

Influence of spatial arrangement in maize-soybean intercropping on root growth and water use efficiency

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Abstract

Background and aims The relationship between transpiration and root distribution under different spatial arrangements of intercropping is poorly understood. The effects of three spatial arrangements in the maize (*Zea mays* L.) - soybean (*Glycine max* L.) intercropping on root distribution, transpiration, water use efficiency (WUE) and grain yield were examined.

Methods Two-year field experiments were conducted using three spatial arrangements of 2 rows maize × 4 rows soybean (M2S4), 2 rows maize × 2 rows soybean (M2S2) and 4 rows maize × 2 rows soybean (M4S2), with their respective sole crops (monocrop) for comparison.

Results The grain yield of maize in intercrops was higher than its monocrop and that of soybean in intercrops was lower than its monocrop. Except for M2S2 in 2014, there were yield advantages in intercropping due

to improvement in the land use efficiency. Transpiration in maize was higher than in soybean regardless of the spatial arrangements. Transpiration of both maize and soybean was influenced by the spatial arrangements of the intercropping with M4S2 or M2S4 tending to have higher daily transpiration than monocrops and other spatial arrangements. Intercropping enhanced root length density (RLD) in both maize and soybean compared to the corresponding monocrop. RLD was higher and land equivalent ratio (LER) was lower under M2S2 than under other spatial arrangements of intercropping. WUE was higher in M4S2 than in other spatial arrangements.

Conclusions Intercropping was more efficient in using the environmental resources than monocropping. The M4S2 spatial arrangement in the maize-soybean intercropping could be selected because of its sustainability and greater land and water use efficiency.

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Introduction

Intercropping is an agricultural practice used for centuries because of the advantages in the efficiency of use of resources (Javanmard et al. 2009). Cereal-legume intercropping, especially maize-soybean mixtures have been recognized as more productive compared to their respective monocrops when grown in water limited environments and dry seasons for its potential effect of saving water (Ouda et al. 2007; Mao et al. 2012). The Loess Plateau of China as one of the most severe eroded areas in the world is suffering from a decrease in total annual precipitation and an increase in mean annual temperature and pan evaporation (Qiu et al. 2003; Xu and Sui 2005; Liu et al. 2008; Zhang et al. 2008). Cropping on the Loess Plateau of China is essentially rainfed (Han 2002) and maize (*Zea mays* L.) and soybean (*Glycine max* L.) are important crops in the region mainly as monocrops (An et al. 2014). Because of the current threat of a shortage of water resources in this region (Zhou et al. 2009), the use of maize-soybean intercropping is of critical importance for the sustainability of agriculture and food security.

There is evidence that spatial arrangements of the components of intercropping influence the growth and yield performance of the intercropping system (Chui and Shibles 1984; Clement et al. 1992; Oljaca et al. 2000; Karasawa and Takebe 2012; Dolijanovic et al. 2013). For instance, a cropping system of 4 rows of maize × 4 rows of peas outperformed the yield and water use efficiency of 2 rows of maize × 4 rows of peas under irrigation (Mao et al. 2012). Previous field studies on intercropping rarely have separated water transpired through the crop from water loss from the soil surface, which might confound the net water need of the crop (Gao et al. 2009; Mao et al. 2012). The sap flow technique has shown adequately to estimate the amount of water transpired (Sellami and Sifaoui 2003; Gao et al. 2013) and it can be a useful technique in measuring the water use by each component of an intercropping system. Few studies have investigated the impact of spatial arrangements of maize-soybean intercropping on the water use efficiency and transpiration of the components under rainfed conditions in a semi-arid environment.

Thus, in this study we use both the water balance (Hillel 1998a) and the heat balance methods (Baker and Vanbavel 1987) to estimate water use and transpiration from crops in the maize-soybean intercrop under five spatial arrangements.

Growth and yield of the components of intercropping depend on the spatial distributions of their root systems (Gao et al. 2010a; Lv et al. 2014). The size and intermingling degree of crop root system under intercropping tended to increase compared to monocrops, especially under adjacent rows of the component crops (Gregory and Reddy 1982; Martin and Snaydon 1982; Li et al. 2006). Thus, the spatial arrangement of the component crops may contribute to the corresponding spatial distributions of their root systems. Soil water availability also influenced the degree of root intermingling in intercrops (Adiku et al. 2001). Water deficit may depress the spatial extension of root systems and reduce the degree of intermingling in intercrops (Adiku et al. 2001). Understanding the rooting patterns of crop species under different spatial arrangements of intercropping in rainfed environments is critical to determine the mechanisms of the belowground interactions and providing basis for the optimization of spatial arrangement of the component crops in intercrops. However, spatial information on root distributions of intercropped crops under rainfed conditions remains scarce (Zhang and Huang 2003; Li et al. 2006; Gao et al. 2010a). We therefore conducted a field experiment to examine the effects of spatial arrangements in maize-soybean intercropping on root distribution, transpiration, water use efficiency and yield. We hypothesized that, compared to the monocrops, maize-soybean intercrop (1) enhanced the grain yield and water use, (2) affected water use pattern by increasing the sap flows of component crops under different spatial arrangements, and (3) increased root length density that contributed to intercrop advantages in yield and water use.

Materials and methods

Experimental site

The study was conducted in 2013 and 2014 at Changwu Agro-ecological Station of the Loess Plateau of China (35.12 N, 107.40 E, 1200 m above sea level). The site is in an arid highland with mean annual temperature of 9.7 °C, long-term mean annual precipitation (1960–

2012) of 577 mm (mostly occurring between July and September). Weather conditions including weekly average rainfall, temperature, solar radiation and vapor pressure deficit during the growing season in 2013 and 2014 were recorded (Fig. 1). The soil is a typical Calcic Regosol (FAO/UNESCO soil classification system; Wang et al. 2010) consisting of 4% sand, 59% silt, 37% clay (Gong et al. 2007). The soil properties at the top 20 cm were: organic matter content of 12.2 g kg^{-1} , total N content of 0.94 g kg^{-1} , Olsen-P of 15.8 mg kg^{-1} , and NH_4OAc -extractable K of 144.8 mg kg^{-1} .

