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RESEARCH

Suppression of Weeds and Increases in Food Production in Higher Crop Diversity Planting Arrangements: A Case Study of Relay Intercropping

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ABSTRACT

Crop diversification plays an important role in increasing land use efficiency and weed suppression. A field experiment was conducted on maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] relay intercropping and corresponding monocultures in Southwest China in 2012 to 2013. Differences were observed in crop productivity, weed diversity, and weed biomass. Grain yield and aboveground biomass for maize did not differ between intercropped and monocultured maize; however, they were lower for soybean in intercropping compared to soybean in monoculture (SM). Greater decreases were evident for the intercropping of one row of soybean alternated with one row of maize (MSRI1) (–46% for yield and –55% for biomass) than the intercropping of two rows of soybean alternated with two rows of maize (MSRI2) (–10% for yield and –27% for biomass). The total grain yield and aboveground biomass in MSRI2 were higher than those in MSRI1 (5.9% for yield and 6.4% for biomass), monoculture maize (MM, 16% for yield and 24% for biomass), and SM (394% for yield and 227% for biomass). Weed diversity and biomass in the intercropped phase were lower in MSRI1 and MSRI2 than in MM and SM, and the total weed biomass during the entire growing season also decreased in intercropping as compared with monocultures and fallow, with decreases of 28, 40, and 60% in MSRI1 and 29, 41, and 61% in MSRI2 compared with MM, SM, and fallow, respectively. In addition, more light was also captured by intercrops than by those in monoculture and fallow. Correlation analysis suggested that crop diversity suppressed weed growth by increasing the interception of light by crops.

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Abbreviations: H', Shannon–Wiener index; MM, monoculture maize; MSRI1, one row of soybean intercropped with one row of maize; MSRI2, two rows of soybean intercropped with two rows of maize; PAR, photosynthetically active radiation; S, species richness; SM, soybean in monoculture.

With the global population expected to exceed 9 billion by 2050 (FAO, 2010), food security is an increasingly important issue. In addition, the heavy reliance on chemical inputs, such as chemical fertilizers, insecticides, and herbicides, in intensive agriculture poses many risks for the environment and human health (Landis et al., 2005; Meehan et al., 2011). Furthermore, the short-term beneficial effect of chemical inputs on grain yield has leveled off in intensively farmed croplands, and there is increasing pressure to reduce the amount of chemical inputs (Bedoussac et al., 2015). Thus, there is an increasing need for sustainable and productive cropping systems to feed the growing global population and ensure a healthy environment.

Cropping system diversification can enhance the ecosystem services provided by cropland (Smith et al., 2008; Ratnadass et al., 2012), such as improving production (Li et al., 2007; Hauggaard-Nielsen et al., 2013), increasing soil conservation (Zougmore et al., 2000), protecting more species (Jones and Sieving, 2006), and controlling weeds and pests (Zhu et al., 2000; Amossé et al., 2013). Intercropping is a traditional cropping practice widely

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distributed around the world that uses cropping system diversification to obtain higher grain yields. Intercropping can enhance the efficiency of the use of natural resources such as light, water, and nutrients (Allen and Obura, 1983; Li et al., 2007; Hauggaard-Nielsen et al., 2013). In addition, the practice has positive impacts on the control of weeds, pests, and diseases in field crops compared with monoculture agriculture (Vandermeer 1992; Zhu et al., 2000; Amossé et al., 2013). Greater competition of intercropped crops with weeds for resources, such as light, water, and nutrients, can result in increased productivity and weed suppression in intercropping (Olasantan et al., 1994; Workayehu and Wortmann, 2011; Corre-Hellou et al., 2011; Nelson et al., 2012).

Maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] relay intercropping, a useful practice in organic agriculture based on cropping system diversification, is widely distributed in Southwest China. The cropping pattern can increase farmer income and reduce shortfalls in the soybean supply in China (Yang et al., 2014). Previous studies have focused on grain yields and the specific relationships between the two intercropped crops (Su et al., 2014; Yang et al., 2015; Yong et al., 2015), but the mechanisms by which intercropping suppresses weeds remain poorly understood. In this type of relay-intercropped system, soybean is relay intercropped before harvesting the maize, and both crops grow alongside each other for nearly 2 mo, which increases the efficiency of land use and improves crop productivity. During the intercrop period, the incoming solar radiation at ground level is reduced, which can suppress weed growth. We hypothesized that the planting arrangement in an intercropping system affects crop productivity and growth of weeds.

We therefore conducted a 2-yr field experiment to evaluate the effects of crop diversity in planting arrangements on crop yields and weed suppression. The aims of this research were (i) to evaluate the grain yield and biomass in different relay intercropping systems as compared with monoculture; (ii) to explore the mechanisms of weeds suppression in relay intercropping systems; and (iii) to find the relationship between light transmittance, weed diversity, total weed biomass, total grain yield, and total crop biomass.

MATERIALS AND METHODS

Site Description

The experiment was conducted during two consecutive years from 2012 to 2013 at the Teaching and Experimental Farm of Sichuan Agricultural University (29°59′ N, 103°00′ E; 576 m asl), located in Southwest China. According to data provided by the local meteorological station, the mean annual temperature is 16.2°C (30-yr average from 1971 to 2000), with mean minimum and maximum temperatures of 6.1 (January) and 25.4°C (July), respectively. The frostless period lasts ~300 d, and mean annual precipitation is 1200 mm. The soil is composed of purple clay loam (pH = 6.8), with 1.33 g kg^{-1} total N, 0.51 g kg^{-1} total P, 26.16 g kg^{-1} total K, and 29.78 g kg^{-1} organic matter. Soil organic matter was determined using the wet combustion method (Lindenbaum et al., 1948). Soil N concentrations were determined by the Kjeldahl method (Bremner, 1960). The P concentrations were analyzed using the ammonium molybdate method after extraction by 0.5 M $NaHCO_3$ (Olsen et al., 1954). Soil K concentrations were determined by flame atomic absorption spectrometry after extraction by 1 M NH_4OAc (Stanford and English, 1949). Previous studies of weed populations listed 24 species of 24 genera belonging to 13 families in the field used in our experiment (Table 1).

