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Effects of ridge–furrow mulching on soil CO_2 efflux in a maize field in the Chinese Loess Plateau

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ABSTRACT

Ridge–furrow mulching system (RFMS) is widely used in arid and semi–arid areas, but its effect on soil respiration (R_s) and its components, including heterotrophic (R_h) and autotrophic respiration (R_a) are still poorly understood. In this study, CO_2 flux from the soil of furrows and ridges was measured across different RFMS practices (i.e., three different ridge/furrow ratios) and conventional flat planting (CK). A trenching method was used to estimate the contribution of R_h to R_s. Compared with CK, RFMS significantly increased soil temperature of the ridge, promoted soil moisture of the furrow, and enhanced microbial diversity at the early crop growth stage, resulting in increased R_s and its components. The ridge soils exhibited much higher R_s (3.43 μmol m^{-2} s^{-1}) than the furrow soils (2.98 μmol m^{-2} s^{-1}) under all three RFMS practices. The contribution ratios of R_h to R_s across the different practices ranged from 50.4% to 59.6%. Soil temperature rather than soil moisture explained the seasonal variation of R_s and its components for both CK and RFMS. Nonetheless, high R_s and R_h values in RFMS did not induce a decline of soil organic carbon during the two–year experimental period. Improved root growth in RFMS practices may provide more exudates to the soil, thus offsetting soil carbon decomposition. Compared with CK, RFMS with ridge/furrow ratios of 40:70 cm, 55:55 cm, and 70:40 cm, significantly increased soil CO_2 emissions by 10.6%, 19.6%, and 20.4%, respectively, while increasing maize yield by 26.1%, 36.4%, and 50.3%, respectively. Carbon emission efficiency (CEE) was significantly higher in RFMS than in CK in both years. This study suggests that, due to its high CEE, RFMS with a ridge/furrow ratio of 70:40 cm could be a highly promising strategy for sustaining crop productivity while minimizing environmental impacts.

1. Introduction

Severe scarcity of agricultural water, combined with unpredictable and limited precipitation and global climate change, has substantially affected agricultural production and productivity (Deng et al., 2006; Wu and Ma, 2018). The development of innovative water–saving technologies and their implementation in semi–humid regions are a promising possibility for increasing water use efficiency (Chai et al., 2014; Gan et al., 2013; Li et al., 2016; Wu and Ma, 2015; Wu et al., 2018). The ridge–furrow mulching system (RFMS) is an advanced water–saving technology that has been widely exploited and applied in rain–fed farming systems because of its capacity to improve soil temperature and moisture conditions, as well as for promoting crop yield in arid and semiarid areas that are subtype of the dry land characterized with an extreme low aridity index (Gan et al., 2013; Gu et al., 2016; Li et al., 2006; Li et al., 2017a). In RFMS with alternate ridges and furrows, the mulched hemispherical ridges, used for runoff collection, serve as rainwater harvesting zones, leading to deeper water penetration, while reducing water evaporation and soil erosion (Li et al., 2017b; Liu et al., 2014).

Beneficial promotion of soil temperature and moisture under RFMS may affect soil microorganisms and root activity, and in consequence alter soil respiration (Chen et al., 2017). Furthermore, Chen et al. (2017) and Zhang et al. (2017a) reported that soil respiration is higher under the mulching method than under the conventional flat planting method, due to increased soil temperature and moisture. In contrast, Gan et al. (2013) suggested that the plastic mulch serves as a physical barrier to reduce greenhouse gas emissions (including CO_2 efflux) to the atmosphere, and could therefore be useful to reduce the carbon (C) footprint of grain crops while increasing grain yield. However, the impacts of RFMS practice on soil CO_2 efflux, and the underlying mechanisms, have not been well studied and need further investigation.

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Different ridge–furrow ratios in RFMS have been shown to have an effect on soil micro–topographic features such as solar surface and the characteristics of crests, which affect rainwater infiltration and the distribution of the field (Li et al., 2017). It is also well–documented that different ratios of ridge to furrow significantly influence soil temperature, soil moisture, crop growth and grain yield (Li and Gong, 2002; Li et al., 2007; Li et al., 2017b; Wang et al., 2015). However, this alternation of soil hydrothermal characteristics is also a driver of soil CO_2 emissions. Thus, we hypothesized that changing the ridge–furrow ratios may amend micro–topographic heterogeneity and thus have a great impact on soil CO_2 emissions.

In general, total soil respiration (R_s) consists of two main components, heterotrophic respiration (R_h) and autotrophic respiration (R_a) (Savage et al., 2013). These two components are regarded as completely different processes and may influence R_s independently. R_h represents the decomposition of root exudates and persistent soil organic C (SOC), which mainly depends on the metabolic rate of soil organisms and on the content of SOC (Cahoon et al., 2016; Kuzyakov and Gavrichkova, 2010; Metcalfe et al., 2011). In contrast, R_a is related to root metabolism, and is mainly involved in substrate consumption during photosynthesis and other associated processes of crop metabolism, which have less impact on soil C storage, compared with R_h (Vargas et al., 2011). Further investigation on the effects of RFMS practice on R_s in terms of R_a and R_h is required, since their partitioning ratio is known to be important for developing C sequestration strategies for sustainable agriculture (Moyano et al., 2007; Zhang et al., 2013).

Soil respiration in agro–ecosystems has been well studied for several decades, and the contributions of R_a and R_h to R_s have been explored in response to different soil types, soil fertilities and crop rotations. For instance, an in–depth meta–analysis based on 50 ecosystem warming experiments across multiple terrestrial ecosystems showed that a 2 °C temperature rise can increase R_h by 21%, without having a significant effect on R_a (Wang et al., 2014). Hence, examining the magnitude and variation of R_h, as well as its contribution to R_s, is necessary to extend our knowledge on the changes in SOC under RFMS practice.

Micro–topographic heterogeneity and associated hydrothermal characteristics might induce spatial variation in soil respiration, depending on the ratio of ridge to furrow in RFMS. Several sampling locations were set up at different distances from the plants in the furrows and ridges in order to measure CO_2 effluxes more precisely, considering the spatial variability between ridges and furrows may lead to an increase in error (%) of the estimated seasonal CO_2 emissions. Overall, this study aimed to (i) determine the change in total soil respiration and its components caused by different ridge/furrow ratios under RFMS practice, and their relationships with soil hydrothermal characteristics; (ii) quantify the contribution of R_h to R_s during the whole crop growing season; and (iii) compare the C emission efficiency between RFMS practices (different ridge/furrow ratios) and conventional flat planting in order to assess the impact of RFMS practice on maize productivity and CO_2 emissions simultaneously.

2. Materials and methods

2.1. Experimental design and field management

The experimental site was located in the Changwu Agro–Ecological Experimental Station in the Loess Plateau in Shaanxi Province, China (107° 40′E, 35° 12′N). The Loess plateau occupies approximately 640,000 km^2 in northwest China and it is extremely important to Chinese agriculture. Average annual sunshine of the experimental site is 2230 h, and its average annual frost–free period lasts for 171 days. The average annual temperature was 9.7 °C and the average annual precipitation was 548 mm from 1980 to 2015. More than half of the total annual rainfall occurred between July and September. The daily average temperature and precipitation during the experimental period are shown in Fig. 1. The soil type in the area is dark loessial soil (Chinese soil taxonomy). At the beginning of the field experiment, the 0–20 cm layer of topsoil had an organic C content of 6.91 g kg^{-1}, and a pH value of 8.1.

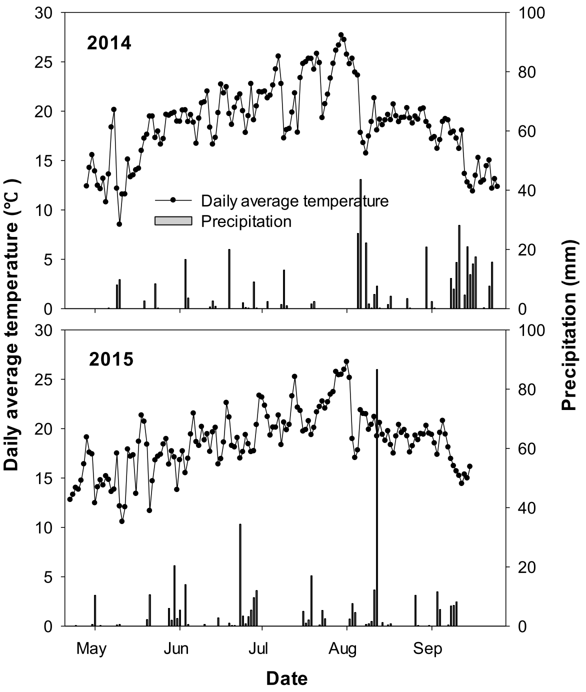

Fig. 1. The daily average temperature and precipitation during maize growing seasons in experimental fields in 2014 and 2015.

