



Land productivity and water use efficiency of maize-soybean strip intercropping systems in semi-arid areas: A case study in Punjab Province, Pakistan

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ABSTRACT

Intercropping improves crop productivity in dryland farms, but little information is available on its application to irrigated land. Therefore, a three-year field trial was conducted to compare two maize-soybean strip-intercropping planting patterns (two-rows of maize intercropped with two-rows of soybean [2M2S] or -three rows of soybean [2M3S]) were studied with sole maize (SM) and sole soybean (SS) systems. Our results showed that wider-strips of soybean grown as 2M3S had significantly higher leaf area index (LAI; 19%), total dry matter accumulation (TDM; 15%), and grain yield (21%) than the narrower 2M2S strips; this is likely related to the reduced effects of maize shading on soybean. Slightly decreased LAI (4%), TDM (8%), and grain yield (5%) of maize were found in 2M3S. On average, intercropped maize and soybean produced 80% and 52% in 2M2S and 76% and 63% in 2M3S compared to SM and SS yields, respectively, demonstrating the dominance of maize over soybean when intercropped. Similarly, maize was a stronger competitor for water than soybean, with partial water equivalent ratio of 0.81 in 2M2S and 0.78 in 2M3S, while that of soybean was 0.54 in 2M2S and 0.66 in 2M3S. In the intercropping systems, the land equivalent ratio ranged from 1.31 to 1.45, and the water equivalent ratio ranged from 1.32 to 1.49, exhibiting that maize-soybean strip-intercropping is a productive strategy to maximize water use efficiency. The results suggest that the maize-soybean strip-intercropping system may be a productive and sustainable strategy to improve the water use efficiency and land productivity under irrigated conditions. This strategy could benefit agriculture with cleaner, and more efficient production under a global scenario of constrained land and water resources. However, more studies are needed to evaluate the feasibility of intercropping systems in various growing conditions.

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1. Introduction

Millions of people in the developing countries live on self-sufficient family farms (FAO, 2013). These small-holder farmers face ever-increasing pressure to produce adequate grain crops (cereals and legumes) to fulfill the nutritional needs of their families (Verschelde et al., 2013), especially under the prevailing conditions of limited land and water resources (Chen et al., 2018; Payero et al., 2006; Rahman et al., 2017). In arid and semi-arid areas, annual evapotranspiration is higher than annual precipitation (Khan and Hasan, 2017), and annual precipitation ranges from 50 mm to 600 mm (Khattak and Ali, 2015). These regions are the buffer zones between pasture and arable agriculture, where crop and livestock farming co-exist (Yuan et al., 2013). Typically, crop production in these areas dependent on irrigation with groundwater (Chai et al., 2014). As a result, in recent years, the water table in many of these regions has fallen significantly due to the over-pumping (Zhang, 2007). Often, the agricultural sector must compete for water resources with fast-developing urban areas (Kendy et al., 2007; Poumanyong et al., 2012). Competition may be severe enough to threaten agricultural production and sustainability (Piao et al., 2010). Therefore, to reduce water losses and improve water use efficiency (WUE; seed yield per unit of water use) in modern crop production, new planting methods (i. e., intercropping) are paramount.

Various approaches have been employed to reduce water demand to save water in agriculture, planting patterns (intercropping) and techniques (reduced tillage, no-till, and straw mulching), the use of planned deficit irrigation, and the implementation of new policies and laws in water resource management (land leveling and cleaning of irrigation canals) (Chen et al., 2018; Fan et al., 2013; Kang et al., 2000; Yin et al., 2015). Among these approaches, some authors suggest that intercropping is the most viable and sustainable method for improving WUE in crop production (Ren et al., 2019; Vandermeer, 1992). Intercropping has such potential benefits as higher crop yields, greater efficiencies of resource use (sunlight, water, and nutrients), reduced diseases and pests, and improved ecological services (Du et al., 2017; Liu et al., 2018; Rahman et al., 2017; Raza et al., 2019c). Additionally, several

researchers have reported that intercropping increases soil water content, decreases run-off, and improves water use, resulting in systems-level yield increases (Gitari et al., 2018; Hu et al., 2017; Sharma et al., 2017; Yang et al., 2011). Under the present global scenario of limited land and water resources, intercropping could enhance both WUE and crop yields. However, the mechanism of how intercropping systems improve WUE and seed yield of intercropped species, especially under irrigation, has not been thoroughly investigated.

Previous research has confirmed the advantages and benefits of cereal-legume strip intercropping (Du et al., 2017; Iqbal et al., 2018). In a recent meta-analysis of different cereal-legume intercropping combinations, maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr) were observed to use with the greatest efficiency when intercropped (Li et al., 2020). Worldwide, soybean is the ninth most important food crop. For instance, in 2018, 121 million hectares were cropped to soybeans with a net value of 79 US \$ billion (Pielke Sr, 2013; Terzić et al., 2018). Soybean is the source of 55% of the edible oilseed oils (Pielke Sr, 2013). Maize is the most important cereal crop with a total cropped area of 228 million hectares; it is a major source of food and feed for humans and animals (FAO, 2018) and a potential source of bioenergy (Battaglia et al., 2017, 2020). However, limited land and water resources limit further expansion of the cultivation area of maize and soybean (Du et al., 2017). Recently, researchers have reported that the expansion of soybean cultivation is the leading cause of deforestation in Brazil and Argentina (Barona et al., 2010). Scientists have claimed that the maize-soybean strip-intercropping system can resolve the conundrum of maintaining or increasing legume and cereal production on less land while simultaneously reducing negative impacts to the environment (Feng et al., 2020). However, the limitation of available resources and socioeconomic conditions of farmers cause variations in the adoption of intercropping. Adversity to change limits the benefits that a cleaner approach to agriculture could bring.