Experimental Design

The field experiment was established in March 2012 and repeated in 2013; plot areas and treatments were the same in each year. Fifteen 6-m × 6-m plots were laid out in a random design, and plots were separated by 1-m intervals. All plots were deeply plowed prior to maize planting each year, and manual weed control was performed in all the plots. There were three replicates for each of the five treatments, which included a control (fallow), monocropping of either crop (maize monoculture [MM] and soybean monoculture [SM]), and two patterns of maize–soybean intercropping (one row of soybean alternated with one row of maize intercropping [MSRI1], and two rows of soybean alternated with two rows of maize intercropping [MSRI2]). The soybean cultivar Nandou12 and the maize cultivar Chuandan418, which are the major cultivars grown in Southwest China, were used in the experiment and were provided by the Zigong Institute of Agricultural Sciences (Zigong, Sichuan Province, China) and the Maize Research Institute of Sichuan Agricultural University (Chengdu, Sichuan Province, China), respectively.

In our experiment, the relay intercropping arrangements were formed as additive mixtures of the component crops. In MSRI1, one row of soybeans was planted directly between maize rows at the tasseling stage of the maize, with a distance of 50 cm between the rows of maize and soybean (Fig. 1A). In MSRI2, we used a wide-narrow row planting pattern with alternating strips of maize and soybean, and soybeans were planted in the wide rows between maize strips (i.e., two maize rows and two soybean rows were planted per strip). The distance between maize and soybean strips was 60 cm, and the space between rows was 40 cm in MSRI2 (Fig. 1B). For MSRI1 and MSRI2, maize was sown on 27 Mar. 2012 and 28 Mar. 2013 within 19-cm intra-row spacing between two hills with one plant per hill; soybean was sown on 15 June 2012 and 13 June 2013 within 19-cm intra-row spacing between two hills with two plants per hill. For MM, maize sowing date and intra-row spacing of maize were the same as for intercropped maize, but the inter-row spacing was 100 cm (Fig. 1C). The SM, sown on the same date and using the same intra-row spacing as intercropped soybean, was planted as solid inter-row spacing of 50 cm (Fig. 1D) with one plant per hill. Hand sowing at high density was performed, and seedlings were subsequently thinned to achieve the target density and uniformity of plant spacing. Whether in relay intercropping or monoculture, the density of maize or soybean was the same. For maize, the density was 52,500 plants ha^{-1}, and for soybean, it was 105,000 plants ha^{-1}. Thus, the density of total crop plants in intercropping

Table 1. Weed species in the experimental field.

No.	Family	Genus	Species
1	Amaranthaceae	*Alternanthera*	*Alternanthera philoxeroides* (Mart.) Griseb.
2	Amaranthaceae	*Amaranthus*	*Amaranthus retroflexus* L.
3	Boraginaceae	*Bothriospermum*	*Bothriospermum tenellum* (Hornem.) Fisch. et Mey.
4	Brassicaceae	*Capsella*	*Capsella bursa-pastoris* (L.) Medic
5	Caryophyllaceae	*Arenaria*	*Arenaria serpyllifolia* Linn.
6	Caryophyllaceae	*Stellaria*	*Malachium aquaticum* (L.)Fries.
7	Compositae	*Cirsium*	*Cirsium setosum* (Willd.) MB.
8	Compositae	*Galinsoga*	*Galinsoga parviflora* Cav.
9	Compositae	*Gnaphalium*	*Gnaphalium affine* D. Don
10	Compositae	*Ixeridium*	*Ixeridium sonchifolium* (Maxium). Shih
11	Compositae	*Turczaninowia*	*Turczaninowia fastigiata* (Fisch.) DC.
12	Cyperaceae	*Cyperus*	*Cyperus rotundus* L.
13	Euphorbiaceae	*Acalypha*	*Acalypha australis* L.
14	Malvaceae	*Abutilon*	*Abutilon theophrasti* Medicus
15	Oxalidaceae	*Oxalis*	*Oxalis corniculata* L.
16	Plantaginaceae	*Plantago*	*Plantago asiatica* L.
17	Poaceae	*Alopecurus*	*Alopecurus aequalis* Sobol.
18	Poaceae	*Echinochloa*	*Echinochloa crusgali* (L.) Beauv.
19	Poaceae	*Eleusine*	*Eleusine indica* (L.) Gaertn
20	Poaceae	*Polypogon*	*Polypogon fugax* Nees ex Steud.
21	Poaceae	*Setaria*	*Setaria viridis* (L.)Beauv
22	Polygonaceae	*Polygonum*	*Polygonum aviculare* L.
23	Ranunculaceae	*Ranunculus*	*Ranunculus sieboldii* Miq.
24	Rubiaceae	*Galium*	*Galium aparine* L. var. *tenerum* Grenet (Godr.) Rebb.

(157,500 plants ha^{-1}) was much higher than in monoculture. Maize was harvested on 28 July 2012 and 1 Aug. 2013, and soybean was harvested on 25 Oct. 2012 and 26 Oct. 2013.

The fertilization rate for maize was 240 kg N hm^{-2}, 105 kg P_2O_5 hm^{-2}, and 112.5 kg K_2O hm^{-2} in both intercropping and monoculture plots, whereas for soybean, it was 60 kg N hm^{-2}, 63 kg P_2O_5 hm^{-2}, and 52.5 kg K_2O hm^{-2}. For maize, half of the N fertilizer was broadcast and incorporated into the soil prior to sowing, and the other half of the N fertilizer was applied at the 12-leaf stage. For soybean, all of the N fertilizer was applied before sowing, as conducted in Yang et al. (2015), to provide N for soybean seedling growth before the formation of root rhizobium. All of the P_2O_5 and K_2O fertilizers were applied before maize or soybean sowing. Herbicides were not applied in the experimental field. Instead, manual weed control was performed five times, at 35, 75, 120, 150, and 180 d after maize sowing, respectively. When drought occurred (i.e., soil water content was <50% of field capacity), irrigation was applied in all the plots to the extent that soil water content reached 90% if field capacity. Other field agricultural management practices were undertaken equally for all treatments.