A field experiment was conducted in 2014 and repeated in the same field in 2015. In both years, the experiment was arranged in a completely randomized design and was comprised of four treatments (Fig. 2a), including: (a) conventional flat planting without mulch (CK); (b) RFMS40 (ridge–furrow mulching system with a ridge/furrow ratio of 40:70 cm); (c) RFMS55 (RFMS with a ridge/furrow ratio of 55:55 cm); and (d) RFMS70 (RFMS with a ridge/furrow ratio of 70:40 cm). Each plot was 8.0 m long and 3.8 m wide with an area of 30.4 m^2. All treatment had three replicates.

The field was tilled one week before sowing. At the time of tilling, a base 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. Ridges were covered with a 0.008–mm–thick plastic film (40, 55 and 70 cm wide for RFMS40, RFMS55 and RFMS 70 practices, respectively), while furrows were kept uncovered.

We used the spring maize variety Xianyu335, which was sown at the same planting density of 72,750 plants ha^{-1} in each plot on April 28, 2014, and April 22, 2015. An additional 45 kg N ha^{-1} was applied as topdressing to the furrows in early July. Maize plants were harvested on September 27, 2014, and September 15, 2015. After harvesting, the ridge and furrow configuration and the plastic mulching were left in the field to be re–built in the following year. The experiment followed locally agronomic recommended management practices for maize production. No irrigation was applied to this semiarid rain–fed environment during the two–year experimental period. Weeds were controlled artificially to avoid any suppression of crop growth due to the effect of herbicide application.

2.2. Measurements and calculation

2.2.1. Soil respiration and its components (R_h and R_a)

Various sampling positions (namely, F1, F2, F3, R1 and R2) were designed in each treatment as indicated in Fig. 2b, and samples from

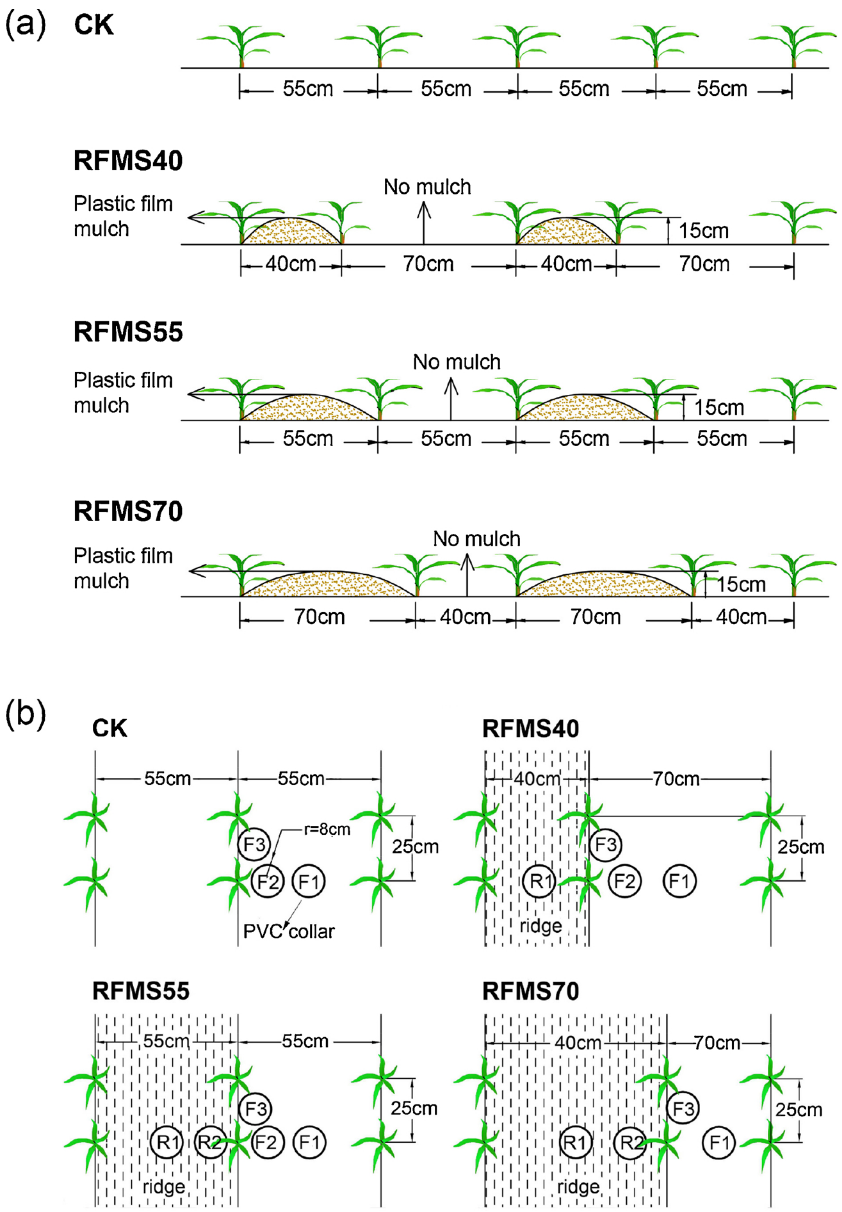

Fig. 2. Schematic diagram for four planting patterns including conventional flat planting (CK), ridge–furrow mulching system with ridge/furrow ratio of 40:70 cm (RFMS40), 55:55 cm (RFMS55), and 70:40 cm (RFMS70) (a); the distribution of five soil respiration sampling positions in each treatment (b). F1 and R1 located in the midway between two rows in the furrow and ridge, respectively. F2 and R2 located in the midway between the maize plant and F1 and R1, respectively. F3 located in the midway between two maize plants.

each specific position was repeated two times as technical replications. A closed–chamber method was used to measure soil respiration during the entire maize cropping season. The apparatus consists of two parts: a portable infrared gas analyzer (GXH 3010E1, Institute of Beijing HUAYUN Analytical Instrument Co., Ltd, Beijing, China) and a closed chamber connected to it by a soft silicone pipe. PVC collars with a height of 10 cm and a diameter of 16 cm were inserted into the soil at each corresponding position after sowing and kept in the field during the entire crop growing season, to avoid any possible effects of soil disturbance on soil respiration. The collars were inserted 5 cm into the soil and extended 5 cm above the surface, and the surface plant material inside the soil collar was cleared.

Soil respiration measurements were made between 09:00 and 11:00 (local time) almost every 6 days from sowing to harvesting in both years. The total CO_2 emissions (TCO_2, kg CO_2 ha^{-1}) for the entire cropping period were computed based on the measured soil respiration rate with the following formulas:

$$R_s = \frac{W_F \times R_{s-F} + W_R \times R_{s-R}}{110} \tag{1}$$

$$TCO_2 = \sum_{i=1}^{n} \frac{R_{s(i+1)} + R_{s(i)}}{2} \times (t_{i+1} - t_i) \times 3.80 \times 10 \tag{2}$$

where R_s represents the total soil respiration rate in each treatment (μmol m^{-2} s^{-1}), W_F and W_R represent the furrow and ridge width (cm), respectively, $R_{s\text{–}F}$ represents soil respiration in the furrow and equals the average of F1, F2 and F3, $R_{s\text{–}R}$ represents soil respiration in the ridge and equals the average of R1 and R2. The number 110 indicates the combined width of one furrow and one ridge expressed in cm. The letters *i* and *n* represent the current and last recorded date, respectively, and t represents the days after sowing (DAS); 3.80 converted μmol m^{-2} s^{-1} to g $CO_2\,m^{-2}$ d^{-1}, 10 converted g $CO_2\,m^{-2}$ d^{-1} to kg $CO_2\,ha^{-1}$. Moreover, diurnal variation of soil respiration for CK and RFMS55 was also measured on June 6 (39 DAS), July 1 (64 DAS), July 21 (84 DAS) and August 18 (112 DAS), 2014. The measurements were taken every 2 h from 07:00 to 19:00 (local time).