Plant material and crop management

Maize (*Zea mays* L.) cv. Zhengdan 958 and soybean (*Glycine max* L.) cv. Zhonghuang 24, two current

commercial cultivars widely grown on the Loess Plateau of China, were planted as sole crops and as maize-soybean intercroops in the field during the growing season of 2013 and 2014. Maize and soybean were sown on 20 April 2013 and 27 April 2014, respectively. The experimental site was ploughed and then divided into 15 plots of 6 m long and 4 m wide each (twelve rows). The plots were sown by hand at the rate of 9 plants m^{-2} for maize and 21 plants m^{-2} for soybean. Five days before sowing, 90 kg N ha^{-1} as urea and $150 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ as $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot 2 \text{ H}_2\text{O}$ (P_2O_5 12%) were broadcast to the experimental plot. Additional nitrogen in the form of urea was applied using a hole-sowing machine with $67.5 \text{ kg N ha}^{-1}$ at bell and silking stages. Plastic film mulching was laid out over all the plots by hand. Manual weeding and other management practices were kept

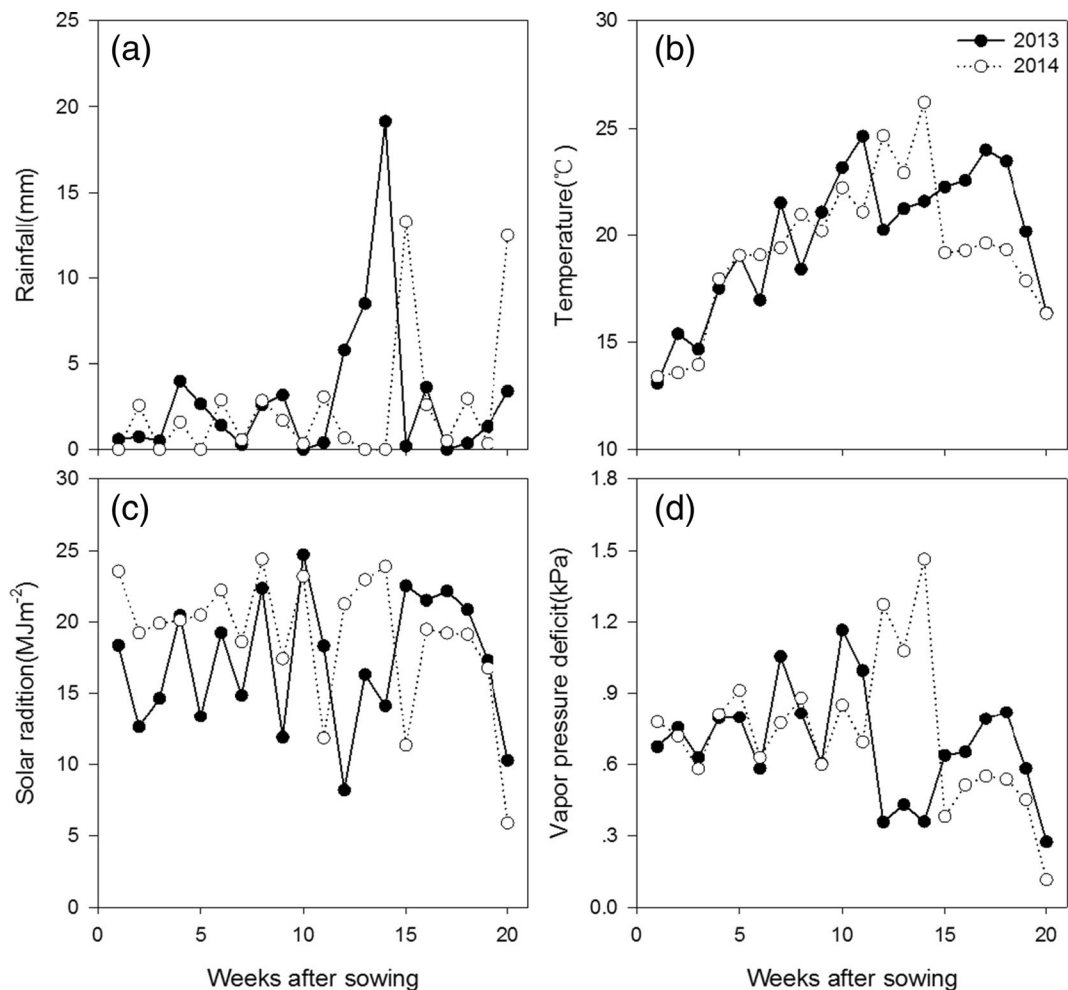


Fig. 1 Weekly average rainfall (a), temperature (b), solar radiation (c) and vapor pressure deficit (d) during the growing season in 2013 and 2014

consistent in all plots. Maize and soybean were harvested on 25 September 2013 and 30 September 2014, respectively.

Spatial managements

There were five spatial management treatments for each year in a randomized complete block design with three replicates of each treatment. The five treatments were:

- T₁: Sole maize (SM)
- T₂: Sole soybean (SSB)
- T₃: 2 rows of maize × 4 rows of soybean (M2S4)
- T₄: 2 rows of maize × 2 rows of soybean (M2S2)
- T₅: 4 rows of maize × 2 rows of soybean (M4S2).

The row spacing and plant spacing of maize was 50 cm and 22 cm, respectively, in both monocrops and intercrops. The row spacing and plant spacing in soybean was 50 cm and 19 cm, respectively, in both monocrops and intercrops. No irrigation was supplied for any treatments to mimic the practice of local farmers.