Measurement of PAR and Calculation of Light Interception

The photosynthetically active radiation (PAR) below the crop canopy was measured in each plot on sunny days between 1030 and 1400 h during the intercropped stage of crops (i.e., R3 stage of maize and the V3 stage of soybean) using a quantum sensor LI-190 (LI-COR) in 2012 and 2013, respectively. Sensors were placed on the horizontal arm of an observational scaffold, at a height of 10 cm above the ground. The measurements were performed midway between maize and soybean rows, under the soybean or maize canopy, and in the center of the soybean or maize rows in MSRI2 (Fig. 2A). The locations of the sensors in MSRI1, MM, and SM are shown in Fig. 2. In the fallow plots, measurements were performed above the weed canopies. In

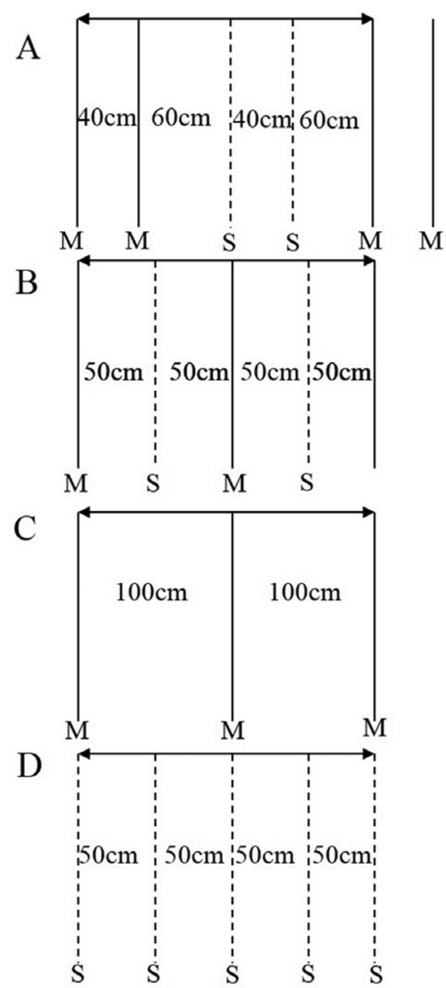

Fig. 1. Layout of (A) a maize–soybean relay intercropping system with one row of soybean and maize, (B) a maize–soybean relay intercropping system with two rows of soybean and maize, (C) a maize monoculture, and (D) a soybean monoculture. S and M stand for soybean rows and maize rows, respectively.

addition, one reading was also taken above the crop canopy in each cropping pattern (Fig. 2). The flux densities of PAR below the crop canopies was measured at 10-s intervals using LI-191SA quantum sensors (LI-COR) with a LI-1400 data logger with three replications for each plot. The light transmittance below the crop canopies was calculated as PAR transmittance (%) = (I_s/I_m) × 100%, where I_s the PAR below the crop canopy, and I_m is the PAR at the top of the crop canopy.

Crop Sampling and Yield Determination

At physiological maturity, maize and soybean grain yields were determined by harvesting a 4-m × 2-m quadrat in each plot. After the harvested plants dried naturally, grain yields, and grain water content were determined. The area outside the harvest plot was used for the sampling of aboveground biomass. Plants were sampled from a 2-m^2 quadrat (1 × 2 m) in each plot by cutting to ground level and dried at 65°C to constant weight to determine the dry matter content.

Land equivalent ratio (LER) was calculated as Yang et al. (2015) described:

$$\mathrm{LER} = \frac{Y_{\mathrm{im}}}{Y_{mm}} + \frac{Y_{\mathrm{is}}}{Y_{\mathrm{ms}}}$$

where Y_{mm} and Y_{im} are the mono- and intercropped maize yields and aboveground biomass, respectively, and Y_{ms} and Y_{is} are the mono- and intercropped soybean yields or aboveground biomass, respectively.

Weed Measurements

After emergence of the maize seedlings, in April 2012, three permanent quadrats (1 × 1 m) were established in each plot for weed sampling. Weed diversity parameters were measured five times in the key growth periods of the crops: the seven-leaf period of maize (V7), the tasseling period of maize (VT), the intercropped phase of maize and soybean (CGS), the beginning seed period of soybean (R5), and the beginning maturity period of soybean (R7). The weed species richness (*S*, species number per quadrat) and the number of each weed species were recorded in the permanent quadrat. All weed species were identified according to Chinese Weed Flora (Li, 1998). Species diversity was studied by comparing *S* and the diversity indices. The Shannon–Wiener index (H') was calculated as $H' = -\sum P_i \ln P_i$, where P_i is the proportion of total individuals in the *i*th species in the sample quadrat (Magurran, 1988). After measurement of the diversity parameters, the aboveground weeds in each quadrat were harvested using a destructive method and dried at 65°C to constant weight to determine the aboveground weed biomass. All weeds were removed by hand in each plot after investigation and sampling.