Meanwhile, a trenching method described by Bowden et al. (1993) was used to divide R_s into R_a and R_h. When the ridge and furrow configuration was constructed, a 60–cm deep trench almost covering the rooting zone was dug on a furrow by excavating the outside edges of a 60 cm × 40 cm rectangle in each plot. The 0.038 mm nylon mesh sheet, which allows the exchange of water, bacteria, organic matter and minerals through the mesh, was placed along the trench walls and then backfilled as a barrier to prevent future root growth. The plots were kept free of vegetation by periodic manual removal during the measurements. Two PVC collars were placed in each plot to measure R_h (without roots). It was assumed that the soil respiration measured in the root–free plots represented R_h, and the difference between R_s and R_h, which was equal to R_a. R_a, here is defined as the sum of respiration by roots and rhizosphere heterotrophs, according to Bowden et al. (1993). Although this method has been used in several studies (Li et al., 2010; Zhang et al., 2013), it should be noted that this root exclusion method does not separate the priming effect of root exudation, and therefore may overestimate the contribution of R_h to R_s (Zhang et al., 2013). Nevertheless, this trench method is still an easy and effective option to divide R_s into R_h and R_a.

2.2.2. Soil temperature, moisture and SOC sampling

Soil temperature and moisture in the alternating furrows and ridges were recorded simultaneously during the sessions of soil respiration measurement, with three replicates in each plot. Soil temperature at 10 cm soil depth was recorded using a set of digital thermometers (Shenyang Huashengchang Mechanical and Electrical Equipment co., LTD, Shenyang, China). Soil volumetric water content (SVWC, %) dynamics at 12 cm soil depth were measured using the Time Domain Reflectometry (Field Scout™ TDR 300 Soil Moisture Meter, Spectrum Technologies, Inc. Aurora, Illinois, America). Soils of 0–20 cm depth were sampled with a soil drill (metal cylinder with a diameter of 5 cm and a length of 20 cm) before sowing and after harvesting, to determine SOC content (g kg^{-1}). Soil cores were sampled from the middle of two rows in the CK practice. But in the three RFMS practices, soil cores were taken from the middle parts of furrows and ridges separately, to differentiate the SOC of furrows and those of ridges. Two drills were made for sampling in each plot.

2.2.3. Soil bacterial community analysis

Only two treatments including CK and RFMS55 were chosen for analyzing the mulching effects on bacterial communities in rhizosphere and non–rhizosphere. The non–rhizosphere soil sample from these two treatments were collected from a depth of 5–20 cm and away from the root system during the tasseling stage and the physiological maturity stage on July 20, and September 20, 2015. The rhizosphere soil sample was collected from the soil firmly adhering to the root system. The soil adhering loosely to the root system was removed by shaking the maize root and then rhizosphere soil was sampled with a brush. Five subsamples were collected from each sampling plot, and the fresh soil samples were passed through a 2 mm sieve and then stored at 4 °C. A total of twelve soil samples (rhizosphere and non–rhizosphere soils in two treatments, with three replicates) were collected. Microbial DNA was extracted in triplicate from each soil sample by using an E.Z.N.A. Soil DNA Kit (Omega Bio Tek, Inc, Norcross, GA, USA). The concentration and quality of DNA were determined using a NanoDrop 2000 spectrophotometer (Thermo Scientific, Wilmington, DE, USA). All extracted soil DNA was stored at −80 °C until PCR amplification and 16S sequencing. Bacterial 16S gene PCR amplification and Illumina sequencing were performed according to the procedure described by Wang et al. (2016).

Both alpha diversity and beta diversity were employed to demonstrate the effect of plastic film mulching on bacterial diversity of rhizosphere and non–rhizosphere soils. Alpha diversity, representing the diversity of microbial communities based on individual samples, was estimated with the Shannon index and the Simpson index using Mothur software (Version 1.30.1) (Schloss et al., 2009). The Shannon index value increases, and the Simpson index value decreases, as the bacterial diversity increases. For beta diversity, a community dissimilarity assessment with Bray–Curtis operational taxonomic units (OTUs), was used to quantify the taxa shared between samples versus those unique to a single sample. Non–metrical multidimensional scaling (NMDS) plot was used to assess the clustering of the soil bacterial communities in different soil types. The degree of similarity between the treatments is reflected by the distance between points (i.e. the higher the similarity, the closer the points appear in the graph). NMDS test was performed using the “vegan” package of the R (Version 3.20) statistical environment. A value of $P < 0.05$ was considered statistically significant.

2.2.4. Root biomass, grain yield and CEE

Root samples were taken from soil cores at a depth of 60 cm using a steel soil auger with a diameter of 7.0 cm. In each plot, the sampling site for soil core was equal to the position of soil respiration measurement with two replicates, i.e., F1, F2, F3, R1, and R2. Root cores were collected on large bell stage, the milk stage and the physiological maturity stage. Following collection, fine roots were separated from the soil using a 0.5 mm mesh sieve. Decayed roots were excluded. The biomass of roots was recorded after oven drying at 65 °C to constant weight. At maturity stage, two rows with 7 m long in the middle of each plot were harvested to determine grain yield on a standard moisture content of 0.12 g H_2O g^{-1} fresh weight. Aboveground biomass was also collected at the jointing stage, the large bell stage, the tasseling stage, the milk stage, the dough stage and the maturity stage, as previously described by Li et al. (2017b). In order to link the association between grain yield and C emission, we use the term “C emission efficiency (CEE, kg grain–eq kg^{-1} C)” which is calculated as crop yield divided by total C emission, as in previous reports (Qin et al., 2013).

2.3. Statistical analysis

All statistical analyses were conducted using SPSS 17.0 software (SPSS Inc., Chicago, IL, USA) to determine treatment effect based on a completely randomized design for each year. Relationships among R_s, R_h, R_a, soil temperature, and moisture were performed using correlation analyses (Statistix 8.0, Tallahassee, FL, USA). Figures were generated using Sigmaplot 12.5 (Systat Software, Inc., San Jose, USA).

3. Results

3.1. CO_2 efflux response to the plastic film mulching

RFMS practices showed significantly higher CO_2 fluxes than CK practice. But no significant differences ($P < 0.05$) were found among the three RFMS practices (Table 1). The total CO_2 emission during the entire cropping season (averaged across two experimental years) in RFMS40, RFMS55, and RFMS70 was 10.6%, 19.6%, and 20.4% higher

Table 1

Grain yield (t ha^{-1}), seasonal average soil respiration rate in the furrow (R_{s-F}, μmol m^{-2} s^{-1}), seasonal average soil respiration rate in the ridge (R_{s-R}, μmol m^{-2} s^{-1}), seasonal average total soil respiration rate (R_s, μmol m^{-2} s^{-1}), total CO_2 emissions (TCO_2, kg CO_2 ha^{-1}) and C emission efficiency (CEE, kg grain–eq kg^{-1} C) of spring maize among different practice patterns in 2014 and 2015.

Treatments	Grain yield	R_{s-F}	R_{s-R}	R_s	TCO_2	CEE
2014						
CK	8.2 d	2.99 a	–	2.99 b	17032 b	1.78 b
RFMS40	10.1 c	3.02 a	3.36 a	3.15 ab	17935 ab	2.08 ab
RFMS55	11.0 b	3.16 a	3.51 a	3.33 ab	19009 ab	2.14 ab
RFMS70	12.3 a	3.24 a	3.63 a	3.49 a	19912 a	2.28 a
2015						
CK	8.3 d	2.50 a	–	2.50 b	13872 b	2.20 b
RFMS40	10.7 c	2.76 a	3.21 a	2.92 ab	16231 ab	2.43 ab
RFMS55	11.5 b	2.92 a	3.55 a	3.23 a	17937 a	2.37 ab
RFMS70	12.5 a	2.80 a	3.30 a	3.12 a	17304 a	2.65 a

Within each column for the same year, means followed by the same lowercase letters are not significantly different according to ANOVA (0.05). Data of grain yield have been previously reported in Li et al. (2017b).

than in CK, respectively. Similarly, the three RFMS practices with different ridge/furrow ratios showed 26.1%, 36.4% and 50.3% more grain yield respectively, than CK. It is of note that CEE was significantly higher in RFMS practices in comparison with that in CK, and that RFMS70 practice showed the highest CEE. In general, no consistent and significant differences in R_{s-F} and R_{s-R} were found between the three RFMS and CK practices.