Maize-soybean strip-intercropping is widely practiced in China, notably in the Sichuan, Shandong, and Ningxia (Iqbal et al., 2018; Liu et al., 2018). In the strip-intercropping system, a higher planting density enables intercrops to capture greater radiation than sole cropping

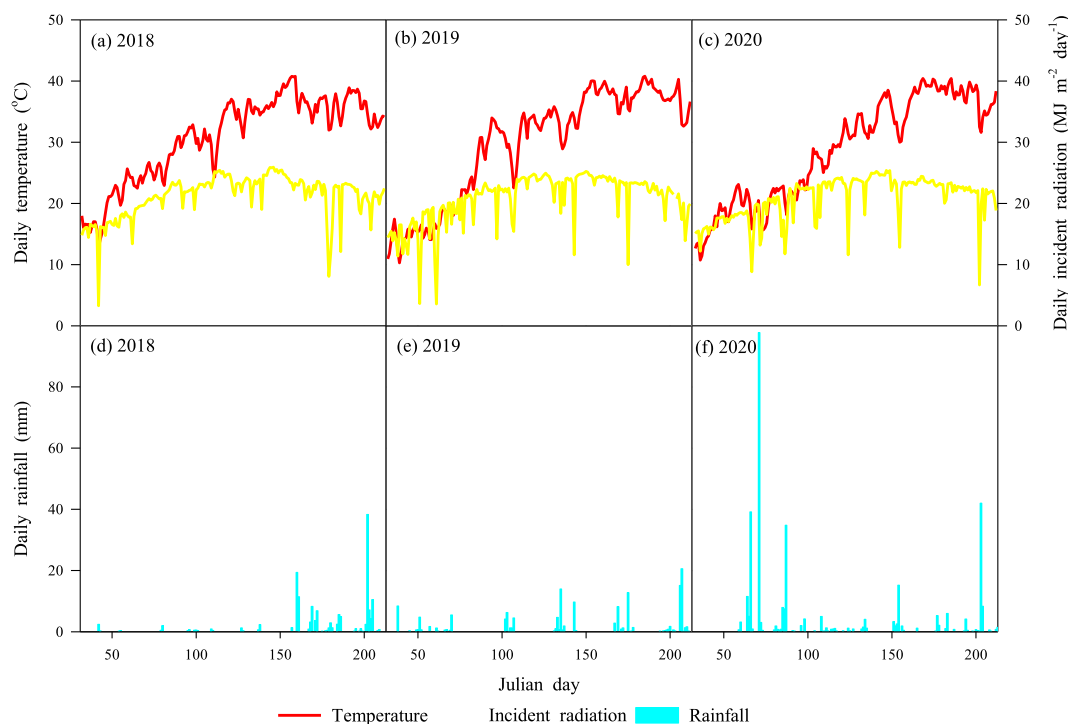


Fig. 1. Daily temperature and incident radiation (a for 2018, b for 2019, c for 2020), and rainfall (d for 2018, e for 2019, f for 2020) during the planting period of crops.

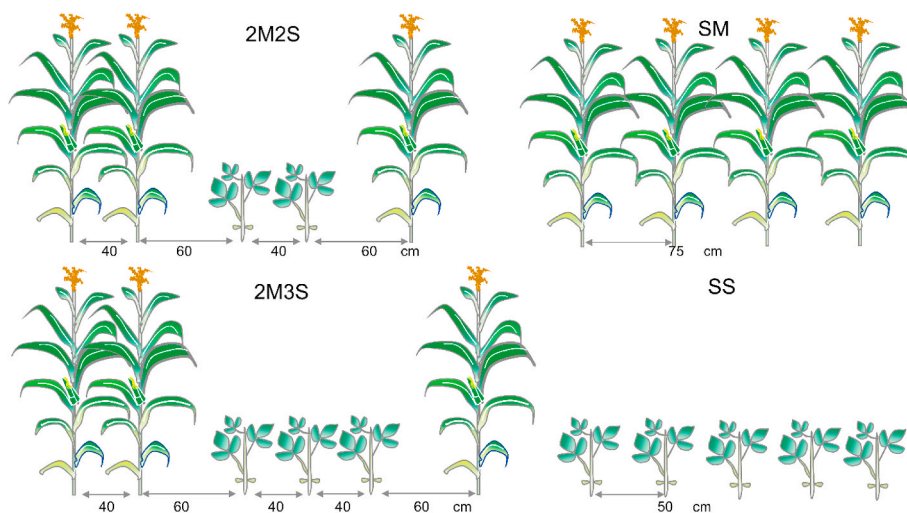


Fig. 2. Field layout of different planting patterns in strip intercropping and sole cropping systems: 2M2S (two-rows of maize intercropped with two-rows of soybean, narrower-strips), 2M3S (two-rows of maize intercropped with three rows of soybean, wider-strips), SM (sole maize), and SS (sole soybean).

systems. This, in turn, substantially increases the water and radiation use efficiencies compared to sole crops (Rahman et al., 2017; Raza et al., 2019a), resulting in land equivalent ratios greater than one (Du et al., 2017; Liu et al., 2018). Thus, the crop yields of the whole system out-performs the sole systems (Iqbal et al., 2018). However, these systems have not obtained much attention in countries such as Pakistan and India. Given the need for enhanced crop production on limited land with scarce water resources, and the call for sustainable agriculture intensification, strip intercropping systems deserve the renewed interest of agriculturists and policymakers (Lithourgidis et al., 2011). Currently, there is no study available in the literature on land productivity and water use efficiency of the maize-soybean strip-intercropping system under irrigation. Therefore, we studied maize-soybean strip-intercropping systems to assess their viability under irrigation. The main objectives of this three-year study were (i) to quantify the growth parameters and grain yields of maize and soybean, and (ii) to quantify the water use and land productivity of maize-soybean strip-intercropping systems compared to sole cropped maize and soybean systems. We hypothesized that a maize-soybean strip intercropping system could enhance water and land use efficiencies and would be a reliable agronomic and economic measure in areas of limited water resources.