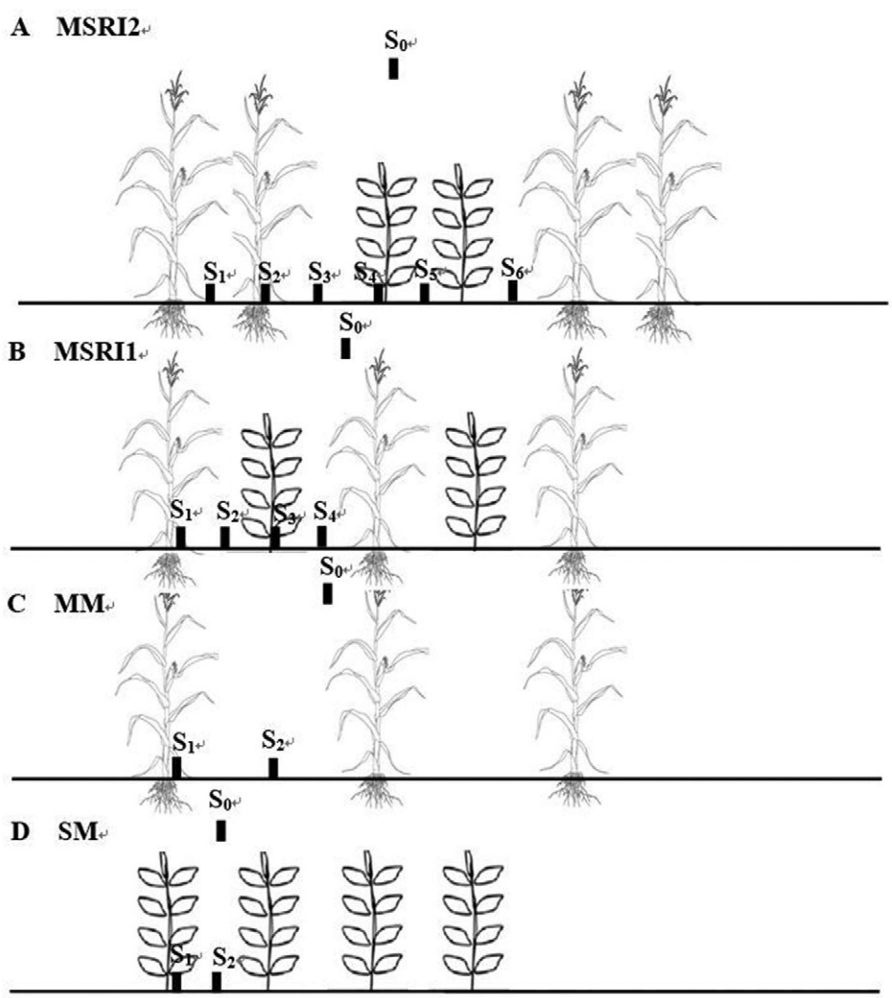

Fig. 2. Setting of photosynthetically active radiation sensors in the different cropping systems for (A) two rows of soybean alternated with two rows of maize (MSRI2), (B) one row of soybean alternated with one row of maize (MSRI1), (C) maize monoculture (MM), and (D) soybean monoculture (SM). S_i is the *i*th position of the sensor.

Statistical Analyses

Data were analyzed using the SPSS software package (SPSS, 2006). Repeated measures ANOVAs were used to examine the effects of year, treatment, and their interaction on crop biomass and grain yield. One-way ANOVA was used to analyze differences of each parameter among treatments were analyzed by post hoc comparisons using the Student–Newman–Kuels test, with differences considered significant if $P \leq 0.05$. The percentage changes in all parameters at each sampling site in relay intercropping vs. monoculture and fallow for each set of treatments within sets of replicates were calculated as [relay intercropping − monoculture(fallow)]/monoculture(fallow) × 100.

RESULTS

PAR and Light Transmittance below Crop Canopies

Photosynthetically active radiation below the crop canopy and light transmittance did not differ between MSRI1 and MSRI2; however, they were lower in MSRI1 and MSRI2 than in MM, SM, and fallow ($P < 0.05$, Fig. 3). The light transmittance in both intercropping

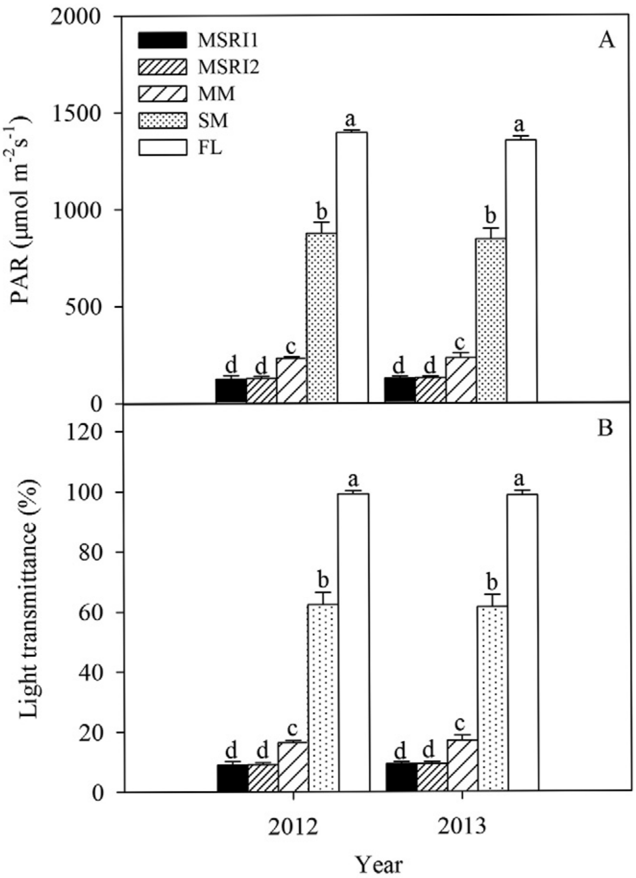

Fig. 3. (A) Photosynthetically active radiation (PAR) under the crop canopy and (B) light transmittance in the intercropped phase in different cropping patterns. MSRI2, two rows of soybean alternated with two rows of maize; MSRI1, one row of soybean alternated with one row of maize; MM, maize monoculture; SM, soybean monoculture; FL, fallow. Values with different letters are significantly different within year ($P < 0.05$).

patterns decreased by 45% compared with MM, by 85% compared with SM, and by 91% compared with fallow (Fig. 3B). This indicates that more light was captured by crops in intercropping than in monocultures and fallow.

Grain Yields

Grain yields of maize did not differ between relay intercropping and MM within year ($P > 0.05$, Table 2). In 2012, grain yields of soybean in both relay intercropping patterns were lower than in SM ($P < 0.05$, Table 2), with decreases of 51 and 17% for MSRI1 and MSRI2, respectively; in 2013, grain yield of soybean in MSRI2 reached a similar value as SM, but in MSRI1, it was still lower than in SM (Table 2). Total grain yields in relay intercropping were higher than those in monoculture ($P < 0.05$). Total grain yield between the two patterns of relay intercropping differed, with MSRI2 being 8% higher than MSRI1 in 2012. Relay intercropping gained remarkably higher total grain yields compared with monocultures. Land equivalent ratio of grain yields in MSRI2 (1.83–1.88) was higher than that in MSRI1 (1.48–1.55) ($P < 0.05$).