Measurements

From middle to late August in both years of the study, at 115–126 DAS, the sap flow of maize and soybean under intercropping and under sole crops was measured using the SGB16/SGB19 and SGA5 sap flow sensors (Dynamax, Houston, TX, USA). The stem diameter which is a parameter needed by procedure to obtain data was measured before installing the sensors (Gao et al. 2013). In maize, the sensor was installed on the second internode above the ground, and the sheath was removed before sensor installation. After eliminating the water on the outer surface of the plant stem, the stem was evenly coated with silica gel. To prevent water from rainfall and sunshine infiltration, the sensors were wrapped in aluminum foil. Similar installation procedures were followed for soybean. The sensors were transferred from one plant to other plants every 5–6 days to prevent tissue damage due to heat and avoid stem growth constraint. Data from sap flow by the heat balance method (Sakuratani 1981) were recorded with a data logger (Flow32-1 K Dynagage Sap Flow, Dynamax, Houston, TX, USA) every hour.

Soil cores (0.09 m diameter × 0.15 m) were collected to 1 m depth using an auger and separated in 0.1 m sections to determine the vertical root distribution at 120 DAS. Several studies (Gao et al. 2010a; Li et al.

2006; Xia et al. 2013; Yang et al. 2010) have focused on measuring the root system in the 0–1 m of the soil depth, because roots below the 1 m of the soil profile accounted for a small fraction of the total root system. To determine the horizontal distribution of the root system under the five spatial arrangements of cropping system, two soil cores were sampled in sole-cropped maize (P1 and P2) and soybean (P4 and P5), five soil cores were sampled from different placements in intercrops (P1–P5) in each plot (Fig. 2). The placements were at the inter-row of maize (P1), intra-row of maize (P2), adjacent row of maize and soybean (P3), intra-row of soybean (P4) and inter-row of soybean (P5). Each soil core section was soaked in water and then stirred vigorously and poured through a sieve (mesh size 0.2 mm²). In intercropping, roots of maize and soybean were distinguished by nodules, color, and smell. Soybean roots had nodules and characteristic smell common; roots of maize and soybean were white and brown, respectively (Li et al. 2006; Gao et al. 2010a). The total root length was measured with a scanner (Epson Perfection V700, Seiko Epson Corp., Suwa, Japan), and it was then analyzed with WinRHIZO (Regent Instrument Inc., Quebec, Canada). The root length density (RLD) was calculated from the volume of the soil cores and root length for each species.

Land equivalent ratio (LER) was calculated using the equation of Rao and Willey (1980) and Coll et al. (2012):

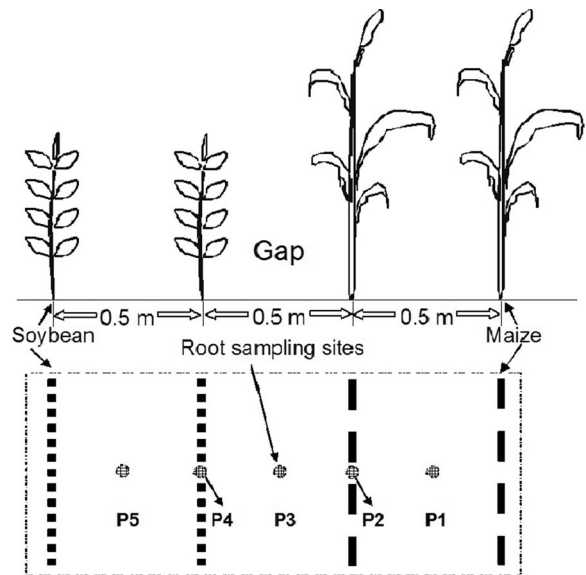
$$\text{LER} = \frac{Y_{\text{MI}}}{Y_{\text{MS}}} + \frac{Y_{\text{SI}}}{Y_{\text{SS}}} \quad (1)$$

where Y_{MI} and Y_{SI} were grain yield of maize and soybean in intercrop according to different proportions of areas (M2S4, 1/3 maize and 2/3 soybean; M2S2, 1/2 maize and 1/2 soybean; M4S2, 2/3 maize and 1/3 soybean), Y_{MS} and Y_{SS} were grain yield of maize and soybean in sole crop. All crop yields in our research was glucose requirements (GR) yield, a transformation of yield of maize and soybean under intercropping, in which each 100 kg of maize grains equals to 136.4 kg GR and each 100 kg of soybean seeds equals to 198.9 kg GR (Loomis and Connor, 1992). $\text{LER} > 1$ indicates yield advantage under intercropping. Water use efficiency (WUE) was calculated using the equation of Timmons et al. (1966):

$$\text{WUE} = \frac{Y}{\text{ET}} \quad (2)$$

Where Y was yield, and ET , the seasonal evapotranspiration, was considered as the total actual

Fig. 2 Diagrammatic representation of the planted strips of maize-soybean in the intercrop plots. Distances between rows and gap sizes (m) are indicated. There were five placements of soil samples in the intercrop: (P1) at the inter-row of maize, (P2) intra-row of maize, (P3) adjacent row of maize and soybean, (P4) intra-row of soybean and (P5) inter-row of soybean



evapotranspiration over the whole growing season. ET was estimated following the water balance equation of Hillel (1998b):

$$ET = P + I + U - D_w - R - \Delta S \quad (3)$$

where P is the total precipitation during the growing season and I is the total irrigation (here $I = 0$ since no irrigation was supplied). U is the total upward capillary flow into the root zone; D_w is the total downward draining-out root zone; R is the total runoff; ΔS is the total change in soil water stored in the upper (0–1 m) layer of soil. Runoff was not observed because the experimental field was flat. The groundwater table is very deep (about 80–90 m), so U was assumed to be negligible. There was no waterlogging event during the growing season, so deep drainage was assumed to be insignificant. Soil water storage was measured gravimetrically for every 0.1 m depth of the soil profile up to 1 m. Sap flow measurements from the individual crops were converted to a vapor flux per unit land area (Ham et al. 1990):

$$TR_j = \left[\sum_{j=1}^n \frac{SF_j / LA_j}{n} \right] LAI \quad (4)$$

where TR_j (mm h^{-1}) is transpiration of n plants of crop j by normalizing the sap flow data for leaf area; SF_j (kg h^{-1}) is the observed value of stem flow; LA_j (m^{-2})

is the average value of leaf area of crop. Leaf area was determined by leaf length \times the greatest leaf width $\times K$ (0.70 for maize and 0.75 for soybean) (Gao et al. 2010b). The leaf area index was calculated by leaf areas based on row and plant spacing.