2. Materials and methods

2.1. Research site

A three-year field study was conducted during the spring seasons of 2018, 2019, and 2020 at Khairpur Tamewali (29.57° N, 72.25° E; altitude 130 m), a demonstration site of Sichuan Agricultural University, in the Punjab Province of Pakistan. The experimental site has a continental

monsoon climate, with a mean annual air temperature of 25.7 °C and annual precipitation of 143 mm. The soil was a sandy clay loam, with 7.8 pH, 3.05 EC, 7.1 g kg⁻¹ organic matter, 0.6 g kg⁻¹ total nitrogen (N), 4.9 mg kg⁻¹ available phosphorus (P), 347.3 mg kg⁻¹ available potassium (K), and 1.49 Mg m⁻³ bulk density. Daily air temperature, rainfall, and incident solar radiation during the experimental years are presented in Fig. 1.

2.2. Experimental design

The field study was a randomized complete block design with three replications. There were four different planting patterns (Fig. 2), i. e., sole maize (SM), sole soybean (SS), two-rows of maize intercropped with two-rows of soybean (2M2S), and two-rows of maize intercropped with three rows of soybean (2M3S). The planting configuration is presented in Table 1. Sole crops were sown according to the local planting densities: 80,000 plants ha⁻¹ for maize and 140,000 plants ha⁻¹ for soybean. The same planting density was used in 2M2S and 2M3S, rendering the relative density of intercropped maize and soybean equal to one. The plot size was 12 m long by 12 m wide. All agronomic practices, i. e., sowing, harvesting, and weeding, were done manually.

Shade-tolerant soybean ‘Nandou-12’ and ‘DK-6317’ semi-compact maize were planted on February 9th in 2018, February 12th in 2019, and February 7th in 2020. Maize was harvested on June 21st in 2018, June 23rd in 2019, and June 22nd in 2020, while soybean was harvested on June 27th in 2018, June 30th in 2019, and June 29th in 2020. Before sowing, N as urea, P as diammonium phosphate, and K as potassium sulfate were applied at the rate of 125, 205, and 150 kg ha⁻¹ for maize and 75, 150, and 100 kg ha⁻¹ for soybean, respectively. At the V₆ and tasseling stages of maize (Abendroth et al., 2011), second and third

Table 1

The row to row and plant to plant distances for maize and soybean under different planting patterns.

Planting patterns	Row distance			Rows		Plant distance		Overall plant density		
	(cm)			(plot ⁻¹)		(cm)		(plants m ⁻²)		
	Maize	Soybean	Distance ^b	Maize	Soybean	Maize	Soybean	Maize	Soybean	Total
2M2S ^a	40	40	60	12	12	12.5	7.2	08	14	22
2M3S	40	40	60	10	12	10.4	9.8	08	14	22
SM	75	–	–	16	–	16.7	–	08	–	08
SS	–	50	–	–	24	–	14.3	–	14	14

^a The 2M2S (two-rows of maize intercropped with two-rows of soybean) and 2M3S (two-rows of maize intercropped with three rows of soybean) refer to two different maize-soybean strip intercropping systems. The SM and SS represent the sole cropping system of maize and soybean, respectively.

^b Distance between maize and soybean rows in intercropping systems.

Table 2

Irrigation distribution (mm) during the summer season of 2018, 2019, and 2020 at the demonstration site of Sichuan Agricultural University, Punjab, Pakistan.

Years	Total irrigation water (mm) ^a					Rainfall (mm)					Total water (mm)				
	Feb	Mar	April	May	June	Feb	Mar	April	May	June	Feb	Mar	April	May	June
2018	57	87	126	165	28	03	03	04	05	62	60	90	130	170	90
2019	28	61	97	117	77	17	09	18	33	28	45	70	115	150	105
2020	49	0	82	151	74	01	216	18	14	31	50	216	100	165	105

^a In all planting patterns (SM, SS, 2M2S, and 2M3S), we used the same amount of irrigation water by irrigating the whole experimental area homogeneously without differentiating the planting patterns.

applications of N were applied at 60 and 100 kg ha⁻¹ for maize rows. All planting patterns were irrigated with the same amount of water across the whole experiment, and the detailed information is shown in Table 2. Irrigation was applied according to the local water application advisory for maize and soybean production, which is equal to 550 ± 100 mm water for both crops depending on the crop or weather conditions. Groundwater was pumped out using a tube-well and applied via the furrow irrigation method.

2.3. Sampling and measurements

The leaf area index (LAI) of maize and soybean was measured at 30, 50, 70, 90, and 110 days after sowing (DAS). Five maize and ten soybean plants were collected from the plot to estimate the leaf area of maize and soybean plants, first by measuring the maximum leaf width and length. Afterward, the maximum area was multiplied by a crop coefficient factor of 0.70 for maize and 0.75 for soybean (Gao et al., 2010). Finally, the LAI was computed using Eq. (1):

$$\text{Leaf area index (LAI)} = \frac{(\text{Leaf area per plant} \times \text{Plant number per plot})}{\text{Plot area}} \quad (1)$$

At 30, 50, 70, 90, and 110 DAS, five maize and ten soybean plants from each planting pattern were collected for total dry matter accumulation (TDM) and partitioning analysis. Maize and soybean roots were sampled using the section sampling method (Cai et al., 2014; Raza et al., 2019b). After sampling, all plant samples of maize or soybean were divided into root, straw (leaves + stem + non-grain parts), and grain. Then, all plant samples were sun-dried for at least ten days to achieve a constant weight.