Crop Aboveground Biomass

Relay intercropping did not change aboveground biomass of maize with MM ($P > 0.05$, Table 3), but it reduced aboveground biomass of soybean (by 54–56 and 19–33% for MSRI1 and MSRI2, respectively) compared with SM ($P < 0.05$, Table 3). The MSRI2 pattern had the largest total aboveground biomass of crops (16–21 Mg ha^{-1}), followed by MSRI1 (15–20 Mg ha^{-1}) and MM (12–18 Mg ha^{-1}), and SM had the lowest total aboveground biomass (5–6 Mg ha^{-1}). Land equivalent ratio of aboveground biomass in MSRI2 (1.66–1.78) was also higher ($P < 0.05$) than in MSRI1 (1.43–1.48).

Weed Diversity

According to our observations, gramineous weeds were the most abundant among species across all treatments. Before soybean was planted in the field, there were no differences in either S or H' among MSRI1, MSRI2, and MM; however, they were lower than in SM and fallow at the maize VT stage ($P < 0.05$, Table 4). At the intercropped phase of maize and soybean (CGS), S and H' of weeds in intercropping patterns were lower than those in MM, SM, and fallow ($P < 0.05$), and there was no difference between MSRI1 and MSRI2. Compared with MM, S was reduced ~25% in intercropping; compared with SM, S was reduced ~33%. In terms of H', its value was 10 to 17% lower in intercropping than in MM and 19 to 26%

Table 2. Grain yields and land equivalent ratio (LER) of grain yields in different cropping patterns.

Year	Treatments†	Grain yield: Maize	Grain yield: Soybean	Grain yield: Total	LER
		Mg ha^{-1}			
2012	MSRI1	7.9 ± 0.1a‡	1.0 ± 0.0c	8.9 ± 0.1b	1.48 ± 0.02b
	MSRI2	8.0 ± 0.1a	1.7 ± 0.0b	9.6 ± 0.1a	1.83 ± 0.08a
	MM	8.0 ± 0.1a	–	8.0 ± 0.1c	–
	SM	–	2.0 ± 0.1a	2.0 ± 0.1d	–
2013	MSRI1	7.2 ± 0.1a	1.0 ± 0.0b	8.2 ± 0.1a	1.55 ± 0.04b
	MSRI2	6.9 ± 0.1a	1.6 ± 0.1a	8.5 ± 0.2a	1.88 ± 0.14a
	MM	7.6 ± 0.2a	–	7.6 ± 0.2b	–
	SM	–	1.7 ± 0.0a	1.7 ± 0.0c	–

† MSRI1, one row of soybean alternated with one row of maize; MSRI2, two rows of soybean alternated with two rows of maize; MM, maize monoculture; SM, soybean monoculture.

‡ Different letters in columns indicate significant mean differences in the different cropping systems within year ($P < 0.05$).

Table 3. Aboveground biomass and land equivalent ratio of aboveground biomass (BLER) in different cropping patterns.

Year	Treatments†	Aboveground biomass: Maize	Aboveground biomass: Soybean	Aboveground biomass: Total	BLER
		Mg ha^{-1}			
2012	MSRI1	17.8 ± 1.2a‡	2.3 ± 0.0c	20.1 ± 0.9b	1.43 ± 0.03b
	MSRI2	17.2 ± 0.8a	4.2 ± 0.1b	21.4 ± 0.8a	1.78 ± 0.16a
	MM	18.0 ± 1.1a	–	18.0 ± 1.1c	–
	SM	–	5.2 ± 0.1a	5.2 ± 0.6d	–
2013	MSRI1	12.2 ± 1.2a	2.9 ± 0.1c	15.1 ± 1.1b	1.48 ± 0.16b
	MSRI2	11.8 ± 0.7a	4.2 ± 0.2b	16.0 ± 1.2a	1.66 ± 0.16a
	MM	12.1 ± 1.3a	–	12.1 ± 0.9c	–
	SM	–	6.3 ± 0.5a	6.3 ± 0.5d	–

† MSRI1, one row of soybean alternated with one row of maize; MSRI2, two rows of soybean alternated with two rows of maize; MM, maize monoculture; SM, soybean monoculture.

‡ Different letters in columns indicate significant mean differences in the different cropping systems within year ($P < 0.05$).

Table 4. Weed species richness (S) and Shannon–Wiener index (H') in each survey period in different cropping patterns.

Year	Item	Treatment†	Maize stage: Seven leaf	Maize stage: Tasseling	Intercropped phase	Soybean stage: Beginning seed	Soybean stage: Beginning maturity
2012	S	MSRI1	10.3 ± 1.5a‡	8.7 ± 0.6b	7.7 ± 0.6d	7.0 ± 1.0b	6.7 ± 1.2b
		MSRI2	11.3 ± 1.5a	8.3 ± 0.6b	8.7 ± 0.6d	7.3 ± 0.6b	7.0 ± 1.0b
		MM	11. 7 ± 2.1a	8.7 ± 0.67b	10.3 ± 0.6c	9.7 ± 1.2a	9.3 ± 1.5a
		SM	13. 7 ± 0.6a	12.3 ± 1.5a	12.7 ± 0.6b	7.0 ± 1.0b	6.7 ± 1.2b
		Fallow	13.3 ± 0.6a	13.3 ± 1.5a	16.3 ± 0.6a	10.7 ± 1.5a	10.0 ± 1.0a
	H'	MSRI1	2.1 ± 0.1a	1.9 ± 0.0b	1.6 ± 0.0c	1.6 ± 0.1b	1.7 ± 0.2b
		MSRI2	2.2 ± 0.1a	1.9 ± 0.1b	1.8 ± 0.2c	1.7 ± 0.0b	1.7 ± 0.1b
		MM	2.2 ± 0.1a	1.8 ± 0.0b	2.0 ± 0.0b	2.0 ± 0.1a	2.0 ± 0.1a
		SM	2.3 ± 0.0a	2.3 ± 0.1a	2.2 ± 0.1a	1.7 ± 0.2b	1.7 ± 0.1b
		Fallow	2.3 ± 0.0a	2.3 ± 0.1a	2.31 ± 0.0a	2.1 ± 0.1a	2.0 ± 0.1a
2013	S	MSRI1	9.7 ± 0.6a	8.7 ± 0.6b	7.7 ± 0.6d	8.3 ± 0.6b	8.0 ± 0.0b
		MSRI2	10.0 ± 1.0a	8.7 ± 0.6b	8.0 ± 1.0d	8.7 ± 0.6b	7.7 ± 0.6b
		MM	9.7 ± 0.6a	8.3 ± 0.6b	10.0 ± 0.0c	12.7 ± 0.6a	10.0 ± 1.0a
		SM	11.0 ± 1.0a	12.3 ± 0.6a	12.3 ± 0.6b	9.0 ± 2.6b	6.3 ± 0.6c
		Fallow	11.0 ± 0.0a	13.0 ± 1.0a	15.0 ± 1.0a	13.0 ± 1.0a	10.3 ± 0.6a
	H'	MSRI1	2.0 ± 0.1a	1.8 ± 0.6b	1.7 ± 0.1d	1.8 ± 0.1b	1.7 ± 0.1b
		MSRI2	2.0 ± 0.0a	1.8 ± 0.2b	1.7 ± 0.0d	1.8 ± 0.0b	1.9 ± 0.1b
		MM	2.0 ± 0.1a	1.8 ± 0.2b	1.9 ± 0.0c	2.2 ± 0.1a	2.0 ± 0.0a
		SM	2.0 ± 0.0a	2.1 ± 0.0a	2.2 ± 0.1b	1.8 ± 0.1b	1.7 ± 0.1b
		Fallow	2.1 ± 0.0a	2.2 ± 0.0a	2.3 ± 0.0a	2.2 ± 0.0a	2.1 ± 0.1a