The seasonal dynamics of soil respiration were similar in 2014 and 2015 for RFMS and CK practices. In both years, the trend increased after sowing, and reached its peak between July and August, when air temperature reached the highest value, and then decreased gradually until the maturity stage (Fig. 3). The average soil respiration rate across two years for CK, RFMS40, RFMS55, and RFMS70 was 1.57, 2.01, 2.14, and 2.39 μmol m^{-2} s^{-1} before jointing stage, 3.38, 3.60, 4.12, and 4.00 μmol m^{-2} s^{-1} from the jointing stage to the dough stage, and 2.80, 3.12, 3.07 and 3.11 μmol m^{-2} s^{-1} from the dough stage to the maturity stage, respectively. The diurnal variation of soil respiration in different growth stages exhibited a similar trend as air temperature (Fig. 4). Soil respiration rates for CK and RFMS55 within furrows reached their peaks at 15:00, which was later than that under the mulched ridge soil of RFMS55. This result suggests that mulching could accelerate the soil respiration peak. Besides, precipitation also had a substantial impact on the seasonal pattern of soil respiration. For example, the soil respiration rate increased greatly after a large precipitation of 91.2 mm, and peaked on August 10, 2014.

Within the furrow, higher soil respiration tended to occur near the maize plant (at position F3), and soil respiration rate at different locations almost followed this rule: inter–maize plants (F3) > near the maize plants (F2) > inter–rows (F1), although not always significantly (Fig. A1). For the CK practice, the mean soil respiration rate across the two years at the F3 position was 7.3% and 14.5% higher than that of F2 and F1 position, respectively. These values were 6.5% and 11.3% for RFMS40, and 5.5% and 10.3% for RFMS55. The ridge soils in the three RFMS ratios exhibited 13.7%, 16.2% and 14.8% higher soil respiration than the furrow soils, respectively.

3.2. Seasonal variations in R_h and R_a

R_h followed almost the same seasonal pattern as R_s, while the seasonal pattern of R_a was shown to be a unimodal curve with a great range of variation (Fig. 5). In 2014, R_h decreased to its lowest level on August 4, due to the drought stress in late July, while the lowest R_h was attained on August 13, due to a large precipitation event in 2015. However, R_a was also greatly influenced by drought stress, rather than by the large precipitation in 2015. Throughout the growing season, RFMS40 and RFMS55 practices showed a significantly higher R_h, compared with CK, but there was no significant difference between the three RFMS practices. The average R_h for CK, RFMS40, RFMS55 and RFMS70 was 1.55, 1.76, 1.75 and 1.62 μmol m^{-2} s^{-1}, while the average R_a across two years was 1.19, 1.28, 1.53 and 1.69 μmol m^{-2} s^{-1}, respectively.

Contribution of R_h to R_s (represented as R_h/R_s) in all practice patterns displayed the same inverted bell–shaped seasonal trend, with the minimum value of about 50% occurring in July (Fig. A2). The seasonal dynamics can be attributed to the rapid changes of R_a rather than of R_h (i.e., increased from sowing date to July and then decreased until the maturity stage). Under the three RFMS practices, the R_h/R_s ratio decreased with increasing ridge width. Across the two years, the average R_h/R_s during the whole growing season under the CK, RFMS40, RFMS55 and RFMS70 methods ranged from 45.9% to 89.9%, from 46.1% to 79.1%, from 42.1% to 69.0% and from 37.6% to 69.6%, respectively.

3.3. Changes in soil temperature, soil moisture, root biomass and SOC

All three RFMS practices showed higher soil surface temperature in the ridge than in the furrow, but the differences between the alternating furrows and ridges were not significant (Fig. 6a). A higher soil temperature in the ridge was observed during the early and middle growing season rather than during the late growth season. No significant

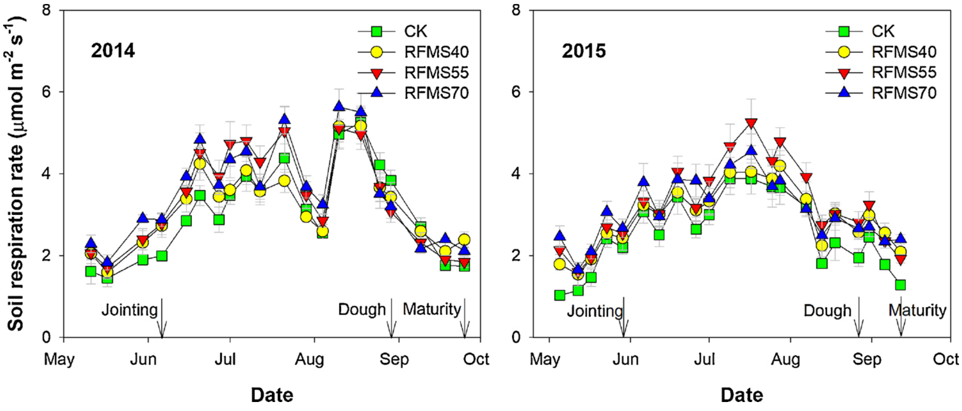

Fig. 3. Seasonal variations of soil respiration rate for CK, RFMS40, RFMS55 and RFMS70 in 2014 and 2015. Bars represent standard deviations (n = 3).

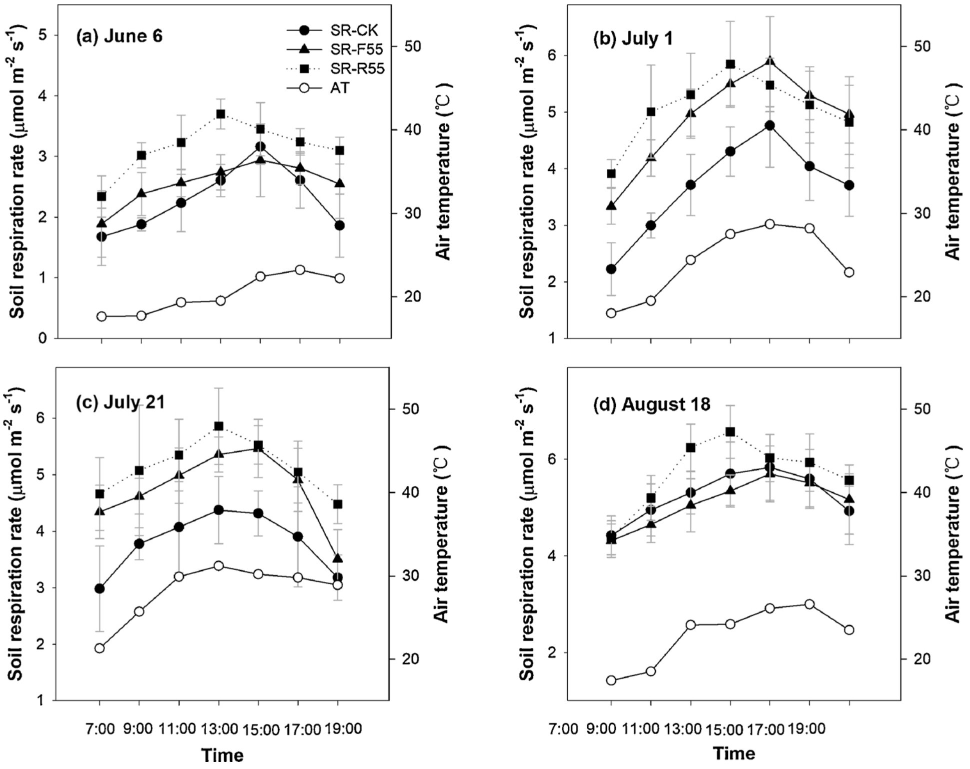

Fig. 4. Diurnal variation of soil respiration (SR) and air temperature (AT) on June 6 (a), July 1 (b), July 21 (c), and August 18 (d) for CK and RFMS55 in 2014. SR–CK, SR–F55 and SR–R55 represents soil respiration rate for CK, furrow and ridge soils in RFMS55, respectively. Bars represent standard deviations (n = 3).