Maize and soybean were manually harvested at maturity; data were collected from a 36 m² (6 m × 6 m) area for SM, SS, 2M2S, and a 43.2 m² (7.2 m × 6 m) area for 2M3S from each plot. The harvested plant samples were then sun-dried for the ten days, manually threshed, and weighed to determine the grain yield. The total yield of 2M2S and 2M3S was calculated by the summation of the maize and soybean grain yields in 2M2S and 2M3S.

To measure the water use efficiency (WUE) of maize and soybean in different treatments, we first measured the total water use (actual crop evapotranspiration, mm) of both crops, and then used the previously published water balance approach Eq. (2) (James, 1988):

$$\text{Water use (WU)} = R + IW + SWb - SWe - SR - DD \pm CW \quad (2)$$

Where R is the total rainfall received during the cropping season (mm), IW is the total amount of irrigation water applied (mm), SR is the surface run-off (mm), DD is the deep drainage water (mm), CW is capillary water rise to the root zone (mm), SWb is the soil water content at the beginning of the experiment (mm), and SWe is the soil water content at the end of the experiment (mm). In the water balance equation (Eq. (2)), SR was negligible because the experimental field is relatively flat. DD was assumed insignificant because there were rarely heavy rains in the experimental region (Allen et al., 1998). CW was also considered zero because the research site's water table was 65 m below the ground. Thus, the estimated water use during the season was calculated following a simplified water balance equation Eq. (3):

$$\text{Water use (WU)} = R + IW + SWb - SWe \quad (3)$$

Finally, the WUE of both crops in SS, SM, 2M2S, and 2M3S was calculated according to Eq. (4) (Zhang et al., 1998):

$$\text{Water use efficiency (WUE)} = \frac{GY}{WU} \quad (4)$$

Where GY is the grain yield of maize or soybean, and WU is the water use (evapotranspiration) calculated with Eq. (3).

The land equivalent ratio (LER) was calculated using the Eq. (5) (Mead and Willey, 1980).

$$\text{Land equivalent ratio (LER)} = pLER_m + pLER_s = \frac{GY_{im}}{GY_{sm}} + \frac{GY_{is}}{GY_{ss}} \quad (5)$$

Where pLER_m and pLER_s are the partial land equivalent ratio of maize and soybean, respectively, GY_{im} and GY_{sm} are maize grain yields in intercropping and sole cropping systems, respectively, and GY_{is} and GY_{ss} are soybean grain yields under intercropping and sole cropping systems, respectively.

The relative WUE of maize and soybean in 2M2S and 2M3S compared to SM and SS, respectively, is defined by the water equivalent ratio (WER) (Bai et al., 2016). WER was estimated using the Eq. (6).

$$\text{Water equivalent ratio (WER)} = pWER_m + pWER_s = \frac{WUE_{im}}{WUE_{sm}} + \frac{WUE_{is}}{WUE_{ss}} \quad (6)$$

Where WUE_{im} and WUE_{is} are the water use efficiencies of maize and soybean in 2M2S and 2M3S, respectively. WUE_{sm} and WUE_{ss} are the water use efficiencies of maize and soybean in SM and SS, respectively.

2.4. Economic analysis

Economic analysis was done using partial budgeting to assess the economic viability of a strip intercropping system for maize and soybean in irrigated areas. Cost of land lease, seedbed preparation, maize and soybean seeds, fertilizer, thinning and weeding, irrigation water, harvesting, and threshing of maize and soybean crops were estimated based on local rates. Total income was calculated by multiplying the measured yields with the yearly local market prices of maize and soybean. Net income was determined by subtracting all expenses from the gross income (Raza et al., 2020b).

2.5. Statistical analysis

Data were analyzed using computer software Statistix 8.1. Significant differences were determined using ANOVA in combination with the LSD (least significance difference) test. The significance of differences was evaluated at $P < 0.05$ levels. Tables and figures report the means and standard errors of calculated means, based on the three replicates per treatment.