† MSRI1, one row of soybean alternated with one row of maize; MSRI2, two rows of soybean alternated with two rows of maize; MM, maize monoculture; SM, soybean monoculture.

‡ Different letters in columns indicate significant mean differences in the different cropping systems within year ($P < 0.05$).

lower than SM. In addition, after harvesting the maize crop, S and H' in plots of MSRI1 and MSRI2, although not different from those in SM, were still lower than in MM and fallow ($P < 0.05$, Table 4).

Weed Aboveground Biomass

Similar to the weed diversity results, weed biomass showed no differences among MSRI1, MSRI2, and MM before the planting of soybean ($P > 0.05$) and was lower than in SM and fallow (Fig. 4). In the intercropped phase, weed biomass in intercropping was lower than in monocultures and fallow ($P < 0.05$), and there was no difference between MSRI1 and MSRI2. Compared with MM, weed biomass in intercropping was suppressed by 22 to 28%, whereas compared to SM and fallow, the reduction was >60 and 80%, respectively (Fig. 4). In addition, after harvesting maize, weed biomass in MSRI1, MSRI2, and SM was lower than in MM and fallow ($P < 0.05$). There was no difference in the total weed biomass for the entire growing season between MSRI1 and MSRI2, which were lower than in MM, SM, and fallow ($P < 0.05$), respectively, by 28, 40, and 60% (Fig. 5).

Relationships among Light Transmittance, Weed Diversity, Weed Biomass, Crop Grain Yield, and Crop Biomass

Shannon–Wiener index of weeds in the intercropped phase and total weed aboveground biomass for the entire growing season were positively correlated with the light

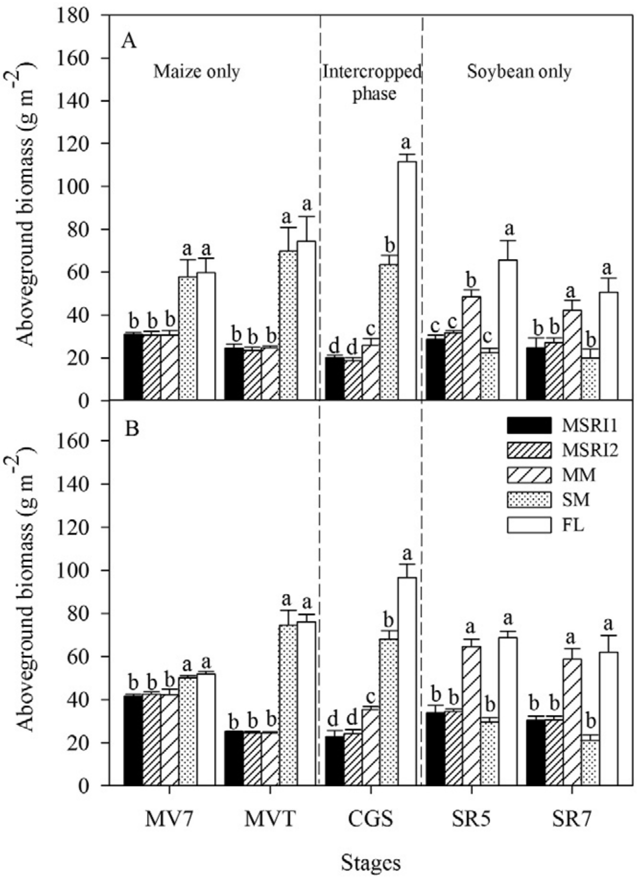

Fig. 4. Weed aboveground biomass in different cropping patterns in (A) 2012 and (B) 2013. MSRI2, two rows of soybean alternated with two rows of maize; MSRI1, one row of soybean alternated with one row of maize; MM, maize monoculture; SM, soybean monoculture; FL, fallow. Values with different letters are significantly different ($P < 0.05$).

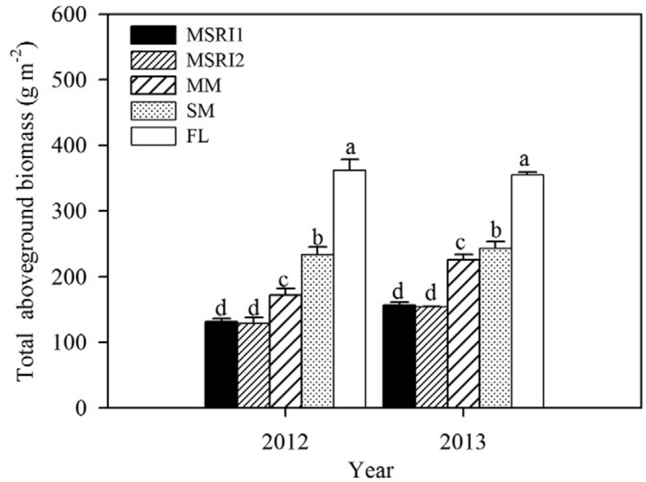

Fig. 5. Total weed aboveground biomass for the entire growing season in different cropping patterns. MSRI2, two rows of soybean alternated with two rows of maize; MSRI1, one row of soybean alternated with one row of maize; MM, maize monoculture; SM, soybean monoculture; FL, fallow. Values with different letters are significantly different within year ($P < 0.05$).

transmittance below the crop canopy in the intercropped phase ($P < 0.01$, Fig. 6A and 6B). Grain yield and crop biomass were negatively correlated with the light transmittance below the crop canopy in the intercropped phase ($P < 0.01$, Fig. 6C and 6D). Weed biomass was also negatively correlated with grain yield and crop biomass (Fig. 6E and 6F).