Statistical analysis

The experimental design was a randomized complete block design ($n = 3$), with five spatial arrangement treatments. The data was statistically analyzed using SPSS 16.0 (SPSS Inc., Chicago, IL, USA). One-way ANOVA was performed with spatial arrangements as main effects and Univariate General Linear Models to assess the variation in grain yield in maize and soybean, LER and RLD, and the effects of year \times spatial arrangement. Mean values were compared by least significant difference (LSD) at the 5% level.

Results

Grain yield

There was no significant difference for grain yield between 2013 and 2014, so the data were combined and the results are shown in Fig. 3. There were significant differences in grain yield between intercrops and the monocrop of maize, but there were no differences among the spatial

arrangements (Fig. 3). On average over the two years, the grain yield of maize under the spatial arrangements of M2S4, M2S2 and M4S2 was higher than under sole maize, respectively (Fig. 3). Soybean grain yield under any spatial arrangement of intercropping was lower or equal to the yield under sole crop (Fig. 3).

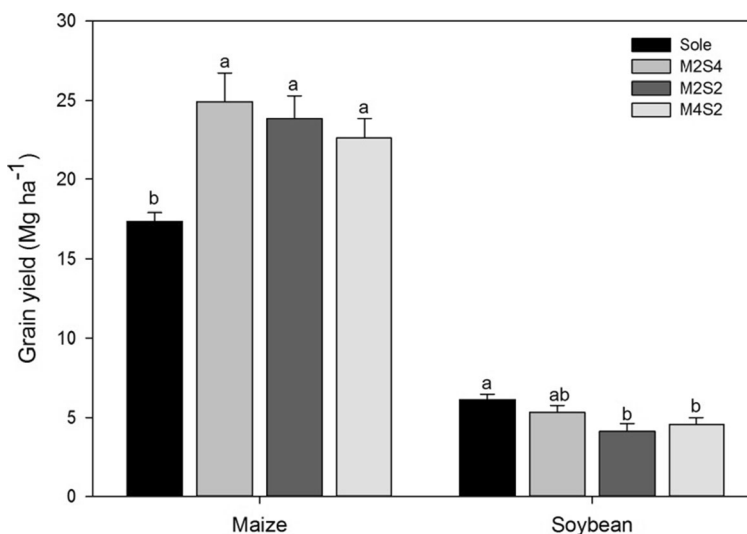
Land equivalent ratio (LER)

LER under the intercropping arrangements in the two years ranged from 0.90 to 1.24 (Table 1). There were intercropping advantages over the monocrops, except under the M2S2 arrangement in 2014. LER was not significantly different among the intercropping spatial arrangements.

Water use efficiency (WUE)

WUE under the intercropping spatial arrangements decreased by the presence of soybean compared to the monocrop of maize (Table 1). In each year, the monocrop of maize had the highest WUE, while the monocrop of soybean had the lowest. WUE under the intercropping spatial arrangements tended to increase with the proportions of intercropped maize. Intercrop improved WUE compared to average of its respective sole crops except M2S4 in 2014. The highest WUE among different spatial arrangements in intercropping was M4S2 (Table 1).

Fig. 3 The mean grain yield (in units of GR-corrected yield) in maize and soybean as sole crops (monocrops) and intercrops in 2013 and 2014. Sole = sole crop for maize or soybean, M2S4 = two rows of maize x four rows of soybean, M2S2 = two rows of maize x two rows of soybean, M4S2 = four rows of maize x two rows of soybean. Vertical bars represent standard error ($n = 3$) where these exceed the size of the symbol. Different letters above the column indicate statistical significance at the $P = 0.05$ level



Sap flow

On average over the spatial arrangements of intercropping, the sap flow in maize and soybean differed significantly between the two years with higher values in 2013 (Fig. 4). Sap flow in maize was higher than in soybean, regardless of the spatial arrangement. During the observation period of sap flow, mean daily sap flow of maize plants (4.77 mm d⁻¹ in 2013 and 3.21 mm d⁻¹ in 2014) was about 1.42 times in 2013 and 2.58 times in 2014 that of soybeans (3.36 mm d⁻¹ in 2013 and 1.25 mm d⁻¹ in 2014). The mean daily sap flow of maize plants (4.11 mm d⁻¹ in 2013 and 2.68 mm d⁻¹ in 2014) and soybean plants (2.64 mm d⁻¹ in 2013 and 0.75 mm d⁻¹ in 2014) in monocrop was significantly lower than that of intercrops (maize: 5.00 mm d⁻¹ in 2013 and 3.39 mm d⁻¹ in 2014; soybean: 3.61 mm d⁻¹ in 2013 and 1.41 mm d⁻¹ in 2014). In both years, there was no difference for daily sap flow in maize under intercrops, the daily sap flow in soybean under the M2S2 arrangement was the lowest in intercrops. In both years, the daily sap flow in soybean under the M4S2 arrangement was the greatest in intercrops, the daily sap flow in maize under the M2S4 arrangement was the greatest in intercrops. There was no difference for daily sap flow of maize and soybean between M2S4 and M4S2 arrangements (Fig. 4).

