Environ Sci Pollut Res (2017) 24:23168–23179
DOI 10.1007/s11356-017-9955-8

RESEARCH ARTICLE

Optimum ridge-to-furrow ratio in ridge-furrow mulching systems for improving water conservation in maize (*Zea may* L.) production

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Received: 15 February 2017 / Accepted: 11 August 2017 / Published online: 21 August 2017

Abstract Water-saving cultivation techniques have been attracting increased attention worldwide. Ridge-furrow mulching system (RFMS), as a prospective rainwater harvesting system, has been widely adopted in arid and semi-arid areas. Field experiments were conducted in 2014 and 2015 to compare soil water storage, soil temperature, maize yield, and water use efficiency (WUE) among different ridge/furrow width arrangements in RFMS comprised of three different ridge/furrow ratios, i.e., 40:70 cm (RFMS40), 55:55 cm (RFMS55), and 70:40 cm (RFMS70) and conventional flat planting (CK, without mulching). All these four planting patterns had the same planting density. The RFMS technique not only increased soil temperature of the ridge but also improved soil moisture of the furrow when compared with CK. These positive effects were intensified with increasing ridge/furrow ratio in RFMS. This improvement in RFMS resulted in more stable and earlier seedling establishment. Maize yields were increased by 26.1, 36.4, and 50.3% under RFMS40, RFMS55, and RFMS70 treatments, respectively, when compared with CK across both years. RFMS did not decrease the evapotranspiration significantly, compared with CK. Eventually, WUE were enhanced by 25.7, 38.7, and 53.9% in RFMS40, RFMS55, and RFMS70, respectively, compared with CK. Taken together, our results suggest that increasing ratio of ridge to furrow in the case of RFMS70, can be recommended as high-yielding cultivation pattern for promoting precipitation use efficiency in the rain-fed semi-arid areas.

Keywords Rainwater harvesting system · Ridge-furrow mulching systems · Ridge/furrow ratio · Soil moisture · Soil temperature

Introduction

Agricultural productivity in arid and semi-arid areas is mainly limited by the lack of water resources (Zhou et al. 2009; Gan et al. 2013; Wang et al. 2015b). Crop management practices must shift from emphasizing production per unit area towards maximizing the production per unit of precipitation consumed (Piao et al. 2010; Wu and Ma 2015). In the Loess Plateau region of China, low and irregular precipitation is the main water resource for crop growth due to unavailability of river and groundwater resources (Ren et al. 2010; Liu et al. 2014a, b). Furthermore, nearly half of the annual precipitation in some parts of this region occurs between July and September (Li et al. 2000a, b; Wang et al. 2015b). Most of the rainfalls are either too low in intensity to be available for crops or may occur in the form of intense thunderstorms which usually cause runoff and soil erosion (Zhao et al. 2005; Hu et al. 2014). Therefore, meeting these challenges to increase agricultural productivity in this region will be possible only if precipitation use efficiency can be maximized by collecting more light rains and retaining runoff from heavy rainstorms, while keeping soil evaporation in control (Li et al. 2016, 2017). Many studies have suggested that

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development of rainwater harvesting technologies that can be adopted by farmers is urgently needed to increase the precipitation use efficiency (Turner and Meyer 2011; Gan et al. 2013; Liu et al. 2014a, b).

The ridge-furrow mulching system (RFMS) with alternate ridges and furrows (Fig. 1) is one of the innovative water-saving technologies which aim to drastically increase the precipitation use efficiency in rain-fed farming systems of arid and semi-arid areas (Li et al. 2006; Gu et al. 2016; Li et al. 2016). In this system, the mulched hemispherical ridges are used for collecting runoff and serve to be a rainwater harvesting zone, while mulched or non-mulched furrow serve to be a planting zone, resulting in deeper water penetration and reduce water loss/evaporation and soil erosion (Zhou et al. 2009; Gan et al. 2013; Li et al. 2017).

The great success of RFMS system in different regions of the world is mainly because of better collection of light or heavy rain driven by ridges/furrows effect that leads to a high runoff efficiency of precipitation (Wang et al. 2007). In order to make effective use of light and heavy rain, choosing appropriate ridge/furrow ratio plays a critical role in the development of more effective RFMS systems (Wang et al. 2015b). The RFMS can vary in its alternative ridge and furrow width or their ratio to change the land solar surface and characteristics of the crests which in turn alter rainwater infiltration and distribution of the field (Jiang and Li 2015). Based on this, we hypothesized that varied ridge/furrow ratios in RFMS may modify the micro-topographic heterogeneity which could further change the soil temperature and water availability to the plants and therefore crop yield and water use efficiency (WUE).

For instance, Wang et al. (2015a) suggested that mulched-ridge widths had significantly positive effect on soil moisture, temperature, and nutrient status of the topsoil rather than the bottom of furrows in oat production. In addition, this study also indicated that the grain yield, WUE and soil water storage increased with increasing ratio of ridge to furrow. Wang et al. (2007) illustrated that the optimum ridge/furrow ratio for potato production ranged from 39:60 to 48:60 cm along the years. Wang et al. (2015b) showed that the optimum width of the ridge was 35 cm with the furrow width of 60 cm for alfalfa and further increasing width of ridge significantly decreased WUE. In maize, Li and Gong (2002) reported that the ridge/furrow ratio of 120:60 cm was superior to 60:60 cm layout.

In general, wider mulched-ridge in RFMS exhibited more merits on soil moisture, crop growth, grain yield and WUE than thinner one. However, the major disadvantage of using wide ridge in RFMS system was that a large land area of ridges and relevant extended mulching material were required to collect water. The extensive construction to build ridges will need increased labor force and extensive use of plastic film for mulching may cause serious white pollution to the soil and environment (Janette and Tim 2006). Therefore, determination of optimum ridge/furrow ratio for developing a more effective RFMS is indispensable, although complex if the economic return and environment concern were taken into consideration.