difference in soil temperature was observed between different sampling sites within either the furrow or the ridge (Fig. A3a). Soil moisture did not exhibit a significant and consistent spatial variability within the furrow and the ridge soils across the two years (Fig. A3b), but RFMS practices had significantly higher soil moisture in the furrow than in the ridge (Fig. 6b). Average soil moisture was found to be 37.4% higher in the furrow than in the ridge across three RFMS practices, as illustrated by the micro–topographic heterogeneity between the alternating

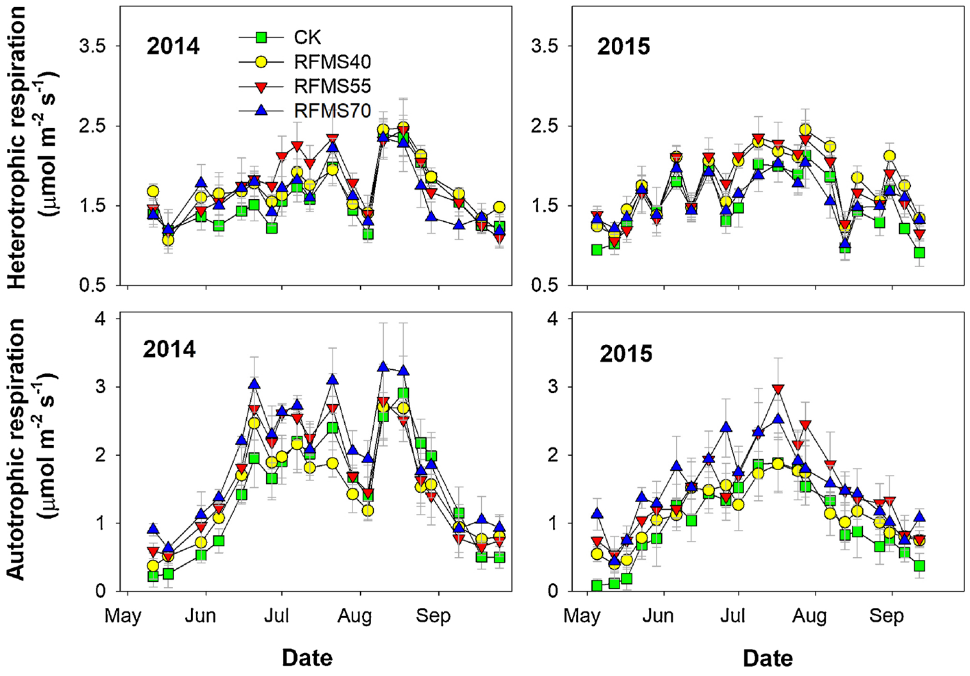

Fig. 5. Seasonal variation of heterotrophic and autotrophic respiration for CK, RFMS40, RFMS55 and RFMS70 in 2014 and 2015. Bars represent standard deviations (n = 3).

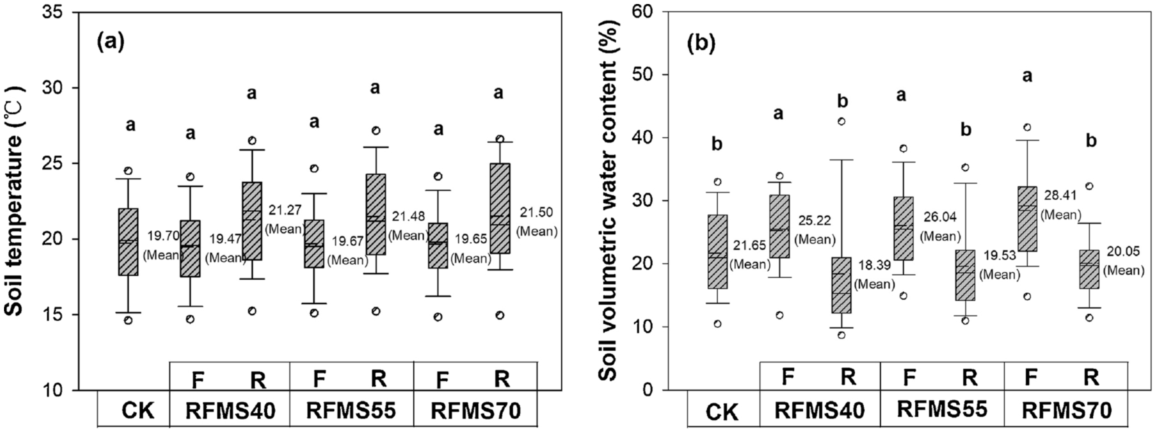

Fig. 6. Comparison of soil temperature (a) and soil volumetric water content (b) for 2014–2015 in between the furrow (F) and ridge (R) for CK, RFMS40, RFMS55 and RFMS70, same character indicates data without significant differences at the 0.05 level. Solid line represents medium value and dashed line represents mean value.

Table 2

Root weight density (mg cm^{-3}) at different sampling locations in the furrow (F1, F2 and F3) and ridge (R1 and R2) in the large bell stage, the milk stage, and the physiological maturity stage. Data was mean across two years.

Sampling stage	Treatment	F1	F2	F3	R1	R2
Large bell	CK	0.054 b	0.081 ab	0.108 a	–	–
	RFMS40	0.079 b	0.126 b	0.236 a	0.107 b	–
	RFMS55	0.114 bc	0.171 ab	0.228 a	0.085 c	0.137 abc
	RFMS70	0.142 b	–	0.269 a	0.076 c	0.127 bc
Milk	CK	0.321 b	0.385 ab	0.514 a	–	–
	RFMS40	0.412 b	0.495 b	0.701 a	0.440 b	–
	RFMS55	0.470 bc	0.564 ab	0.705 a	0.376 c	0.496 abc
	RFMS70	0.582 ab	–	0.873 a	0.384 b	0.512 b
Maturity	CK	0.240 b	0.289 ab	0.337 a	–	–
	RFMS40	0.293 b	0.352 ab	0.439 a	0.299 b	–
	RFMS55	0.369 ab	0.443 a	0.480 a	0.295 b	0.377 ab
	RFMS70	0.426 ab	–	0.554 a	0.266 c	0.332 bc

The same letters in the same row indicate no significant difference between different sampling sites according to LSD (0.05).

furrows and ridges. Soil moisture in the furrow of RFMS40, RFMS55 and RFMS70 was found to be 16.5%, 20.3% and 31.2% higher in comparison with CK, respectively.

Root weight density among different sampling sites is shown in Table 2. The F3 position exhibited the highest root density, compared with other sampling sites in the large bell stage, the milk stage, and the physiological maturity stage. All three RFMS practices showed higher root density than CK, although the difference was not always significant. RFMS decreased SOC in the furrow, compared with CK. However, this kind of decline of SOC was not found in the ridge soils (Table 3). No significant differences in SOC were found between the three RFMS practices in both years. However, ridge soils in RFMS40 exhibited significantly higher SOC than in the other two RFMS practices.

3.4. Relationships of soil respiration with soil temperature and soil moisture

The relationship between soil respiration and soil moisture was weak (data not shown). However, soil respiration showed a significantly positive correlation with soil temperature both within the furrow ($R^2 = 0.22^{**}–0.38^{**}$) and the ridge ($R^2 = 0.11^{**}–0.36^{**}$) with pooled data of two years, respectively (Fig. 7). In addition, the temperature sensitivity (Q_{10}) of soil respiration under the furrow ranged from 1.62 to 2.05, which is substantially higher than under the ridge, which ranged from 1.14–1.63. These results imply that soil temperature provides a good explanation for the temporal variation of soil respiration in different practices and between alternating furrows and ridges. Besides, aboveground biomass showed a strong relationship with R_s, irrespective of various practice patterns (Fig. A4a). Root biomass closely correlated with R_s and R_a in CK and in the three RFMS practices, and it was more strongly correlated with R_a than with R_s. (Fig. A4b).