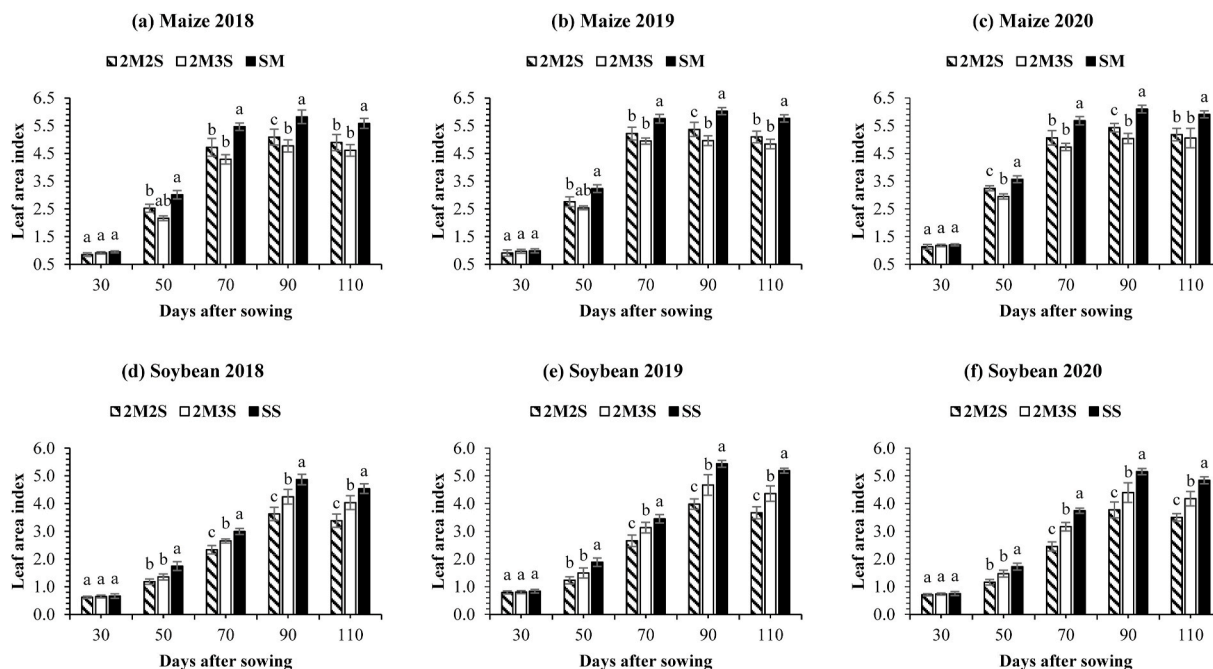


Fig. 3. Leaf area index of maize and soybean at 30, 50, 70, 90, and 110 days after sowing under different planting patterns. Bars show \pm standard errors, ($n = 2$). Within a bar, same and different lowercase letters show a non-significant and significant difference ($p < 0.05$) among different planting patterns, respectively.

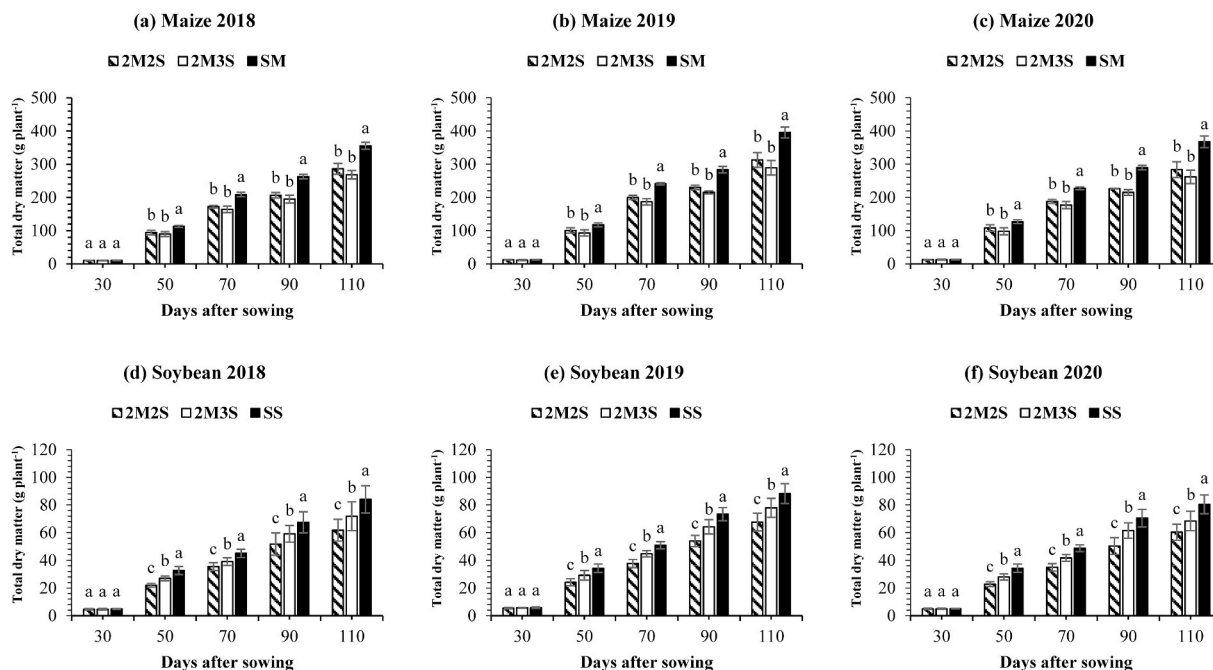


Fig. 4. Total dry matter accumulation in maize and soybean at 30, 50, 70, 90, and 110 days after sowing under different planting patterns. Bars show \pm standard errors, ($n = 2$). Within a bar, same and different lowercase letters show a non-significant and significant difference ($p < 0.05$) among different planting patterns, respectively.

3. Results

3.1. Leaf area index

The planting pattern was significant at the $P < 0.05$ level on the LAI of both maize and soybean at all sampling times except for 30 DAS across the three years of this experiment (Fig. 3). At all sampling times, the LAI of SM and SS planting patterns were greater than those of the 2M2S and 2M3S intercropped systems. At 110 DAS in intercropping

planting patterns, the mean maximum LAI of maize (5.1) and soybean (4.2) were observed in 2M2S and 2M3S, respectively; by contrast, the mean minimum LAI of maize (4.8) and soybean (3.5) were measured under 2M3S and 2M2S, respectively.

3.2. Total dry matter accumulation and partitioning

The TDM of maize and soybean plants rapidly increased from 50 to 110 DAS, achieving the highest values at 110 DAS (Fig. 4). Across years,

Table 3
Dry matter distribution in the root, straw, and seed of maize at 30, 50, 70, 90, and 110 days after sowing (DAS) as affected by different planting patterns during the summer season of 2018, 2019, and 2020.