DISCUSSION

Increasing Food Production by Increasing Light Capture

Crop diversification has been shown to increase crop productivity by increasing the interception and use efficiency of solar radiation (Gao et al., 2010; Liu et al., 2017), and our results support this finding. The lower PAR and light transmittance at the crop canopy (10 cm above the ground) in the intercropped phase in the maize–soybean relay intercropping compared with the monocultures indicated that more light was captured and used by crops from the intercropping planting arrangement (Fig. 3). The complementary utilization of growth resources such as light, water, land, and nutrients by the intercropped crops, and niche differentiation in space and time, can lead to increased resource availability and greater acquisition of limiting resources in intercropping systems (Tilman et al., 2001; Li et al., 2014). Therefore, complementarity and facilitation may be the most important mechanisms for increasing yield in intercropping (Hector et al., 1999; Li et al., 2014). In our study, total grain yield and crop biomass were negatively correlated with the light transmittance at the bottom of the crop canopy in the intercropped phase (Fig. 6C and 6D). Therefore, higher yield in the maize–soybean relay intercropping might be attributed to a greater interception of solar radiation in the intercropped phase by the intercropping planting arrangement.

Soybean was planted in the maize rows ~2 mo before maize maturity in the maize–soybean relay intercropping. Compared with SM, the tall maize plants create a distinct microenvironment for soybean seedlings (Gao et al., 2010; Su et al., 2014), which can have negative effects on soybean growth and final yields (Yang et al., 2014). Our previous studies showed that the light environment in which soybean grew in maize–soybean relay intercropping was altered by changes in spatial planting patterns, and MSRI2 provided a more favorable light environment for soybean growth than MSRI1 (Yang et al., 2014). In this study, soybean in MSRI2 performed better than in MSRI1, with higher total grain yields, land equivalent ratio of grain yields, and total biomass, which may be attributed to a more favorable light environment for soybean growth in MSRI2.

Weed Reduction by Greater Light Competition of Crops

With increasing awareness of food quality and the environmental impacts of conventional industrial agriculture, the use of herbicides in agriculture production is