Table 1 Land equivalent ratio (LER), LER/Root length density (m^{-3}) and water use efficiency (WUE) in the maize-soybean intercropping under the spatial arrangements of SM = sole crop of

maize, SSB = sole crop of soybean, M2S4 = two rows of maize x four rows of soybean, M2S2 = two rows of maize x two rows of soybean, M4S2 = four rows of maize x two rows of soybean

Treatment	LER		LER/Root length density		WUE ($kg\ ha^{-1}\ mm^{-1}$)	
	2013	2014	2013	2014	2013	2014
SM					44.0 ± 3.8a	39.2 ± 4.0a
SSB					15.7 ± 1.9c	13.1 ± 1.6d
M2S4	1.09 ± 0.13a	1.03 ± 0.10a	4.24 ± 0.48b	6.81 ± 0.58a	30.5 ± 5.3b	25.6 ± 1.6c
M2S2	1.15 ± 0.12a	0.90 ± 0.14a	4.15 ± 0.63b	4.49 ± 0.67b	38.7 ± 1.1a	27.7 ± 2.5c
M4S2	1.24 ± 0.11a	1.01 ± 0.18a	5.92 ± 0.42a	7.33 ± 1.15a	44.1 ± 1.0a	33.4 ± 3.3b

Different letters within a column indicate statistical significance at the $P = 0.05$ level. Values are the mean ± SD

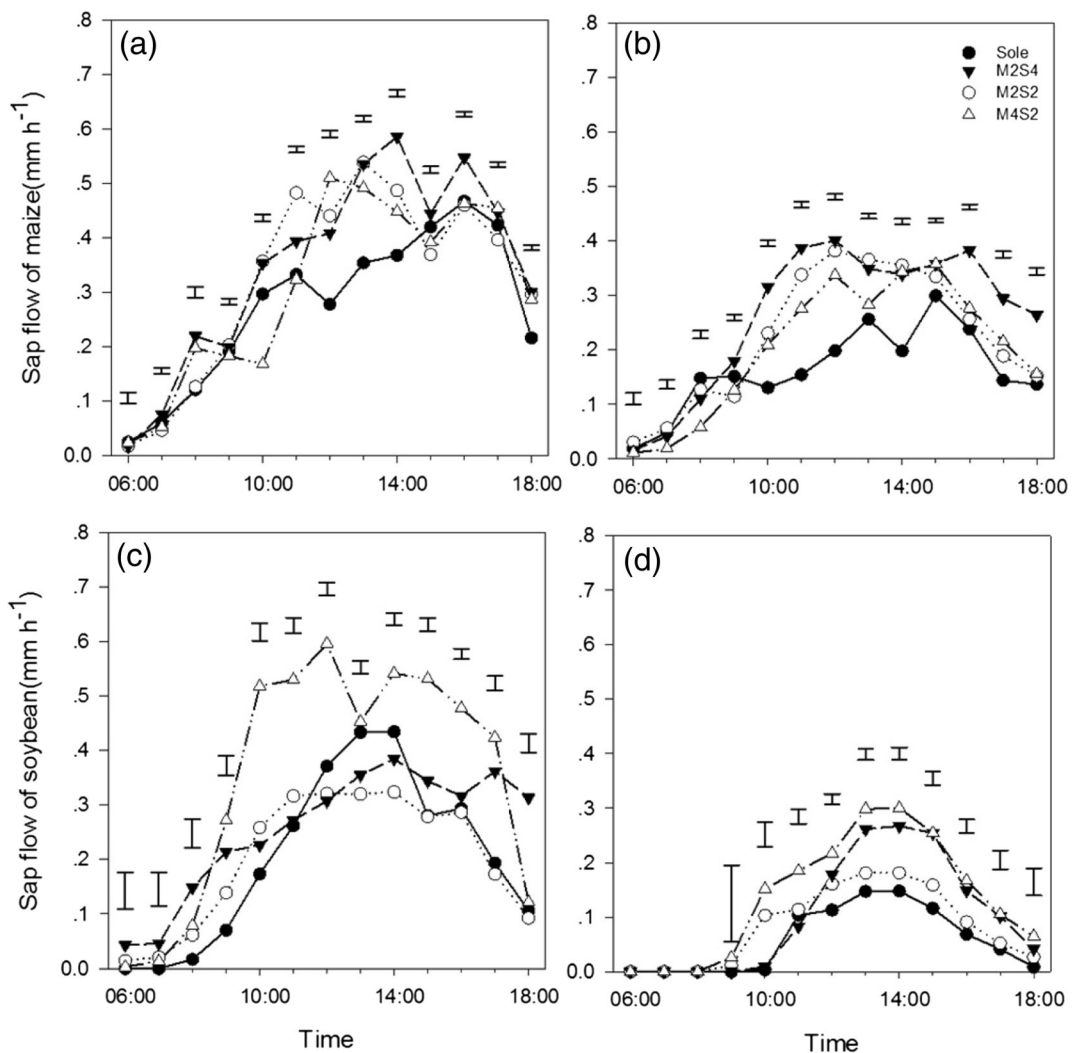


Fig. 4 Hourly sap flow in maize and soybean as sole crops and intercrops during the observational period in 2013 (a, c) and 2014 (b, d). Sole = sole crop for maize or soybean, M2S4 = two rows of

maize x four rows of soybean, M2S2 = two rows of maize x two rows of soybean, M4S2 = four rows of maize x two rows of soybean. Vertical bars represent coefficient of variation ($n = 96$)

Root length density (RLD)

The RLD of maize and soybean was affected by cropping systems and year and their interaction (Table 2). Averaged over the spatial arrangements and sampling placements (P3, P4, P5), RLD in 2013 was higher than that in 2014 (Figs 5, 6). The RLD in soybean at two sampling placements (P1 and P2) was higher in 2014 than in 2013 (Fig. 6). Maize RLD in 2013 and 2014 was significantly different between intercrops and sole crop at the P2 placement with higher RLD in intercrops in 2013, but higher in sole crop in 2014. At the P1 placement, significant differences between intercrops and sole crop were only observed in 2014 (Fig. 5). There was a significant effect of spatial arrangement on the total RLD (P1-P5) for maize in both years. Total RLD in M2S2 was generally greater than in other intercropping spatial arrangements although there were no significant difference in 2014. Total RLD of intercropped soybean in M2S2 was significantly greater than those of sole cropped soybean at P4 and P5 in both years (Fig. 6). Similarly to maize, soybean in M2S2 had higher total RLD than in other intercrops although there were no significant difference between M2S2 and M2S4 in 2013.