Year	Planting patterns	Maize dry matter distribution (g plant ⁻¹)														
		30 DAS			50 DAS			70 DAS			90 DAS			110 DAS		
		Root	Straw	Grain	Root	Straw	Grain	Root	Straw	Grain	Root	Straw	Grain	Root	Straw	Grain
2018	2M2S	1.2 ± 0.1 ^{NS}	8.9 ± 0.4 ^{NS}	8.5 ± 1.0 ^b	85.7 ± 5.9 ^b	17.8 ± 1.3 ^b	154.4 ± 5.1 ^b	21.0 ± 2.2 ^b	172.9 ± 8.2 ^b	12.6 ± 2.0 ^b	24.2 ± 1.5 ^b	184.6 ± 12.7 ^b	77.3 ± 5.2 ^b	22.1 ± 1.8 ^b	172.3 ± 10.3 ^b	74.1 ± 4.6 ^b
	2M3S	1.2 ± 0.1	8.8 ± 0.4	8.1 ± 1.0 ^b	81.6 ± 6.3 ^b	15.2 ± 0.8 ^b	148.9 ± 9.2 ^b	19.3 ± 1.3 ^b	164.3 ± 9.4 ^b	11.2 ± 1.9 ^c	22.1 ± 1.8 ^b	172.3 ± 10.3 ^b	74.1 ± 4.6 ^b	22.1 ± 1.8 ^b	172.3 ± 10.3 ^b	74.1 ± 4.6 ^b
	SM	1.2 ± 0.1	9.2 ± 0.8	11.2 ± 1.1 ^a	101.7 ± 2.9 ^a	23.3 ± 1.2 ^a	185.5 ± 7.5 ^a	27.5 ± 1.9 ^a	217.1 ± 7.2 ^a	18.1 ± 1.6 ^a	28.7 ± 1.9 ^a	229.9 ± 8.0 ^a	96.8 ± 3.5 ^a	28.7 ± 1.9 ^a	229.9 ± 8.0 ^a	96.8 ± 3.5 ^a
	LSD	0.09	0.99	1.42	12.28	3.23	21.91	6.21	36.14	1.07	4.10	39.41	15.01	4.10	39.41	15.01
2019	2M2S	1.4 ± 0.1 ^{NS}	10.8 ± 1.2 ^{NS}	10.0 ± 1.4 ^b	90.5 ± 7.5 ^b	18.7 ± 2.2 ^b	181.2 ± 7.4 ^b	22.9 ± 2.3 ^c	189.5 ± 6.0 ^b	17.8 ± 1.3 ^b	25.0 ± 2.2 ^b	206.2 ± 16.1 ^b	81.6 ± 8.1 ^b	25.0 ± 2.2 ^b	206.2 ± 16.1 ^b	81.6 ± 8.1 ^b
	2M3S	1.4 ± 0.1	10.0 ± 1.4	8.7 ± 1.2 ^{ab}	84.5 ± 8.4 ^b	16.5 ± 1.8 ^b	170.4 ± 7.7 ^b	20.0 ± 1.3 ^b	180.1 ± 3.5 ^b	15.2 ± 3.0 ^{ab}	22.9 ± 2.4 ^b	190.0 ± 14.8 ^b	76.3 ± 8.7 ^b	22.9 ± 2.4 ^b	190.0 ± 14.8 ^b	76.3 ± 8.7 ^b
	SM	1.4 ± 0.2	11.1 ± 0.9	11.9 ± 1.7 ^a	105.8 ± 4.1 ^a	24.4 ± 3.2 ^a	217.0 ± 5.5 ^a	29.2 ± 1.6 ^a	231.2 ± 8.1 ^a	23.3 ± 1.2 ^a	30.5 ± 2.2 ^a	260.1 ± 10.7 ^a	105.0 ± 4.2 ^a	30.5 ± 2.2 ^a	260.1 ± 10.7 ^a	105.0 ± 4.2 ^a
	LSD	0.38	2.49	2.07	14.61	3.69	27.77	2.79	23.18	5.72	5.17	48.56	22.48	5.17	48.56	22.48
2020	2M2S	1.4 ± 0.1 ^{NS}	11.0 ± 1.0 ^{NS}	10.5 ± 1.6 ^b	97.9 ± 8.3 ^b	15.7 ± 2.3 ^b	172.2 ± 7.9 ^b	19.8 ± 2.5 ^b	191.0 ± 3.7 ^b	15.5 ± 2.5 ^b	21.7 ± 1.3 ^b	194.6 ± 15.4 ^b	67.6 ± 9.9 ^b	21.7 ± 1.3 ^b	194.6 ± 15.4 ^b	67.6 ± 9.9 ^b
	2M3S	1.4 ± 0.1	11.2 ± 1.5	9.1 ± 1.5 ^c	89.0 ± 9.2 ^b	13.8 ± 1.7 ^b	163.3 ± 9.9 ^b	17.3 ± 1.1 ^b	184.5 ± 7.0 ^b	13.3 ± 2.2 ^c	20.7 ± 1.7 ^b	179.8 ± 13.3 ^b	61.4 ± 7.7 ^b	20.7 ± 1.7 ^b	179.8 ± 13.3 ^b	61.4 ± 7.7 ^b
	SM	1.5 ± 0.1	11.5 ± 0.9	12.2 ± 1.6 ^a	114.7 ± 4.3 ^a	19.8 ± 2.8 ^a	207.6 ± 6.7 ^a	26.9 ± 1.7 ^a	241.4 ± 7.7 ^a	21.5 ± 2.9 ^a	26.9 ± 1.4 ^a	247.2 ± 11.7 ^a	93.4 ± 8.4 ^a	26.9 ± 1.4 ^a	247.2 ± 11.7 ^a	93.4 ± 8.4 ^a
	LSD	0.29	2.20	0.59	15.49	3.66	26.54	4.72	28.37	2.12	3.24	50.72	18.23	3.24	50.72	18.23

Means are averages over three replicates ± standard error of the mean. Means that do not share the same letters in a column differ significantly at $p \leq 0.05$ using least significant differences (LSD), calculated separately for each year; NS= Non-significant.