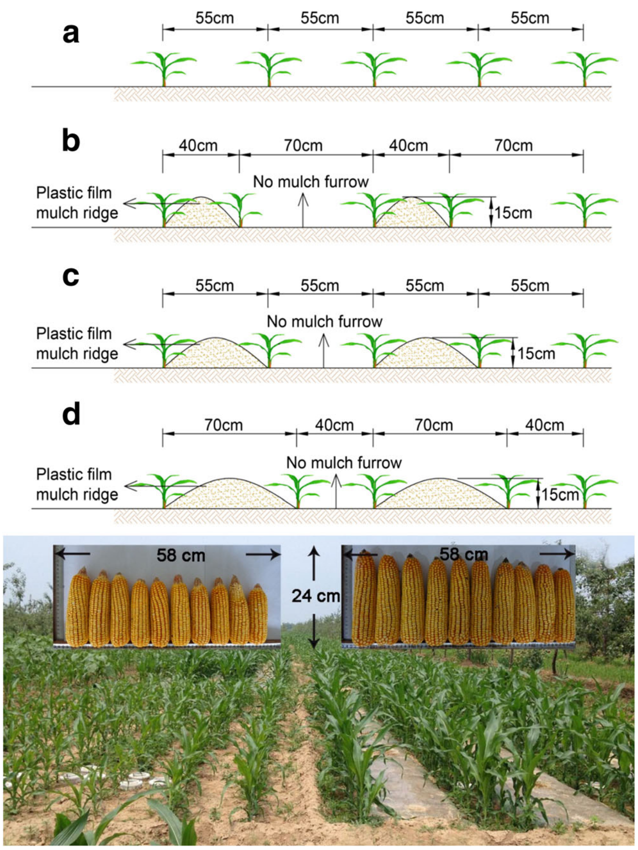

Fig. 1 Schematic diagram for conventional flat planting, CK (**a**); ridge-furrow mulching system with ridge/furrow ratio of 40:70 cm, RFMS40 (**b**), 55:55 cm, RFMS55 (**c**), and 70:40 cm, RFMS70 (**d**), and the field performance of RFMS70 (right) in comparison with CK (left)

Nevertheless, there are few previous studies that have been carried out to determine the appropriate ridge/furrow ratio on maize production (Li and Gong 2002) and several case studies in other crops (Wang et al. 2007, 2015a, b). Optimum ridge/furrow ratio depends on several factors including precipitation characteristic, soil type, crops species, land topography, and climate (Wang et al. 2005; Li et al. 2007; Li et al. 2008; Gan et al. 2013). Literature review further reveals that no adequate attention has been paid to soil moisture and temperature difference or heterogeneity between alternate ridges and furrows caused by the micro-topographic alteration described earlier. This effect should be considered seriously for its significant role in collecting and retaining the precipitation (Jia et al. 2006; Li et al. 2013; Dong et al. 2014). This study aims to (i) examine the effect of various ridge/furrow ratios on soil moisture and temperature between alternate ridges and furrows caused by micro-topographic heterogeneity, (ii) compare the WUE and maize yield under

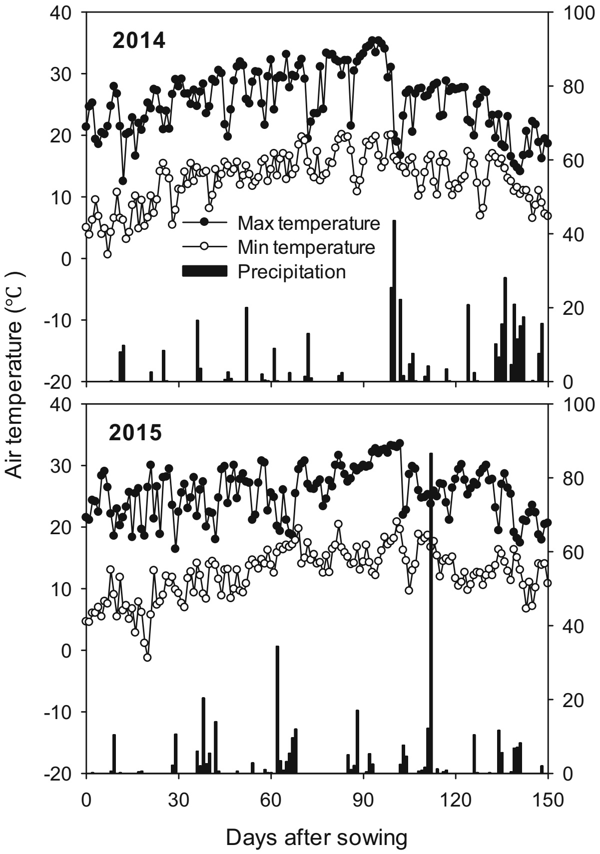

Fig. 2 The daily maximum/minimum temperature and precipitation during maize growing seasons in experimental fields at Changwu Agricultural Research Centre in Shaanxi Province, China, in 2014 and 2015

conventional flat planting and there different ridge/furrow ratios in RFMS, and (iii) determine the appropriate ridge/furrow ratio for maize production in rain-fed cropping systems of the Loess Plateau region in China.

Materials and methods

Site description

Field experiments were conducted in 2014 and 2015 at the Changwu Agricultural Research Centre in Shaanxi Province, China (107° 40′ E, 35° 12′ N). The experimental site is a typical representative of Loess Plateau region. The mean annual temperature is 9.9 °C. The average annual sunshine is 2230 h, and the average annual frost-free period lasts for 171 days. The average annual rainfall is approximately 580 mm and 57% of the total annual rainfall occurs between July and September. Both air temperature and rainfall during the experimental period were monitored by an automated meteorological observation station at the Changwu Agricultural Research Centre, located approximately 500 m away from the experimental site. The mean daily maximum/minimum temperatures and precipitation during the experimental period are shown in Fig. 2. The annual precipitation in 2014 and 2015 was 616.9 and 578.2 mm, while the precipitation during maize growing season was 392.0 and 346.7 mm, respectively. The soil type in the area is dark loessial soil according to the Chinese soil taxonomy and the soil properties in 0–20 cm soil layers are shown in Table 1.