3.5. Soil bacterial community diversity

The Shannon and the Simpson indexes representing the soil bacterial alpha diversity between RFMS and CK practices at tasseling and maturity stage are shown in Fig. 8. RFMS practice increased bacterial diversity greatly in comparison with CK, for both rhizosphere and non–rhizosphere soil at the tasseling stage (Fig. 8a). However, at the physiological maturity stage, the bacterial diversity for both rhizosphere and non–rhizosphere soils were lower under the RFMS than

Table 3

Soil organic carbon (SOC, g kg^{-1}) within furrow or ridge at 0–20 cm soil depth among four practice patterns from sowing to harvesting in 2014 and 2015.

Treatments	2014				2015			
	Sowing	Harvesting			Sowing	Harvesting		
		Furrow	Ridge	Mean		Furrow	Ridge	Mean
CK	6.91	5.74 a	–	5.74 a	6.33 b	6.08 a	–	6.08 a
RFMS40	6.91	5.65 a	7.10 a	6.18 a	6.64 b	5.69 a	7.45 a	6.33 a
RFMS55	6.91	5.53 a	6.74 a	6.14 a	6.48 b	5.63 a	6.86 b	6.25 a
RFMS70	6.91	5.69 a	6.50 b	6.20 a	7.39 a	5.88 a	6.70 b	6.40 a

Within each column, means followed by the same letter are not significantly different according to LSD (0.05).

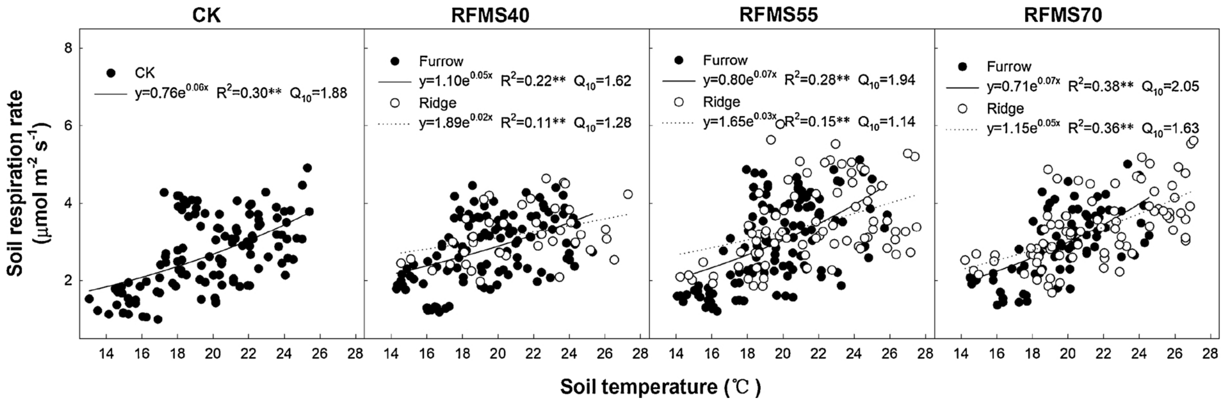

Fig. 7. Relationships between soil respiration and soil temperature in the furrow (Furrow) and ridge (Ridge) of CK, RFMS40, RFMS55 and RFMS70. All of the individual values represent the instantaneous measurements of soil respiration rate and soil temperature at different sampling positions in the furrow and ridge soils for each treatment in 2014 and 2015.

under the CK practice, although not significantly (Fig. 8b). In both CK and RFMS, non–rhizosphere soil exhibited higher bacterial diversity than the rhizosphere soil in both sampling stages. Moreover, a larger distance was found between rhizosphere and non–rhizosphere soils in the NMDS plots than between CK and RFMS practice (Fig. 8c and d). In addition, RFMS practice also enhanced the difference in bacterial diversity between rhizosphere and non–rhizosphere soils in both sampling stages.

4. Discussion

This study confirmed that RFMS not only increases soil temperature of the ridge, but also improves soil moisture of the furrow compared with CK. This means that the micro–topographic heterogeneity under the RFMS practice promotes soil hydrothermal characteristics. The improved soil temperature and soil moisture conditions under RFMS practice are beneficial for the microbial population and its activities (Li and Sarah, 2003; Sing, 2013). These improved conditions under RFMS are favorable to the mineralization process as well as to plant growth (Cuello et al., 2015). For instance, it was evidenced that compared with CK, RFMS promotes bacterial diversity at the tasseling growth stage. Accordingly, it was found that the three RFMS practices (i.e. RFMS40, RMS55 and RFMS70) respectively produced 10.6%, 19.6% and 20.4% higher total CO_2 emissions than CK. More importantly, these three RFMS practices also increased grain yield by 26.1%, 36.4% and 50.3%, respectively, compared with CK, which has been previously reported by

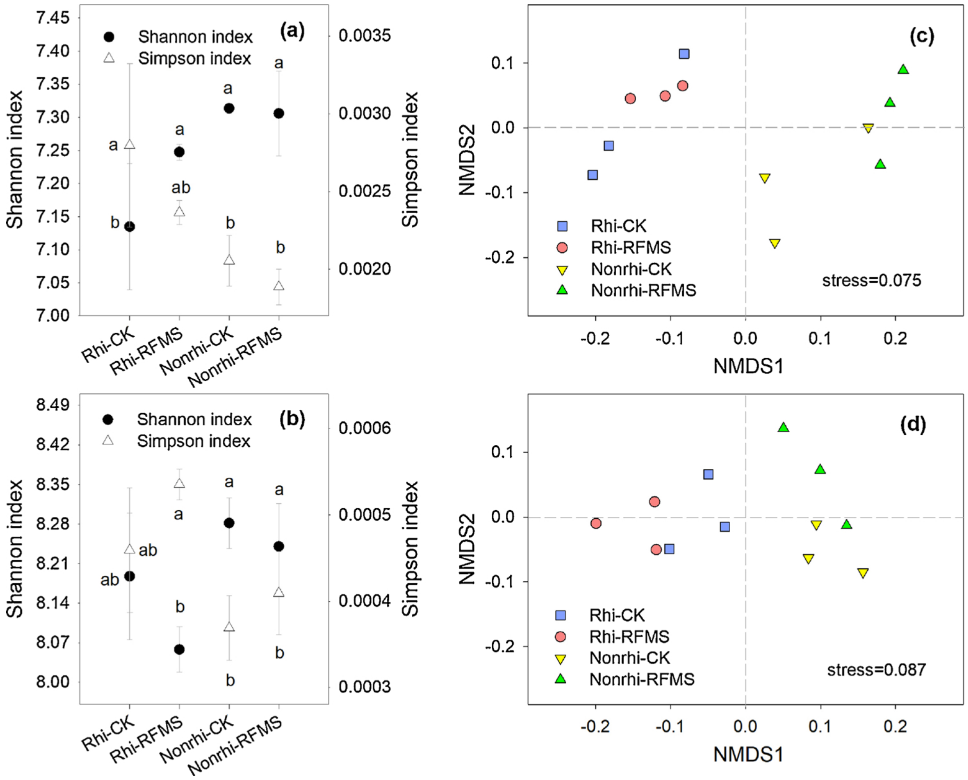

Fig. 8. Alpha diversity (Shannon index and Simpson index) of bacterial communities of rhizosphere and non–rhizosphere soils between RFMS and CK practices at the tasseling stage (a) and the physiological maturity stage (b), and soil bacterial community comparisons indicated by non–metric multidimensional scaling (NMDS) plots at the tasseling stage (c) and the physiological maturity stage (d) based on Bray–Curtis dissimilarity. Same character in (a) and (b) indicates no significant differences at the 0.05 level for the Shannon index or the Simpson index. Rhi–CK and Rhi–RFMS indicates the rhizosphere soil under CK and RFMS practices, respectively; Nonrhi–CK and Nonrhi–RFMS indicates the non–rhizosphere soil under CK and RFMS practices, respectively.

Li et al. (2017b). It is interesting to note that CEE was significantly higher under RFMS practice in comparison with CK, although no consistent and significant differences were found among three RFMS practices. This result may imply that RFMS70 could be a highly recommended promising strategy for sustaining crop productivity while minimizing environmental impacts, due to its low C emission per unit of grain yield produced.