Table 4

Dry matter distribution in the root, straw, and seed of soybean at 30, 50, 70, 90, and 110 days after sowing (DAS) as affected by different planting patterns during the summer season of 2018, 2019, and 2020.

Year	Planting patterns	Soybean dry matter distribution (g plant ⁻¹)														
		30 DAS			50 DAS			70 DAS			90 DAS			110 DAS		
		Root	Straw	Grain	Root	Straw	Grain	Root	Straw	Grain	Root	Straw	Grain	Root	Straw	Grain
2018	2M2S	0.5 ± 0.0 ^{NS}	4.1 ± 0.5 ^{NS}	0.9 ± 0.1 ^c	21.1 ± 1.3 ^c	1.8 ± 0.2 ^b	33.7 ± 2.6 ^c	4.0 ± 0.3 ^c	42.5 ± 7.0 ^b	5.3 ± 0.8 ^c	6.6 ± 1.3 ^c	46.1 ± 6.2 ^c	9.1 ± 0.4 ^c	6.6 ± 1.3 ^c	46.1 ± 6.2 ^c	9.1 ± 0.4 ^c
	2M3S	0.5 ± 0.0	4.2 ± 0.5	1.0 ± 0.1 ^b	25.9 ± 1.7 ^b	2.2 ± 0.1 ^{ab}	37.0 ± 2.7 ^b	4.4 ± 0.4 ^b	47.7 ± 4.6 ^{ab}	7.0 ± 1.0 ^b	8.5 ± 1.7 ^b	53.6 ± 8.6 ^b	9.8 ± 0.2 ^b	8.5 ± 1.7 ^b	53.6 ± 8.6 ^b	9.8 ± 0.2 ^b
	SS	0.6 ± 0.1	4.3 ± 0.2	1.2 ± 0.1 ^a	31.5 ± 2.8 ^a	2.5 ± 0.2 ^a	42.6 ± 2.8 ^a	5.0 ± 0.5 ^a	53.6 ± 5.8 ^a	8.8 ± 1.4 ^a	10.0 ± 2.0 ^a	61.8 ± 7.5 ^a	12.3 ± 0.4 ^a	10.0 ± 2.0 ^a	61.8 ± 7.5 ^a	12.3 ± 0.4 ^a
	LSD	0.11	0.82	0.06	3.76	0.48	0.77	0.38	6.39	1.31	1.28	6.53	0.35	1.28	6.53	0.35
2019	2M2S	0.7 ± 0.0 ^{NS}	4.8 ± 0.6 ^{NS}	1.0 ± 0.1 ^b	23.1 ± 2.4 ^c	2.1 ± 0.2 ^c	35.5 ± 2.8 ^c	4.0 ± 0.4 ^c	44.2 ± 3.6 ^c	5.8 ± 0.3 ^c	7.1 ± 1.1 ^c	50.5 ± 3.9 ^c	10.1 ± 1.5 ^c	7.1 ± 1.1 ^c	50.5 ± 3.9 ^c	10.1 ± 1.5 ^c
	2M3S	0.7 ± 0.0	5.0 ± 0.3	1.2 ± 0.1 ^{ab}	27.9 ± 3.4 ^b	2.5 ± 0.3 ^b	42.3 ± 2.0 ^b	4.7 ± 0.5 ^b	51.9 ± 4.1 ^b	7.6 ± 0.7 ^b	8.9 ± 1.3 ^b	57.0 ± 4.0 ^b	12.0 ± 1.9 ^b	8.9 ± 1.3 ^b	57.0 ± 4.0 ^b	12.0 ± 1.9 ^b
	SS	0.7 ± 0.0	5.1 ± 0.5	1.4 ± 0.1 ^a	32.9 ± 2.9 ^a	2.9 ± 0.2 ^a	48.0 ± 2.4 ^a	5.5 ± 0.5 ^a	58.3 ± 3.8 ^a	9.6 ± 0.5 ^a	10.6 ± 1.5 ^a	63.5 ± 4.8 ^a	14.1 ± 1.0 ^a	10.6 ± 1.5 ^a	63.5 ± 4.8 ^a	14.1 ± 1.0 ^a
	LSD	0.08	2.06	0.26	2.22	0.19	1.91	0.47	2.95	0.87	1.09	2.10	1.80	1.09	2.10	1.80
2020	2M2S	0.7 ± 0.1 ^{NS}	4.2 ± 0.5 ^{NS}	1.1 ± 0.1 ^b	21.7 ± 1.8 ^c	2.4 ± 0.5 ^c	32.6 ± 2.4 ^c	4.9 ± 0.7 ^c	40.5 ± 4.8 ^c	4.9 ± 0.5 ^c	6.3 ± 0.3 ^c	45.8 ± 4.9 ^c	8.2 ± 0.7 ^c	6.3 ± 0.3 ^c	45.8 ± 4.9 ^c	8.2 ± 0.7 ^c
	2M3S	0.7 ± 0.1	4.3 ± 0.4	1.3 ± 0.2 ^{ab}	26.5 ± 2.2 ^b	2.8 ± 0.4 ^b	38.9 ± 2.4 ^b	5.7 ± 0.8 ^b	49.3 ± 4.0 ^b	6.6 ± 0.9 ^b	7.9 ± 0.4 ^b	51.1 ± 5.8 ^b	9.4 ± 0.8 ^b	7.9 ± 0.4 ^b	51.1 ± 5.8 ^b	9.4 ± 0.8 ^b
	SS	0.8 ± 0.1	4.3 ± 0.2	1.6 ± 0.2 ^a	32.7 ± 3.0 ^a	3.1 ± 0.5 ^a	45.6 ± 2.2 ^a	6.5 ± 1.0 ^a	55.4 ± 4.4 ^a	8.7 ± 1.0 ^a	9.9 ± 0.8 ^a	59.2 ± 5.4 ^a	11.3 ± 0.7 ^a	9.9 ± 0.8 ^a	59.2 ± 5.4 ^a	11.3 ± 0.7 ^a
	LSD	0.26	1.22	0.32	2.67	0.19	1.23	0.61	2.91	0.94	1.46	2.41	0.50	1.46	2.41	0.50