Experimental design and field management

The experiment was conducted according to completely randomized design and comprised of four treatments: (i) conventional flat planting without mulch, CK (Fig. 1a); (ii) ridge-furrow mulching system with ridge/furrow ratio of 40:70 cm, RFMS40 (Fig. 1b); (iii) RFMS with ridge/furrow ratio of 55:55 cm, RFMS55 (Fig. 1c); and (iv) RFMS with ridge/furrow ratio of 70:40 cm, RFMS70 (Fig. 1d). Each treatment was replicated three times and each plot was 8.0 m long and 3.8 m wide with an area of 30.4 m^2. The field was tilled about 1 week before sowing. At the time of tilling, a basal dose of fertilizer was spread evenly over the topsoil at a rate of 180 kg N ha^{-1} and 40 kg P ha^{-1}. One day before sowing, ridges and furrows were formed alternately in each plot and then mulching was applied to the RFMS treatments. Ridges were covered with 0.008-mm-thick plastic film (40, 55, and 70 cm wide for RFMS40, RFMS55, and RFMS70 patterns), while furrows were kept bare (uncovered).

The spring maize (Xianyu335) was sown on April 28, 2014, and on April 22, 2015, at the same plant density of 72,750 plants ha^{-1} for all treatments. The plant spacing in the row was 25 cm. An additional 45 kg N ha^{-1} as a topdressing was applied into the furrow in early July. Maize was harvested on September 27, 2014 and September 15, 2015. After harvesting in 2014, the ridge and furrow configurations were left in the field to be re-built in the following year. No

Table 1 Soil chemical properties of the top 0–20 cm layer in experimental fields at Changwu Agricultural Research Centre in Shaanxi Province, China, in 2014 and 2015

Year	pH	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
2014	8.12	13.51	0.87	0.67	14.72	8.74	205.17
2015	8.17	12.30	0.80	0.71	14.64	6.06	189.03

SOM soil organic matter, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium

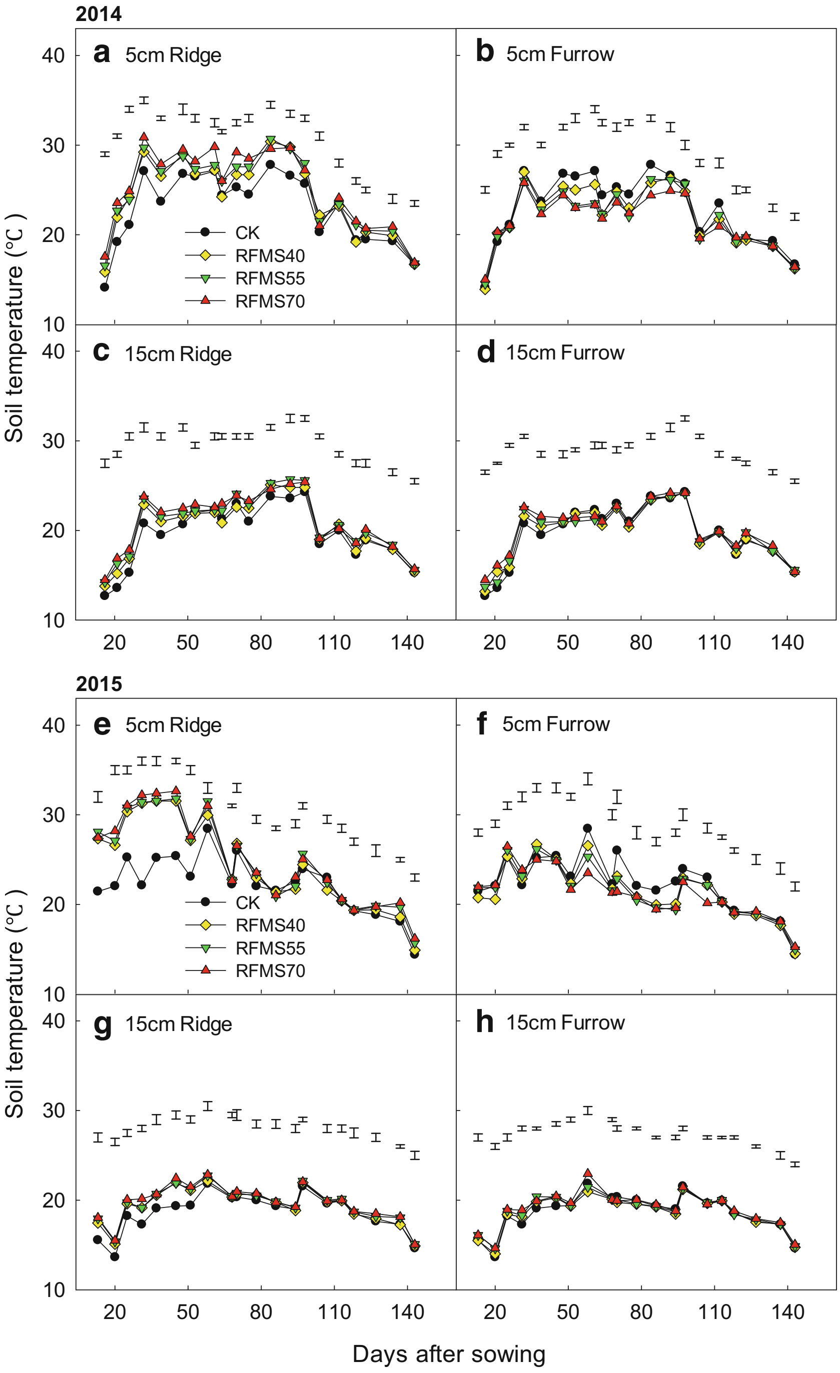

Fig. 3 Changes of soil temperature at different ridge/furrow ratios in RFMS and conventional flat planting at two soil depths (5 and 15 cm) during maize growing seasons in 2014 (**a**–**d**) and 2015 (**e**–**h**). Vertical bars represent the $LSD_{0.05}$ ($n = 3$)

irrigation or herbicide was applied during both years. Weeds were controlled manually.