However, previous studies (e.g. Li et al., 2011; Yang et al., 2012) suggested that total soil CO_2 emissions were reduced under plastic film mulching systems, although soil CO_2 concentrations were increased, which is mainly because the mulching treatment prevents the gas from being released into the atmosphere. On the other hand, higher soil temperature in the ridge could accelerate gas molecule activity and gas release from the soil (Lal and Shukla, 2004; Zhang et al., 2017a), which might diminish the barrier effect of the plastic film. It is of note that the plastic film could increase the complexity of soil gas emission to the atmosphere, because of low Q_{10} values, and the weak relationship between soil respiration and soil temperature found in the ridge (Fig. 7). Similar results were also reported by Nan et al. (2016) and by Zhang et al. (2017a).

Besides the substantial influences of mulching on soil CO_2 emissions, weather conditions such as air temperature and rainfall events also affect the temporal variations in soil respiration. It is because that air temperature can significantly influence soil surface temperature (Hao et al., 2014; Zheng et al., 1993), and thus indirectly determines the gas exchange between soil and atmosphere. In general, high air temperature is associated with strong solar radiation. Mulched–ridges receive most incoming solar energy during the early growing stage, when the canopy of maize plants is still small. Meanwhile, the clear plastic film covering ridges does not absorb solar radiation but transmits most solar radiation to the soil, and this high heat flux leads to an increase in soil temperature and promotes soil respiration accordingly. This explanation is highly in agreement with the diurnal variation of soil respiration during a single day, as indicated in Fig. 4. Soil respiration showed a parabolic curve with its peak occurring at 15:00, a trend that is consistent with air temperature.

The impact of precipitation on soil respiration largely depends on precipitation amount, frequency and distribution (Borken et al., 2003). On the one hand, rainfall could force CO_2 in soil pores out into the atmosphere and cause an excitation of microbial activities, both of which could result in an increase in soil CO_2 emission. However, this priming effect does not work well under severe wet conditions. For instance, rainfall events between late August and early September 2014, when soil volumetric water content was high (23.9%–39.8%), did not induce an increase in soil respiration.

A critical concern for sustainable agriculture is the accelerating decomposition of SOC under RFMS practice due to its high mineralization rate. In this study, no significant differences in SOC between RFMS and CK were found at the harvest stage in any of the two years of the experimental period (Table 3). This is in agreement with Zhang et al. (2017b), who showed that SOC content did not significantly differ between mulched and un–mulched soils after four years of cultivation. Under RFMS practice, high content of SOC in the ridges strongly counterbalanced the low SOC in the furrows, resulting in higher SOC than for the CK practice. The difference of SOC content between the furrow and ridge soils may be related to the soil preparation method before sowing. Therefore, top soil with a higher SOC content than the deep soil, was collected artificially to build the hemisphere ridge in this study, which may lead to increased SOC heterogeneity between furrows and ridges. In addition, the plastic film cover could have caused a reduction in oxygen (Khan and Datta, 1991) and low soil moisture in the ridges (Fig. 6b), resulting in restricted microbial decomposition of SOC in the ridge area.

R_h is reported to better reflect decomposition of soil organic matter than R_s (Trumbore, 2000). In this study, the trenching method was used to measure R_h. Many studies have suggested that R_h is strongly related to soil temperature and soil moisture (Gomez-Casanovas et al., 2012; Li et al., 2010; Wang et al., 2014). It is in agreement with the present results that the increased soil moisture within furrows under RFMS is favorable for microbial respiration. Nevertheless, a high R_h in RFMS did not result in a detectable decline of SOC in the furrow compared with CK. This can be accounted for by the improved root growth in RFMS practices, which provide more exudates to the soil than CK practice, and could therefore offset soil C decomposition through increased soil respiration (Zhang et al., 2017b). Meanwhile, the enhanced root growth also promoted R_a in this study, which is consistent with other previous studies (Qin et al., 2013; Savage et al., 2013; Yu et al., 2016).

The contribution of R_h to R_s varies greatly, from 15% to 92%, depending on the type of crop and soil, weather conditions and research methods (Hanson et al., 2000; Li et al., 2010; Subke et al., 2006). Tomotsune et al. (2013) used three methods including trenching, root biomass and a root excision method to partition soil respiration into R_h and R_a, and they concluded that the trenching method was the best procedure used in the deciduous forest. In this study, the average R_h/R_s ratio across two years during the whole growing season for CK, RFMS40, RFMS55 and RFMS70 was 59.6%, 59.2%, 54.8% and 50.4%, respectively. These values are comparable to previous findings by Zhang et al. (2013), who reported that the seasonal average R_h/R_s ratios for wheat and maize plants were 64% and 71%, respectively. However, a low value of 33% in the average R_h/R_s ratio was also reported, using the trenching method in a *Setaria italica* field (Li et al., 2010).

5. Conclusions

This study indicates that RFMS practices significantly increases the soil temperature of the ridge, promotes soil moisture of the furrow, and enhances the diversity of microbial communities at the early crop growth stage, which results in higher R_s and its components compared with CK. Under the three RFMS practices, the ridge soils exhibited much higher soil respiration rate (3.43 $\mu mol\ m^{-2}\ s^{-1}$) than the furrow soils (2.98 $\mu mol\ m^{-2}\ s^{-1}$). The contribution ratios of R_h to R_s during the whole growing season (for the two–year experimental period) for CK, RFMS40, RFMS55 and RFMS70 was 59.6%, 59.2%, 54.8% and 50.4%, respectively. Soil temperature rather than soil moisture explained the seasonal variation of soil respiration and its components for both CK and RFMS practices. Nonetheless, high R_s and R_h in RFMS practice did not result in a decline of SOC during the two–year experimental period. Improved root growth in RFMS practices could provide more exudates to the soil, thus offsetting soil C decomposition. Three RFMS practices, namely RFMS40, RFMS55 and RFMS70, significantly increased soil CO_2 emissions by 10.6%, 19.6% and 20.4%, respectively, compared with CK practice, and increased maize yield by 26.1%, 36.4% and 50.3%, respectively. CEE, which represents grain yield produced per unit of C emission, was significantly higher under RFMS than under CK practice. These results imply that, on account of its high CEE, RFMS with a ridge/furrow ratio of 70:40 cm could be highly recommended as a promising practice for sustaining crop productivity, while minimizing environmental impacts.

Competing interests

The authors declare no competing interests.

Acknowledgements

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Appendix A

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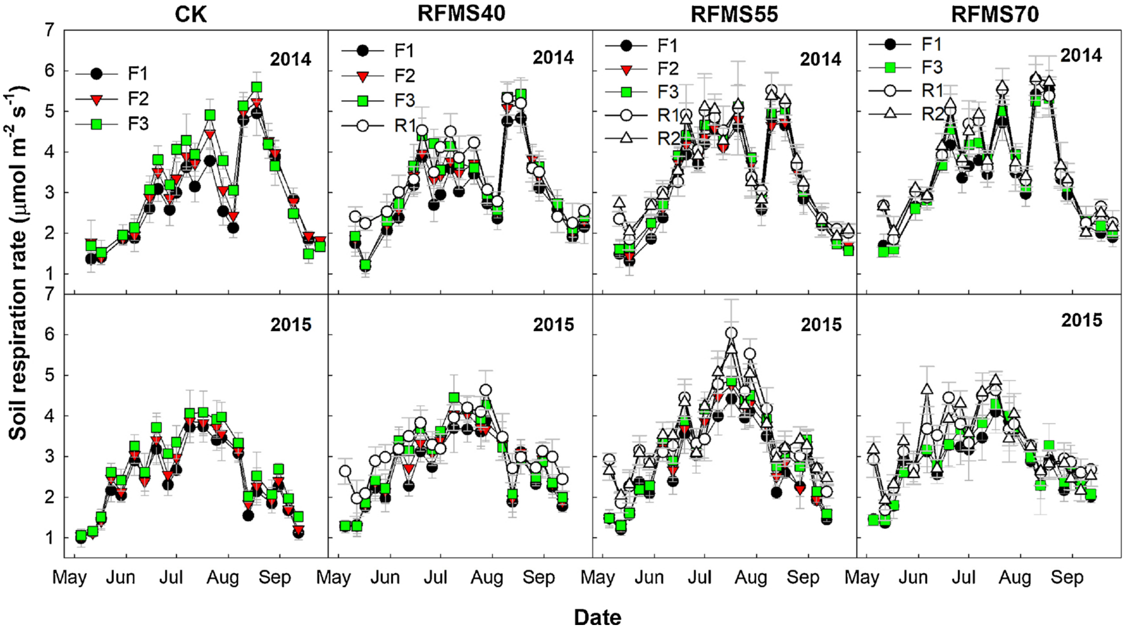

Fig. A1. Seasonal and spatial variations of soil respiration in the furrow and ridge for CK, RFMS40, RFMS55 and RFMS70 in 2014 and 2015. F1, F2 and F3 represents three different positions in the furrow, and R1 and R2 represents two different positions in the ridge, respectively. Bars represent standard deviations (n = 3).