A negative linear relationship was found between LER and total RLD in both years. The ratio of LER to RLD in M4S2 was the greatest, followed by M2S4 and M2S2, under intercropping systems in both years

(Table 1). The ratio of LER to RLD in M4S2 was significantly higher than that of M2S2 in both years.

Discussion

Intercropping advantage

Maize monocrop had the highest WUE in both years, presumably because maize as a C4 crop is most favorable in growing conditions (Coll et al. 2012). Averaged WUE under intercropping was highly correlated with the mean grain yield of maize in the corresponding intercropping arrangement (Pearson's $\rho = 0.980$, $p < 0.001$), indicating that maize WUE was the main contributor for the WUE in maize-soybean spatial arrangements. Maize-soybean intercrop improved WUE compared to soybean and to the average of its respective sole crops. This result supports the first hypothesis in water use efficiency. Complementary traits of intercrop species in water use (Mao et al. 2012), and higher water capture due to better use of water resources (Morris and Garrity 1993) may contribute to the enhanced WUE in maize when intercropped with soybean. Mutual shading under intercrops by micro-climatic regulation and reductions in soil evaporation improved transpiration (Wallace 2000).

Maize-soybean intercropping had an advantage in the land equivalent ratio in all the spatial arrangements,

Table 2 Different spatial arrangement effects on total root length density of maize and soybean measured at five placements (P1-P5) in maize-soybean intercropping

Source	Root length density									
	P1		P2		P3		P4		P5	
	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
Maize										
Year	***		***				***		**	
Cropping system	***		*		***		***		***	
Cropping system \times year	***		***				***		***	
Soybean										
Year	***		***		***		***		***	
Cropping system	***		***		**		***		***	
Cropping system \times year	**		*		***		*		***	

The placements were: P1 = inter-row of maize, P2 = intra-row of maize, P3 = adjacent row of maize and soybean, P4 = intra-row of soybean, P5 = inter-row of soybean

* = significant at 0.05 level, ** = significant at 0.01 level, *** = significant at 0.001 level

Fig. 5 Root length densities of maize at five placements in different spatial arrangements of maize-soybean intercropping. SM = sole crop of maize, M2S4 = two rows of maize and four rows of soybean, M2S2 = two rows of maize and two rows of soybean, M4S2 = four rows of maize and two rows of soybean. P1 = inter-row of maize, P2 = intra-row of maize, P3 = adjacent row of maize and soybean, P4 = intra-row of soybean, P5 = inter-row of soybean. Vertical bars represent standard error ($n = 3$)