Sampling and measurements

Soil temperature at the 5 and 15 cm soil depths were recorded using a set of digital thermometers (Shenyang Huashengchang Mechanical and Electrical Equipment Co., LTD, Shenyang, China) which were inserted into the middle of both furrows and ridges for all plots. Soil temperature from sowing to harvesting was recorded approximately every 7 days at 10:00 a.m.

Soil volumetric water content (SVWC, %) dynamics at 3.8 and 20 cm soil depth in both furrows and ridges were measured by using a soil moisture meter (Field Scout™ TDR 300 Soil Moisture Meter, Spectrum Technologies, Inc., Aurora, IL, USA). In addition, the gravimetric water content (GWC) (g g^{-1}) to a depth of 200 cm at 20 cm intervals at sowing time (0 days after sowing, DAS), the jointing stage (40 DAS in 2014, 37 DAS in 2015), the large bell stage (62

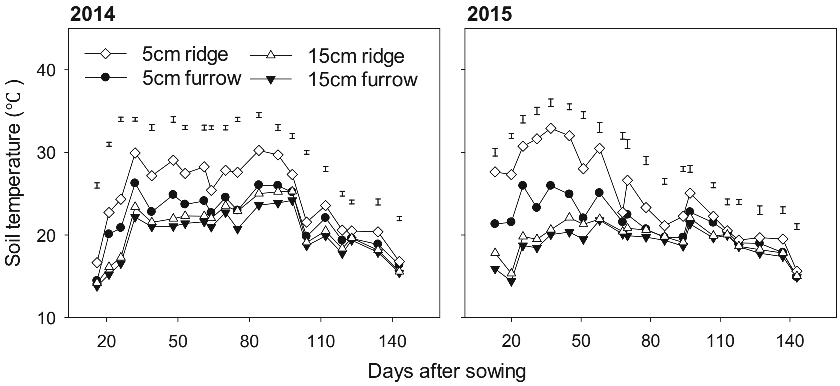

Fig. 4 The soil temperature difference between the ridge and furrow at two soil depths of 5 and 15 cm in 2014 and 2015. Data are the averages of three ridge/furrow ratios. Vertical bars represent the $LSD_{0.05}$ ($n = 3$)

DAS in 2014, 61 DAS in 2015), the tasseling stage (81 DAS in 2014, 82 DAS in 2015), the milk stage (101 DAS in 2014, 105 DAS in 2015), the dough stage (121 DAS in 2014, 126 DAS in 2015), and physiological maturity stage (144 DAS in 2014, 146 DAS in 2015) were measured by drying the soil at 105 °C to a constant weight. Soil cores were sampled from the middle of both furrows and ridges at sowing and harvesting stage. At other sampling times, soil cores were from middle of furrows in RFMS treatments. Before sowing in 2014, soil bulk densities were determined from 0 to 200 cm at 20 cm intervals according to Robertson et al. (1999), listed as 1.25, 1.38, 1.39, 1.41, 1.31, 1.30, 1.32, 1.38, 1.50, and 1.48 g cm^{-3}. The total soil water storage (SWS, mm) in the 200 cm profile was calculated in each plot as follows:

$$\mathrm{SWS\ (mm)} = \sum_{i=1}^{n} (10\rho_i\theta_i h_i) \tag{1}$$

where n is the number of soil layers, ρ_i is the soil bulk density (g cm^{-3}), θ_i is the GWC (g g^{-1}), and h_i is the soil layer thickness (cm) in soil layer i.

Evapotranspiration (ET, mm) in each plot was determined for the whole maize growing season and for the duration between different growth stages as follows:

$$\mathrm{ET(mm)} = P(\mathrm{mm}) + \Delta W(\mathrm{mm}) \tag{2}$$

where P is precipitation, and ΔW is the SWS change (0–200 cm depth) between sowing and harvesting time, or between two different growth stages. Deep percolation and runoff were not considered. WUE was calculated as maize yield (kg ha^{-1}) divided by total ET (mm) during the growing season.

Three representative maize plants were sampled randomly from each plot on the same day of soil sampling throughout the growing season. The plant height was determined by a measuring tape, and the stem diameter was measured using a digital caliper 2 cm above the ground. The leaf area of each sampled plant was measured by multiplying leaf length by the greatest width and multiplying a correction factor (0.75) according to McKee (1964). Leaf area index (LAI) was then calculated as the ratio of the leaf area to the ground area.

Maize plants samples were dried in an oven at 105 °C for 1 h and then at 75 °C to reach a constant weight, and then total plant biomass was recorded. At harvesting time, two central rows having 7 m length were sampled in each plot to determine grain yield with the standard moisture content of 0.12 g H_2O g^{-1} fresh weight. The kernel number per spike was counted on five maize cobs per plot. Weight of 100-kernels was determined by counting a subsample of 1000 grains and obtaining the dry weight. The harvest index (%) was calculated by the total kernel weight divided by aboveground biomass at the mature stage.

Statistical analysis

All statistical analyses were conducted using the SPSS 17.0 software (SPSS Inc., Chicago, IL, USA) to determine treatment effect based on a completely randomized design for both years. Means among different treatments were compared based on the least significant difference test ($LSD_{0.05}$). Figures were generated using the SigmaPlot 12.5 (Systat Software, Inc., San Jose, USA).

