supplementary irrigation offers a new idea for the development of water-saving agriculture.

## Conclusions

In the northwestern region of China, the ridge and furrow configuration improved the soil water-temperature environment, promoted maize canopy growth, and ultimately obtained a 20.5% increase of grain yield. This increase was mainly attributable to an optimized maize canopy structure (a higher post-flowering photosynthetic capacity and enhanced light energy interception) and source–sink relationships, resulting in higher dry matter accumulation and grain yield. Overall, the R<sub>2</sub>F<sub>2</sub> treatment (two rows of maize both on ridges and in furrows) could be regarded as a more suitable configuration for improving maize yield in Northwestern China.

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## Declarations

**Conflict of interest** 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.

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