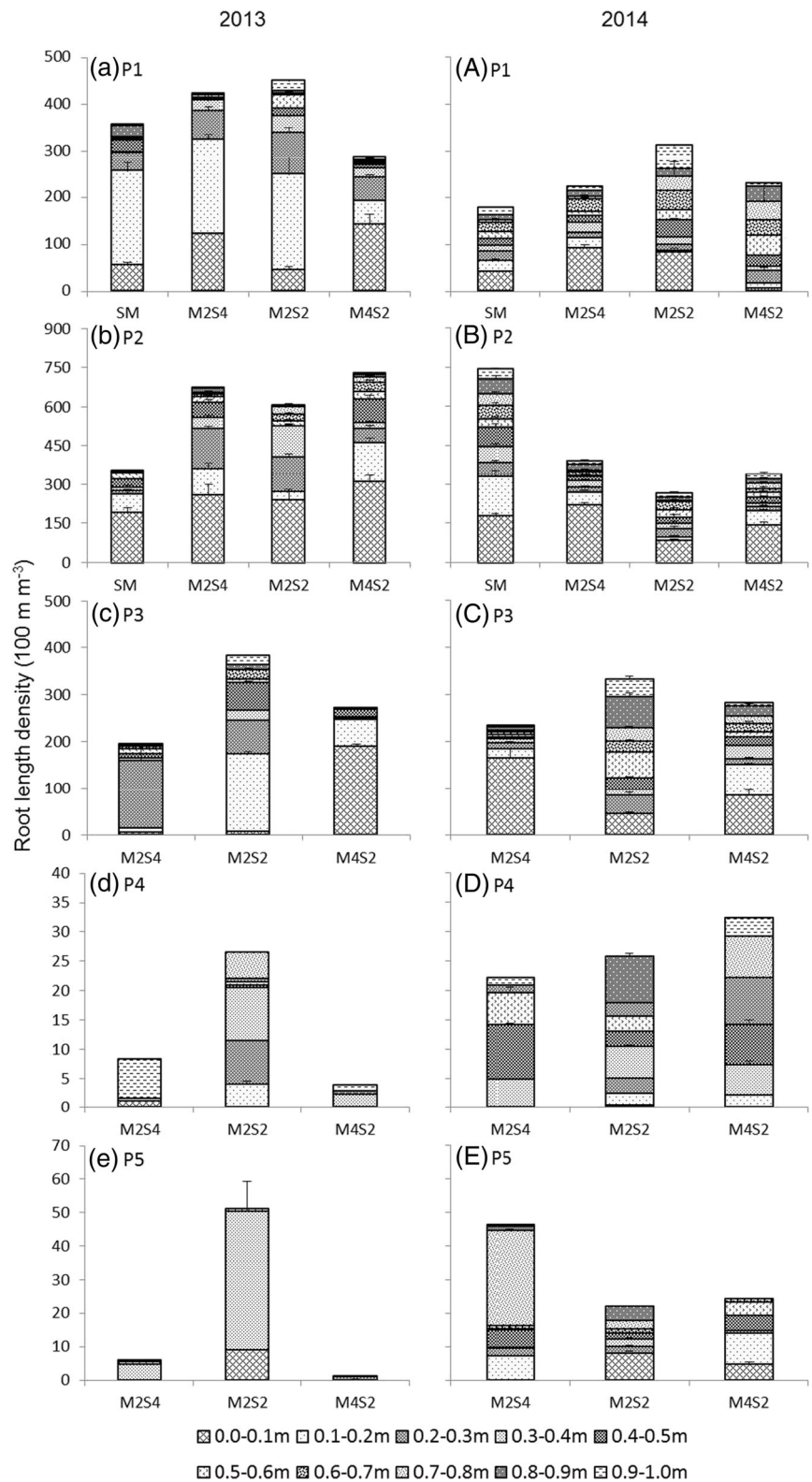
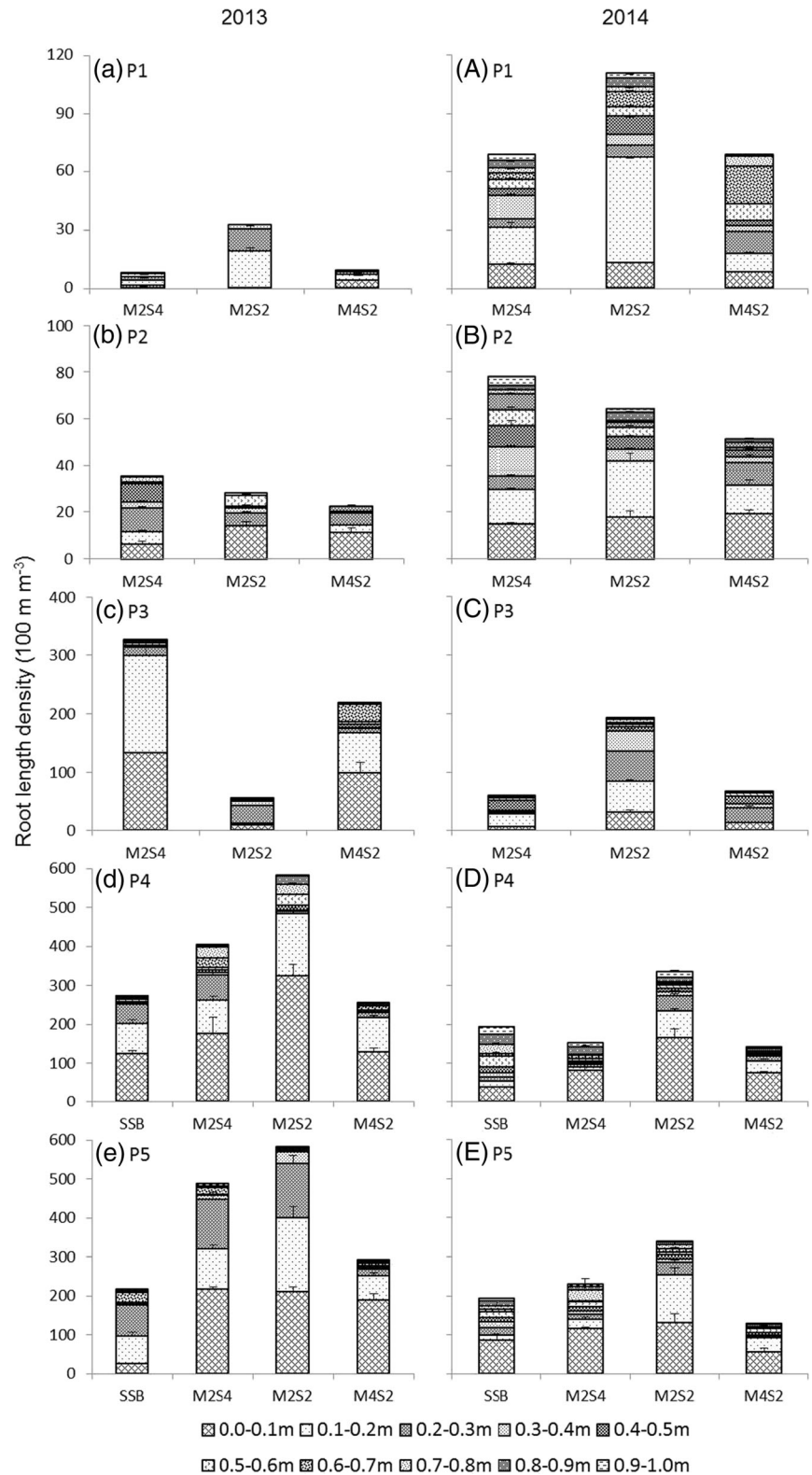


Fig. 6 Root length densities of soybean at five placements in different spatial arrangements of maize-soybean intercropping. SSB = sole crop of soybean, M2S4 = two rows of maize and four rows of soybean, M2S2 = two rows of maize and two rows of soybean, M4S2 = four rows of maize and two rows of soybean, P3 = adjacent row of maize and soybean, P4 = intra-row of soybean, P5 = inter-row of soybean. Vertical bars represent standard error ($n = 3$)



except under the M2S2 arrangement in 2014, which is supporting the first hypothesis. Intercropping has been hypothesized to have a grain yield advantage over the monocrop due to complementary interactions between intercropped species. The reason is that a relatively stronger effect of facilitation compared to competition is met for at least one intercropped species (Zhang and Li 2003; Xia et al. 2013). Interspecific facilitation in maize-soybean intercrops may be due to increased efficiency of resource use (radiation, water and soil nutrients) (Hamel et al. 1991; Ouda et al. 2007; Gao et al. 2010b), compensatory distribution of root systems (Gao et al. 2010a) and the suppression of occurrence of associated diseases (Gao et al. 2014). To reduce interspecific competition, intercropped species should differ in resource foraging in space and time (Xia et al. 2013). Our results showed that intercrop advantage in yield over the monocrop resulted from synergistic effects of increased facilitation owing to higher water use (WUE under intercrops) and decreased competition as a result of crops using resources differently in space.