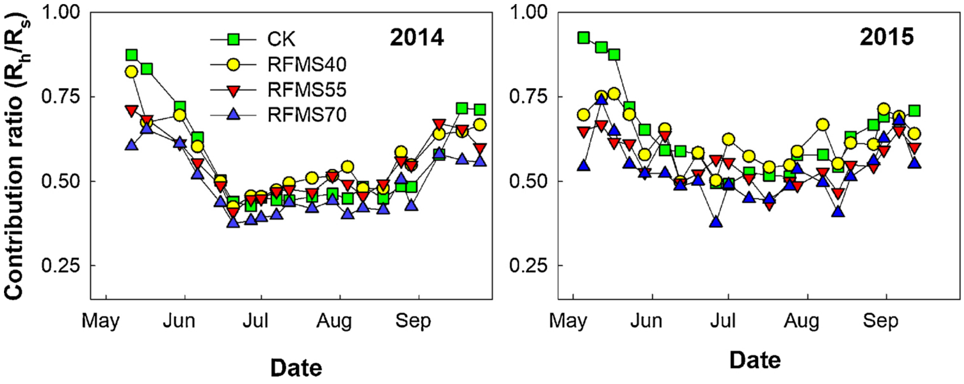

Fig. A2. Contribution of heterotrophic respiration to total soil respiration (R_h/R_s) for CK, RFMS40, RFMS55 and RFMS70 in 2014 and 2015.

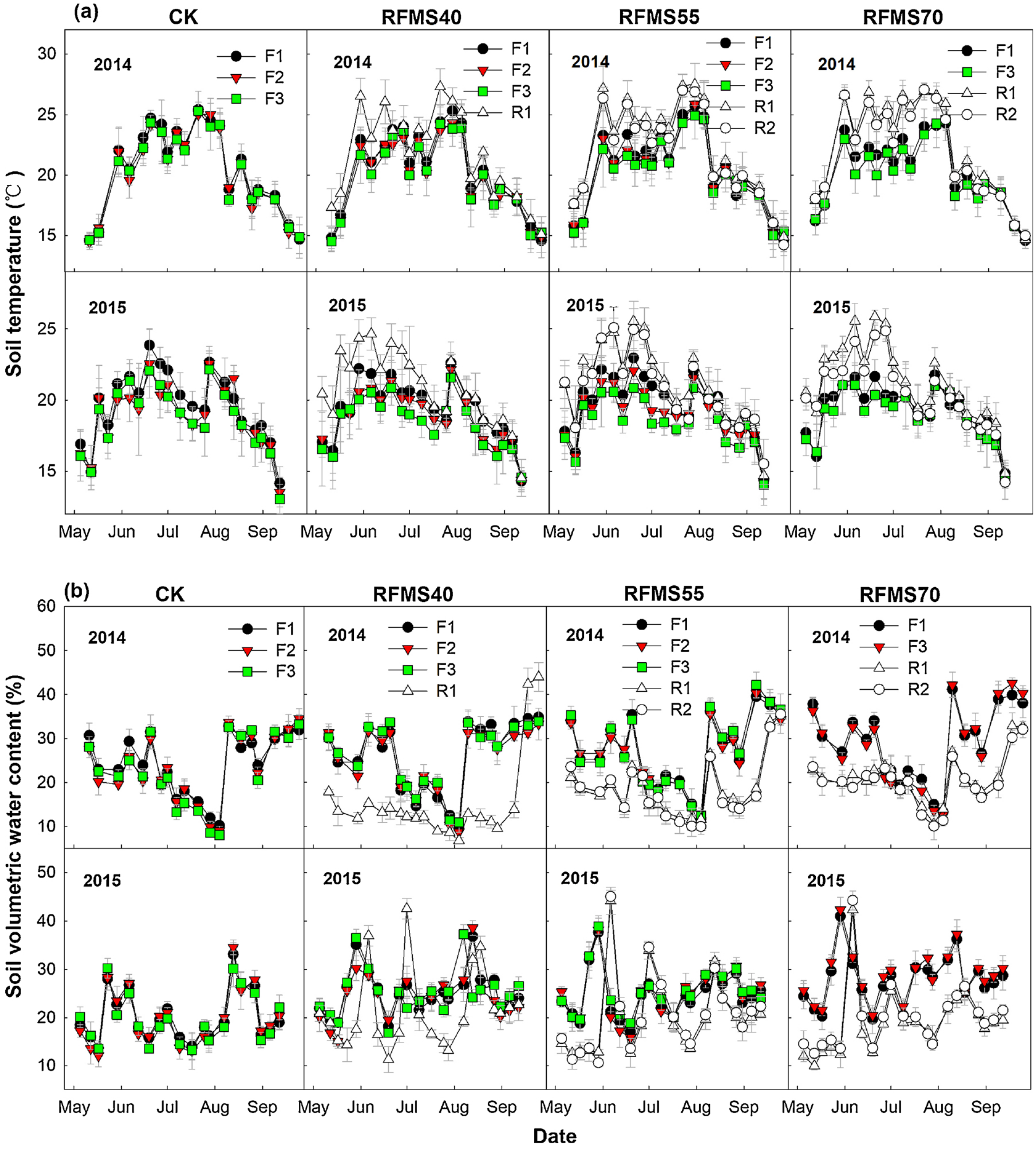

Fig. A3. Seasonal and spatial variation of soil temperature (a) and soil volumetric water content (b) for CK, RFMS40, RFMS55 and RFMS70 in 2014 and 2015. Bars represent standard deviations (n = 3).

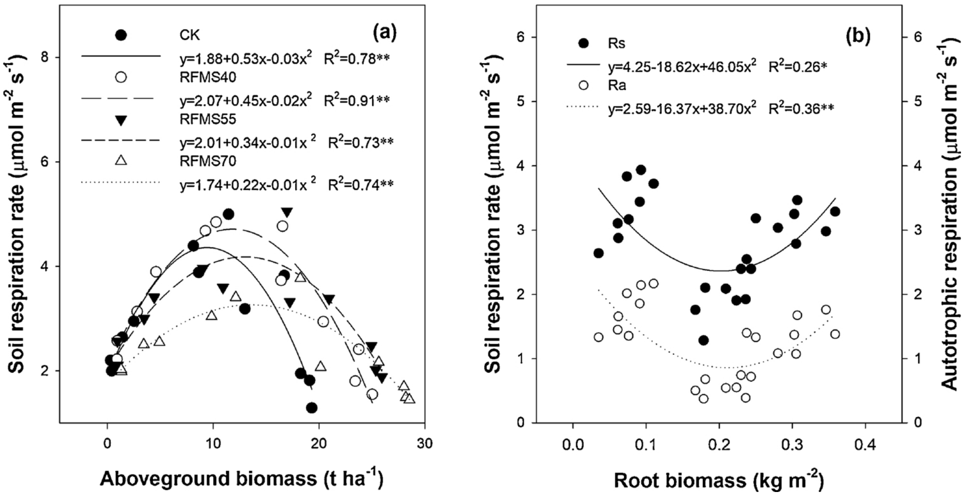

Fig. A4. Relationships between soil respiration with aboveground biomass (n = 12) for CK, RFMS40, RFMS55 and RFMS70 (a); and between soil respiration (R_s), autotrophic respiration (R_a) and root biomass (n = 24) under all treatments (b).

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