Results

Soil temperature

The temporal variations in soil temperature at soil depths of 5 and 15 cm in the furrows and ridges of all the treatments during 2014 and 2015 are shown in Fig. 3. All RFMS treatments increased soil temperature in the ridge and decreased it in the shallow soil (5 cm) of the furrow, compared with CK. Among the three RFMS ratios, the increasing soil temperature in the ridges and decreasing soil temperature in furrows were accentuated with the increasing ratio of ridge to furrow, especially in early

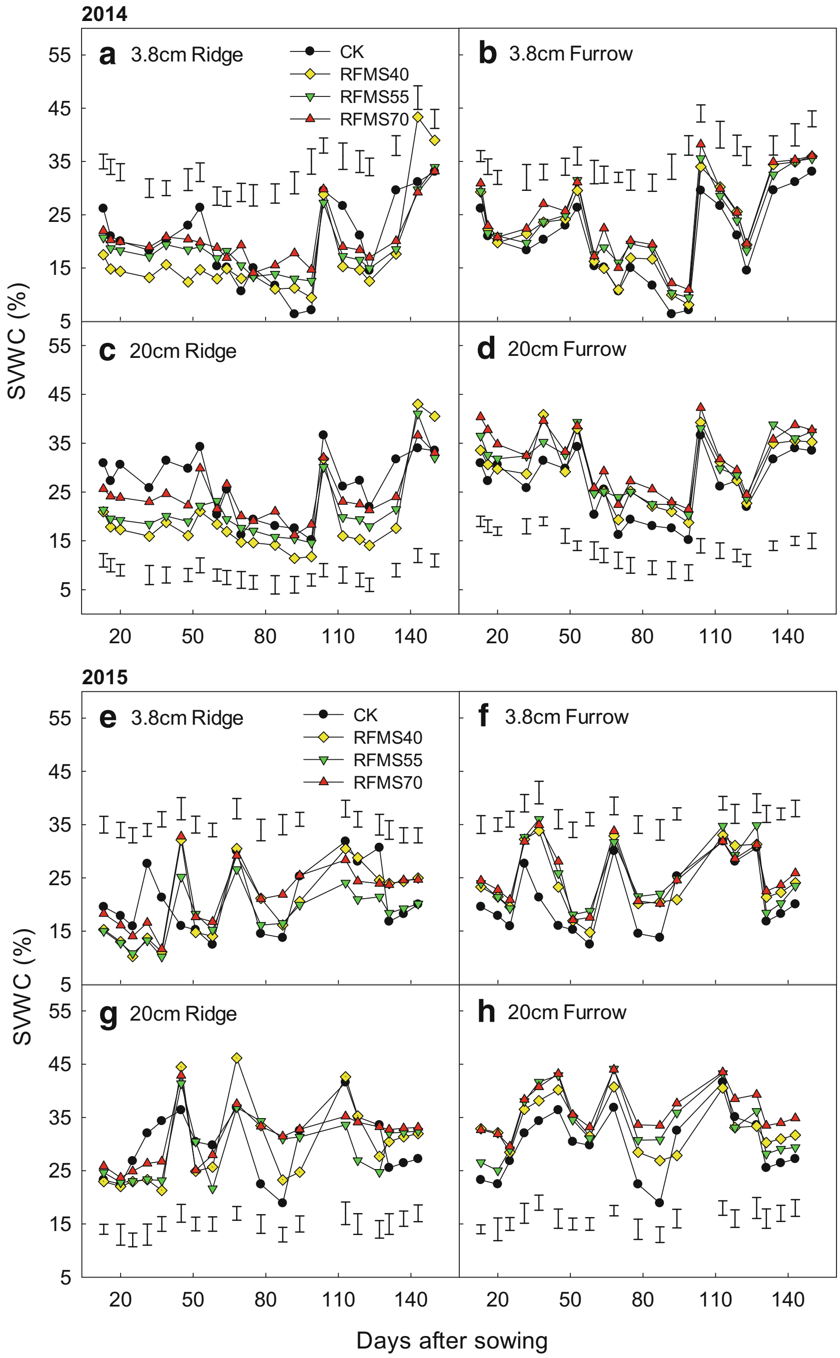

Fig. 5 Changes of soil volumetric water content (SVWC, %) at different ridge/furrow ratios in RFMS and conventional flat planting at two soil depths (3.8 and 20 cm) during maize growing season in 2014 (**a**–**d**) and 2015 (**e**–**h**). Vertical bars represent the $LSD_{0.05}$ ($n = 3$)

growth stages. The 2-year mean soil temperatures for RFMS40, RFMS55, and RFMS70 at soil depth of 5 cm were 22.0, 21.8, and 21.5 °C in the furrow and 24.3, 24.8, and 25.0 °C in the ridge, respectively, in comparison with 22.7 °C in CK, while at soil depth of 15 cm were 19.2, 19.3, and 19.6 °C in the furrow and 20.1, 20.5, and 20.7 °C in the ridge, compared with 19.1 °C in CK. Besides, the average soil temperature of three RFMS ratios in the ridges and furrows at 5 and 15 cm soil depths (Fig. 4) illustrated the micro-topographic heterogeneity. This effect of mulching on soil temperature became weaker with an increase in soil depth.

Soil moisture

Soil volumetric water content

Figure 5 shows the temporal variations of SVWC at soil depths of 3.8 and 20 cm in the furrows and ridges of all the treatments during 2014 and 2015. RFMS treatments increased

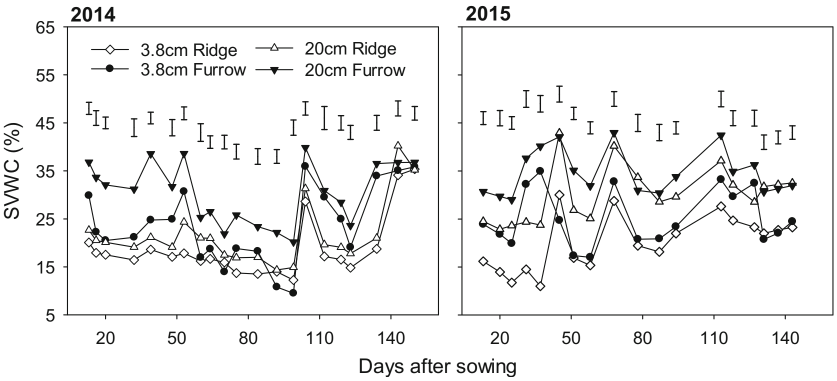

Fig. 6 The soil volumetric water content (SVWC, %) difference between the ridge and furrow at two soil depths of 3.8 and 20 cm in 2014 and 2015. Data are the averages of three ridge/furrow ratios. Vertical bars represent the $LSD_{0.05}$ (n = 3)

SVWC of the topsoil (0–20 cm) in the furrows, compared with CK. However, the SVWC of the ridges in RFMS was lower than that in the CK during most of the maize growing season. In the three RFMS ratios, the SVWC in both furrows and ridges increased with an increased ridge/furrow ratio, regardless of maize growth stages. The mean SVWC values averaged across 2 years for RFMS40, RFMS55, and RFMS70 at soil depth of 3.8 cm were 23.7, 24.4, and 25.1% in the furrow, and 18.8, 18.4, and 20.4% in the ridge, in comparison with 20.5% in CK, while at soil depth of 20 cm the values were 31.3, 32.1, and 34.3% in the furrow and 24.6, 25.2, and 27.8% in the ridge compared with 28.1% in CK. The amount of SVWC was largely influenced by precipitation, especially in the ridges of the RFMS40 (Fig. 5a–g). The SVWC in the RFMS at depths of 3.8 and 20 cm (Fig. 6) also showed the micro-topographic heterogeneity between the alternate furrows and ridges.