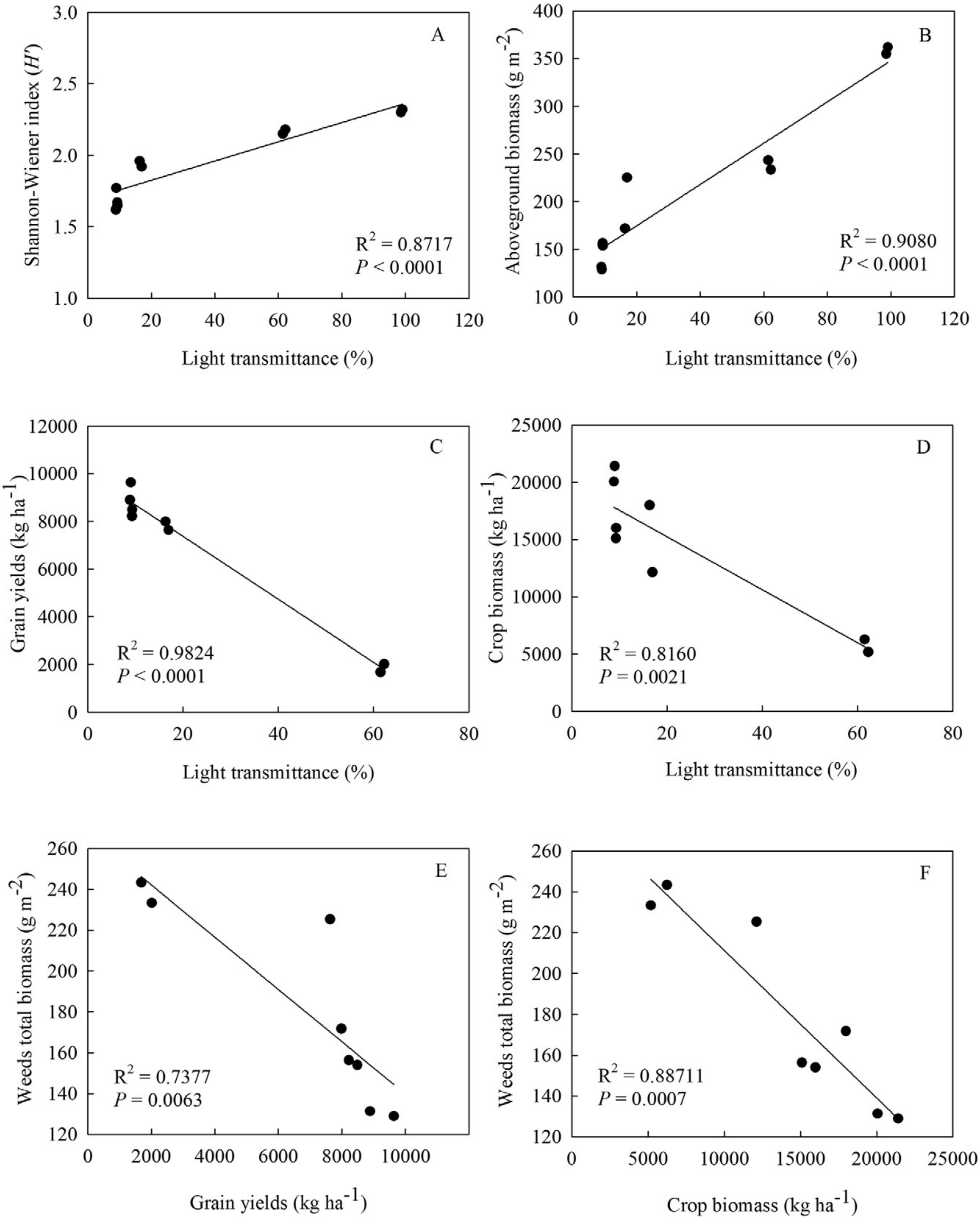

Fig. 6. The relationship of the light transmittance below the crop canopy in the intercropped phase with (A) weed diversity, (B) weed biomass, (C) crop grain yield, and (D) crop biomass, and the relationship of weed biomass with (E) crop grain yield and (F) crop biomass. Regression lines, R^2, and P are for 2012 and 2013 data. For weed diversity and weed biomass, $n = 10$. For grain crop yield and biomass, $n = 8$

becoming less popular because of their negative impacts on food safety, public health, and the environment (Ying and Williams, 1999; Bastiaans et al,. 2008). The use of cropping system diversification to suppress weeds and harmful insects in agronomic practices, based on ecological principles, is vital for the sustainable development of agriculture (Zhu et al., 2000). Numerous studies have reported that weed suppression is greater in intercropping systems compared with the planting of a single crop cultivar (Szumigalski and Van Acker, 2005). Musambasi et al. (2002) reported that, compared with maize planted alone, there were 79, 55, and 59% fewer *Striga asiatica* L. plants in maize–cowpea [*Vigna unguiculata* (L.) Walp.] intercropping 8, 10, and 12 wk, respectively, after crop emergence. Baldev et al. (2004) found that intercropping reduced weeds and dry matter compared with pearl millet (*Pennisetum glaucum* L.) planted alone. In this study, the weed *S*, *H′*, and aboveground biomass in maize–soybean relay intercropping were lower than in monoculture and fallow in the intercropped phases of maize and soybean (Table 4, Fig. 4); however, these indices were not different between the two intercropping patterns. These results suggested that the maize–soybean relay intercropping planting arrangement (i.e., more crop species) tended to provide greater weed reduction than monocultures of the corresponding crops and fallow.

Outcompeting weeds for resources or suppressing their growth through allelopathy can be an important mechanism for superior weed control in intercropping relative to monoculture (Olorunmaiye, 2010). Compared with monoculture, crops in intercropping systems would capture a greater share of available resources, such as light and macronutrients (Abraham and Singh, 1984; Olasantan et al., 1994; Lithourgidis et al., 2011), which increases their effectiveness in preempting the use of resources by weeds and suppressing weed growth. The *H′* of weeds in the intercropped phase and the total weed aboveground biomass over the entire growing season were positively correlated with the light transmittance below the crop canopy in the intercropped phase (Fig. 6A and 6B). This implies that the decrease in weed diversity and biomass in maize–soybean relay intercropping can be attributed to the higher light interception by crops and therefore less light available to weeds in intercropping than in monoculture. Before soybean sowing, weed diversity and biomass in the maize–soybean relay intercropping did not differ from those in MM, and they were also not different between intercropping and SM after harvesting maize (Table 4, Fig. 4). These results support the hypothesis that cropping system diversification suppresses weeds.

A Sustainable Method for Soybean Production in China

Due to the low economic benefits of soybean, the total area planted with soybean has continuously decreased in many major soybean production regions in China (e.g., Northeast China Plain and Huang-Huai-Hai Plain) since 2008. However, the demand for soybean consumption by the Chinese population has increased in recent years (Chinese Statistical Bureau, 2013). An increasing amount of soybean has been imported from other countries, consuming large amounts of energy in transportation and emitting more CO_2 into the atmosphere, contributing to global climate change (Liu and Diamond, 2005). Therefore, soybean production in China is facing a growing challenge in balancing food supply and environmental protection. In our study, both patterns of maize–soybean relay intercropping not only yielded the same amount of maize yield and biomass as in MM, but also yielded soybean, grain yield, and biomass, which were higher in MSRI2 than in MSRI1 (Table 3). These results indicated that the use of different planting arrangements in maize–soybean relay intercropping could provide an effective approach to relieve the deficit in soybean supply, as well as reduce CO_2 emissions from the transportation of imports into China.

Moreover, in an attempt to produce more food from cropland to meet the needs of the increasing global population, in the past five decades, vast amounts of chemical fertilizer, insecticides, and herbicides have been used in most parts of the world, especially in China (Ju et al., 2009). In China, the total area of cropland using herbicides is ~9.1×10^5 million ha (accounting for 60% of the total arable land), and this has resulted in many negative impacts on the environment and human health (Foley et al., 2011), such as soil contamination, degradation in the quality of agricultural products, and decreases in diversity. Therefore, the use of more sustainable agronomic practices for weed management has attracted renewed interest. Maize–soybean relay intercropping systems can suppress weeds through increased interception of solar radiation by crops, which will decrease the use of herbicides and thus reduce environmental impacts.

CONCLUSIONS

The PAR and light transmittance at the crop canopy at 10 cm above the ground in the intercropped phase were lower in the maize–soybean relay intercropping system than in monoculture. This implies that, compared with monocultures, more light was captured by crops in the maize–soybean relay intercropping system, reducing the light availability for weeds. Our intercropping configurations yielded the same amount of grain yield and aboveground biomass for maize as MM but yielded lower soybean grain yield and aboveground biomass than SM. The MSRI2 system yielded a larger amount of soybean grain and aboveground biomass than MSRI1. The total grain yield and aboveground biomass with intercropping were higher than in the monocultures, particularly in MSRI2. Weed diversity and biomass in the intercropped phase were lower in the maize–soybean relay intercropping system than in monocultures. The total weed biomass over the entire growing season was also lower in the maize–soybean relay intercropping system than in monoculture and fallow. There were strong relationships between the light transmittance below the crop canopy in the intercropped phase and weed diversity in the intercropped phase, total weed biomass over the entire growing season, total grain yield, and total crop biomass.

Conflict of Interest

The authors declare that there is no conflict of interest.

Acknowledgments

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