Plant transpiration

The estimated daily plant transpiration from the accumulated sap flow was different between intercrop and the maize and soybean monocrops, among years and crops. The transpiration in maize was higher than in soybean regardless of weather conditions and treatments, indicating that there was a competitive advantage in water use in maize over soybean. Similar results were reported for maize when intercropped with soybean (Gao et al. 2013) and sorghum (Ozier-Lafontaine et al. 1997). The maize had a higher growth rate than soybean over the entire growing season (Ren et al. 2016); and the carbon assimilation rate of transpiration in maize as C4 crop was higher than that of soybean as C3 crop (Mao et al. 2012), which are consistent with the higher amount of water transpired in maize than in soybean. This highlights the importance of transpiration in the interspecific competition among the component species (maize and soybean) in the intercropping arrangements. The mean value of daily accumulated transpiration was significantly different between years with a greater value in 2013 than in 2014, which was consistent with greater vapor pressure deficit during the period of measurements in 2013 than in 2014. This is consistent with other studies in which sap flow was found to be closely

related to solar radiation and vapor pressure deficit (Granier et al. 1996; Gao et al. 2013).

Transpiration in intercropped soybean was significantly higher than transpiration of monocropped soybean, supporting the second hypothesis. Shading within the canopy of a taller crop such as maize reduces soil evaporation and temperature (Jaya et al. 2001), wind speed and leaf wetness duration (Ong et al. 1991), which may contribute to decrease intraspecific competition for water and enhance crop transpiration among soybean plants. In agreement with the transpiration in soybean, the transpiration in intercropped maize was significantly higher than the monocrop of maize. Improved transpiration of intercrop species may be due to complementary use in water resources (Walker and Ogindo 2003), a greater root growth such as increased root length density may explore a higher soil volume to make full use of the water resource in the soil compared to sole crop. The findings are in accordance with plant transpiration in maize-bean intercrop (Walker and Ogindo 2003; Ogindo and Walker 2005), date-palm intercrop (Sellami and Sifaoui 2003), maize-cowpea intercrop (Adiku et al. 2001). Our transpiration result sustains the fact that intercrop advantage in yield may result from converting a higher water uptake to yield.

Spatial arrangement had a significant effect on the transpiration of the component species (maize and soybean). Co-occurrence tendency of lowest plant transpiration and lowest LER in the M2S2 spatial arrangement indicated the importance that transpiration has under intercropping. Additional research on microclimatic factors and physiological performance of component species under different spatial arrangements are required.

Root length density

The interspecific facilitation through spatial distribution of the root system of the component species has been suggested to enhance grain yield and nutrient uptake (Tofinga et al. 1993; Seran and Brintha 2010; Yang et al. 2010). Our results supported the asymmetric interspecific facilitation, giving likely to the intercrop an advantage over the monocrop in the capture of water and nutrients (Li et al. 2006; Gao et al. 2010a). This indicates that the root system distribution played an important role in the intercropping advantage. Compared with the monocrops, total RLD of both maize and soybean under intercropping increased, indicating that intercropping enhanced crop root proliferation and the

soil volume used to explore water resources in the soil profile. This result supports the third hypothesis that there is intercrop advantages in yield and water use under maize-soybean intercropping owing to improved root length density. Increased RLD under intercropping compared to that under the sole crop for maize and soybean has been reported previously (Gao et al. 2010a).

Spatial arrangements had a significant influence on the total RLD under intercropping for both maize and soybean. Total RLD in M2S2 was generally higher than those in other arrangements. Root interaction between intercropped crops is suggested to occur more frequently in the adjacent rows of crops in the intercrop (Gregory and Reddy 1982). However, our results indicated that there is a greater probability of below-ground interspecific competition under M2S2 than under other spatial arrangements and this may drive more root growth in both maize and soybean. There was higher root growth and lower LER in the M2S2 and lower root growth and higher LER in the M2S4 and M4S2 spatial arrangements. There are two possible explanations for the root growth in response to competition with another plant (O'Brien et al. 2005; de Kroon 2007). One possibility is that there was a trade-off between root growth and yield growth. This means that plants produced more roots and less grain yield when grown under competition with another plant than when the plants were grown alone (Gersani et al. 2001). Another possibility is that plants produced more roots and more grain yield when grown under competition with another plant because more roots are likely better to obtain water and nutrients to promote the growth and yield (de Kroon 2007; Hess and De Kroon 2007). Our results indicate that M2S2 intercrop supported the former possibility, while M2S4 or M4S2 intercrop supported the latter possibility. Compared to M2S4 and M4S2 intercrop, M2S2 intercrop overproduced roots at the expense of yield. The key reason for yield and WUE increase under M2S4 and M4S2 was that crop produced more roots to obtain water resources.

Conclusions

Yield, root growth, and water use were influenced by the different spatial arrangements in maize-soybean intercropping. The M4S2 spatial arrangement was optimal among all the spatial arrangement in the maize-

soybean intercropping because of its greater land and water use efficiency. Maize-soybean intercrop advantages in yield and water use are due to improvements in root length density. Compared to monocrop, total RLD of both maize and soybean under intercropping increased, indicating that a greater root growth may explore a higher soil volume to make full use of the water resource in the soil profile, and to improve transpiration of crop (maize and soybean) in intercrops.

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