Soil water storage and evapotranspiration

In 2014, the amount of SWS showed an obvious decrease after sowing and reached the lowest level till the end of July (81 DAS) and increased again with time till harvest (Fig. 7). In 2015, SWS dynamics under all plots were different from those in 2014 due to different precipitation conditions (Fig. 2). The trend of SWS in 2015 basically leveled off before 82 DAS or after 105 DAS, but with an obvious decreased trend during 82–105 DAS. Three RFMS ratios showed higher SWS during the early and later growth stages of both years, but it was not found during the middle growth period, compared with CK (i.e., 81–121 DAS in 2014 and 82–105 DAS in 2015; Fig. 7).

ET among three RFMS ratios and CK during different growing stages in both years is shown in Table 2. In the early growth stage, soil evaporation comprised of most portion of ET, while plant transpiration could be neglected due to the low LAI. Three RFMS ratios reduced ET because the soil evaporation was significantly restricted through mulching of ridges. RFMS70 showed the largest effect on reducing ET with an average decrease of 22.2 mm before 62 DAS across 2-year data in comparison with CK. Afterwards, ET increased quickly because of the great contribution of plant transpiration during the middle growth stage or after (62–121 DAS in 2014 and 61–126 DAS in 2015). In contrast, three RFMS ratios illustrated higher ET compared with CK, although its soil evaporation was relatively low. In the late growing stage (after 121–126 DAS), both soil evaporation and plant transpiration declined in all plots. Overall, ET during the entire crop growing season, for RFMS40, RFMS55, and RFMS70 was decreased by 5.0, 11.1, and 16.8 mm, respectively, compared with CK across the 2 years.

Crop growth parameters, maize yield, and WUE

The aboveground biomass, plant height, stem diameter, and LAI in three RFMS ratios were significantly higher than those of CK in both years (Fig. 8). Stem diameter and LAI in CK

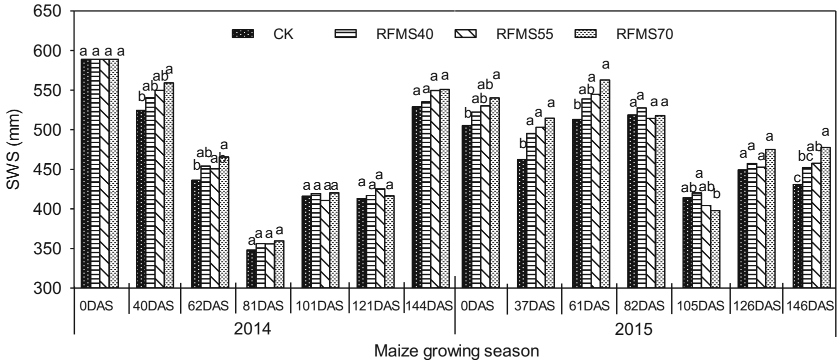

Fig. 7 Changes of soil water storage (SWS, mm) in 0–200 cm layers among three ridge/furrow ratios and conventional flat planting at different maize growing stages in 2014 and 2015. Different letters indicate significantly different according to $LSD_{0.05}$ (n = 3)

Table 2 Field evapotranspiration (ET, mm) of different maize growing periods in 0–200 cm soil layers among conventional flat planting (CK), ridge-furrow mulching system with ridge/furrow ratio of 40:70 cm (RFMS40), 55:55 cm (RFMS55), and 70:40 cm (RFMS70) in 2014 and 2015

Year	DAS	CK	RFMS40	RFMS55	RFMS70
2014	0–40	96.1 a	80.4 ab	71.0 ab	61.5 b
	> 40–62	142.8 ab	140.8 b	153.6 a	148.1 ab
	> 62–81	112.9 b	122.6 ab	119.5 ab	130.7 a
	> 81–101	8.1 a	12.6 a	21.2 a	15.3 a
	> 101–121	73.1 a	73.0 a	55.8 a	74.0 a
	> 121–144	18.9 a	16.4 ab	10.5 ab	0.4 b
	0–144	452.0 a	445.8 a	431.4 a	430.0 a
2015	0–37	59.0 a	42.0 a	43.1 a	41.6 a
	> 37–61	3.6 a	10.7 a	12.5 a	5.9 a
	> 61–82	74.5 c	91.7 b	110.9 a	125.4 a
	> 82–105	152.9 b	155.7 b	158.1 b	168.2 a
	> 105–126	88.4 a	86.2 a	75.2 a	46.2 b
	> 126–146	42.5 a	29.8 ab	19.43 b	22.0 b
	0–146	420.8 a	417.0 a	419.1 a	409.3 a

Means within a row followed by the same letter are not significantly different according to $LSD_{0.05}$ ($n = 3$)

plots reached their peaks almost 20 days later than that of RFMS during both years. The RFMS70 ratio showed significantly greater maize growth parameters than both RFMS55 and RFMS40, although not always statistically significant.

Similarly, the maize yield and WUE were also significantly higher in three RFMS ratios than that of CK, especially under increased ridge/furrow ratio (Table 3). Maize yield of RFMS40, RFMS55, and RFMS70 were increased by 26.1, 36.4, and 50.3%, and WUE were increased by 25.7, 38.7, and 53.9%, respectively, compared with CK across both years. The great yields under RFMS were always accompanied by high kernel number per spike and high 100-kernel weight. It was further confirmed by the significant relationships of maize yield with kernel numbers per spike and 100-kernel weight (R^2 = 0.92** and 0.97**, respectively). In addition, RFMS system showed higher harvest index (%) than CK, whereas no significant difference was found among the different ridge/furrow ratios.

Discussion

It seems logical to infer that different ridge/furrow ratios generate different impacts on soil temperature and soil moisture, although planting density was kept the same in this study. Mulched ridges reduced heat exchange between the soil and ambient air, and therefore, the solar energy reached ridge will significantly increase topsoil temperature of mulched ridges at daytime compared to CK (Gan et al. 2013; Wang et al. 2015b; Li et al. 2016). RFMS70 having the widest mulched-ridges received majority of solar energy during early growing stage when plant canopy was small, and this high heat flux warmed the topsoil on ridges in present study. This is because that RFMS70 resulted in relatively sparse plant canopy above the ridges and could lead more radiation to pass through the plant canopy, thereby enhancing the thermal effect of solar energy.

Since no mulching in furrows in the present design of RFMS system, there are no much differences of soil temperature at furrow zone among all treatments, although soil heat may be transmitted from ridge to furrow zone. When full plant canopy was established, small differences of soil temperature among treatments was found. It is noteworthy that intercepting more solar radiation by the leaves due to higher canopy, especially in RFMS70 having high LAI allowed lesser amounts of radiation to reach the ground and thus resulted less increment of soil temperature or even decrease compared to CK or other RFMS plots. This might be one of the probable causes which led to a non-significant difference in soil temperature between three ridge/furrow ratios and CK plots (during the middle and later growth stages; Fig. 3). Above all, the distinct difference of soil temperature between alternated ridges and furrows clearly illustrated the micro-topographic heterogeneity in RFMS system, although it may be relieved by canopy covering (i.e., 90 DAS).

Throughout the maize growing season, precipitation had pronounced effects on the SVWC of both furrows and ridges in RFMS, among which RFMS40 with the thinnest ridges width fluctuated the most (Fig. 5a–g). This unstable water status may be attributed to the extensive lateral movement of water retained in the furrow into the shallow layer of the ridge, a phenomenon of rainwater infiltration and redistribution also observed by Ren et al. (2010) and Jiang and Li (2015).

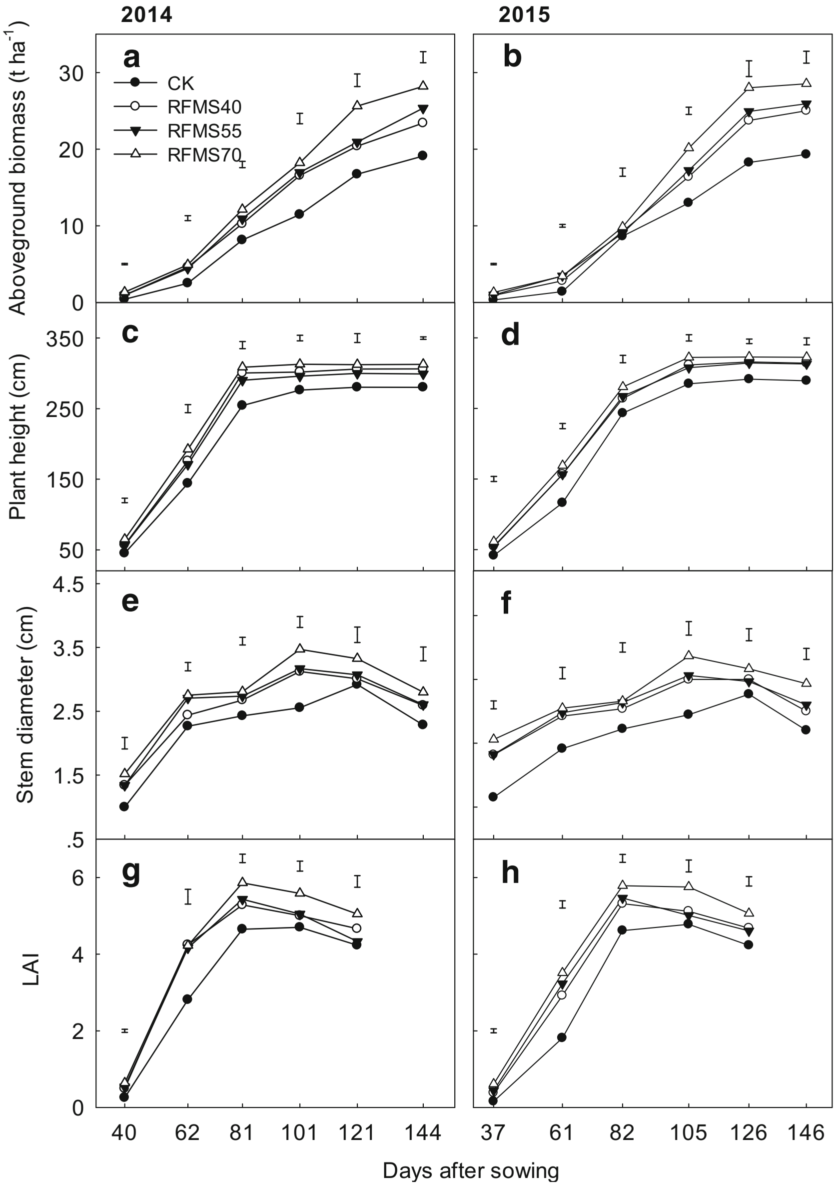

Fig. 8 Changes of aboveground biomass accumulation (**a**–**b**), plant height (**c**–**d**), stem diameter (**e**–**f**), and leaf area index (LAI, **g**–**h**) at different maize growing stages in 2014 and 2015. Vertical bars represent the $LSD_{0.05}$ ($n = 3$)

Meanwhile, water availability in the ridge may also compensate for the soil water in the furrow zone when the soil becomes dry (Li et al. 2001). Soil evaporation of this region (where this study was conducted) is extensively high in July, reaching up to 7 mm evaporation per day. Under such conditions, rainwater in the furrow could completely evaporate in a few days, especially for RFMS40 with the thinnest ridges width. An unbalanced water status between the alternate ridges and furrows (shown in Fig. 6) further evidenced the micro-topographic heterogeneity in RFMS. A number of mulching practices with gravel, straw, or plastic film in the furrow zone have been suggested to prevent soil evaporation and increase water availability and stability in RFMS (Wang et al. 2015a). In present study, RFMS70 having the widest mulched-ridges led to the least soil evaporation and therefore retained rainwater more effectively and increased SWS, compared with other two ridge/furrow ratios in the field.

The RFMS induced higher soil temperature in the plastic-mulched ridges and improving soil moisture in the furrows, compared with the bare soils under CK. The result is in agreement with previous studies (Zhang et al. 2009; Li et al. 2013; Wang et al. 2016; Li et al. 2017). Maize seeds were planted at the junction between ridges and furrows where it was also beneath the plastic film. The elevated temperature and sufficient water available of the soil surrounding the seeds could induce seedling emergence several days (data not shown) ahead in RFMS treatments compared with that in CK. This was consistent with the results of Li et al. (1999, 2004, 2016) that seedlings with mulching ridges emerged about 1 week earlier than traditional flat planting.

Table 3 Grain yield (t ha^{-1}), harvest index (%), kernel number per spike, 100-kernel weight (g), and water use efficiency (WUE, kg ha^{-1} mm^{-1}) of spring maize in 2014 and 2015

Treatments	Grain yield	Harvest index	Kernel number per spike	100-kernel weight	WUE
2014					
CK	8.2 d	49.3 b	513.8 d	26.8 c	18.9 d
RFMS40	10.1 c	51.0 a	528.7 c	28.8 b	22.7 c
RFMS55	11.0 b	51.3 a	561.6 b	29.9 b	25.6 b
RFMS70	12.3 a	51.6 a	601.4 a	31.8 a	28.7 a
2015					
CK	8.3 d	50.5 b	505.4 c	27.3 d	19.7 d
RFMS40	10.7 c	51.8 a	564.0 b	30.5 c	25.7 c
RFMS55	11.5 b	52.1 a	561.4 b	30.9 b	27.5 b
RFMS70	12.5 a	52.6 a	605.7 a	32.0 a	30.4 a

Within a column for each year, means followed by the same letter are not significantly different according to $LSD_{0.05}$ ($n = 3$)

The results further revealed that the RFMS70 pattern increased SWS of 0–200 cm soil depth by 24.5 mm in 2014 and 46.6 mm in 2015 compared with CK. The increasing SWS is in line with previous studies of Li et al. (2001) and Liu et al. (2014b). SWS is not only related to the rainwater collected from the field but also to the water loss from the soil evaporation and plant transpiration. Research on wheat (Li et al. 2016) and maize (Liu et al. 2014b) reported that faster canopy development induced greater plant transpiration and more water consumption from the soil. The higher transpiration from the RFMS plants gradually offset the difference of SWS between CK and RFMS treatments induced by the effect of mulching ridges, especially when the rainfall was scarce. Therefore, there is small difference of SWS in total ET between CK and three ridge/furrow ratios in both years (Table 2), which is consistent with previous studies (Bu et al. 2013; Liu et al. 2014b). Based on this acknowledge, if soil water balance in RFMS in optimal ridge/furrow ratio can be sustainable in a "long-term" aspect without soil desiccation in deep soil layer is still unknown and warrants further exploration with long-term field study.

WUE was significantly higher under RFMS compared to CK during both years which were mainly achieved by the improved grain yield since their ET was mostly similar. We further analyzed the effects of soil hydrothermal conditions on maize yield and found its significantly positive correlations ($R^2 = 0.95^{**}$ with soil temperature in the ridges; $R^2 = 0.94^{**}$ with soil moisture in the furrows). The improved soil temperature and moisture conditions in RFMS also induced higher 100-kernel weight and kernel number per spike and produced greater aboveground biomass and LAI, which contributed to higher great yield.

Choice of optimal ridge/furrow ratio or width depends largely on rainfall, soil type, soil water status, cultivation practice, land topography, or climatic conditions that need further verification. The present result recommends RFMS70 at widest mulched-ridges as a high water-saving method for maize production because of its highest attainable yield and WUE. But, it should be noted that wider mulched-ridge establishment requires more labor and plastic film input and then would cause a major environmental problem (white pollution) to the soil, which is not good for soil tillage and soil sustainability. There is no strategy available that can effectively deal with this concern. Application of biodegradable film in the RFMS system may be an environmentally smart solution to this issue (Wang et al. 2015a, b). Further efforts are urgently need to reserve soil fertility and improve agriculture sustainability for generations to come.

Conclusions

This study indicates that RFMS can increase soil temperature in the mulched ridges and preserve more water in the furrow, representing a highly micro-topographic heterogeneity in RFMS system. These beneficial effects induce earlier seedling establishment and the promotion of maize growth (larger LAI and aboveground biomass) and eventually increase the maize yield and WUE significantly in comparison with CK. Although RFMS did not reduce total ET significantly, it enhanced the capability of the field to collect rainwater and thus efficiently fulfill the water demand of crop. The altered micro-topographical features of the field due to differences in ridge/furrow ratio led to different maize growths, grain yields and WUE. Among the three RFMS ratios, RFMS70 showing the widest mulched-ridges can be recommended for maize production as a high water-saving method in the semi-arid Loess Plateau area of China, although it may need more labor and lead to environmental pollution problems, which calls for further investigations of this technique.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Project No. 31401348), the planning subject of "The Twelfth Five-Year-Plan" in National Science and Technology for the Rural Development in China (2015BAD22B03), the science and technology coordinating innovative engineering projects of Shaanxi Province (2015KTZDNY01–02), and the key agricultural science and technology innovation projects of Shaanxi Province (2016NY–001). We are grateful to the Institute of Soil and Water Conservation, Northwest A&F University, for providing the experimental site.

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