Means are averages over three replicates ± standard error of the mean. Means that do not share the same letters in a column differ significantly at $p < 0.05$ using least significant differences (LSD), calculated separately for each year; NS= Non-significant.

at 110 DAS, the highest (372.9 g plant⁻¹) average TDM of maize in SM was 27% and 36% higher than those under 2M2S and 2M3S, respectively; in soybean, the highest (84.2 g plant⁻¹) TDM in SS was 33% and 16% higher than that for 2M2S and 2M3S, respectively. Similar, to total dry matter accumulation, different planting patterns significantly ($P < 0.05$) affected the partitioning of dry matter to various plant parts in maize (Table 3) and soybean (Table 4) at 50, 70, 90, and 110 DAS, but not at 30 DAS. As expected, the different components of each crop at and after 50 DAS were highest when maize and soybean grew alone as sole crops (SM and SS, respectively). For example, at 110 DAS, the average highest partitioning of dry matter in roots, straw, and grains was noticed under SM and SS, respectively. The average lowest dry matter partitioning in roots, straw, and grains of maize and soybean plants was recorded in 2M3S and 2M2S, respectively. In intercropped planting pattern 2M2S, the dry matter of maize grains increased by 8% compared to 2M3S (Table 3), while planting pattern 2M3S enhanced the dry matter of soybean grains by 15% compared to 2M2S (Table 4).

3.3. Grain yields

Maize and soybean yields differed significantly ($P < 0.05$) in all planting patterns, while the non-significant ($P < 0.05$) differences were found between 2M2S and 2M3S for maize yield + soybean yield (Table 5). The highest maize and soybean yields were always obtained in the sole cropped maize and soybean systems. However, averaged across the years, maize and soybean yields were 8390 kg ha⁻¹ (80% of sole maize yield) and 1171 kg ha⁻¹ (52% of sole soybean yield) in 2M2S, while they were 7975 kg ha⁻¹ (76% of sole maize yield) and 1417 kg ha⁻¹ (63% of sole soybean yield), respectively, in 2M3S. On average, the maize yield in 2M2S was 5% higher than the corresponding maize yield in 2M3S, whereas, the soybean yield in 2M3S was 21% higher than the soybean yield in 2M2S.

3.4. Land equivalent ratio

The total LER (pLERm + pLERs) values of the intercropping systems ranged from 1.31 to 1.45, demonstrating a substantial increase in land-use efficiency (Table 5). The total LER generally was higher in 2M3S than 2M2S, and the difference was significant ($P < 0.05$) in 2020 (Table 5). The partial land equivalent ratio (pLER) values of intercropped species in intercropping systems ranged from 0.51 to 0.84 across years and intercropped species (Table 5). In intercropping planting patterns, maize had the maximum average partial land equivalent ratio (pLERm; 0.81 in 2M2S and 0.76 in 2M3S), while soybean had the minimum average partial land equivalent ratio (pLERs; 0.53 in 2M2S

and 0.64 in 2M3S). Despite the low pLER values for soybean, both intercropping systems achieved high values of total LER because 2M2S and 2M3S slightly decreased the maize yields compared to SM. Nevertheless, in intercropping systems, the pLER of soybean was higher in 2M3S than in 2M2S.

3.5. Water use efficiency and water equivalent ratio

Averaged over the years, WUE of intercropped maize (14.6 kg ha⁻¹ mm⁻¹ in 2M2S and 14.1 kg ha⁻¹ mm⁻¹ in 2M3S) and soybean (2.0 kg ha⁻¹ mm⁻¹ in 2M2S and 2.5 kg ha⁻¹ mm⁻¹ in 2M3S) was significantly ($P < 0.05$) lower than that of the sole maize (18.0 kg ha⁻¹ mm⁻¹) or sole soybean (3.8 kg ha⁻¹ mm⁻¹) (Table 6). However, in intercropping systems, planting pattern 2M2S increased the WUE of maize by 4% compared to 2M3S, and planting pattern 2M3S enhanced the WUE of soybean by 18% compared to 2M2S.

The intercropping impact on WUE was measured using the water equivalent ratio (WER). The WER characterizes whether intercropped maize and soybean yield in 2M2S and 2M3S would be produced with less water (WER < 1) or more water (WER > 1) in SM and SS. The average total WER (pWERm + pWERs) values of both intercropping systems (1.35 for 2M2S and 1.44 for 2M3S) were higher than one, indicating the water use advantage over the sole cropping systems (Table 6). Additionally, for total WER, the differences in 2018 and 2019 were non-significant ($P < 0.05$), while in 2020 it was significant ($P < 0.05$) (Table 6). However, the planting pattern 2M3S increased the WER by 7% in 2018, 6% in 2019, and 7% in 2020 compared to 2M2S. Moreover, in all years of the experiment, the pWERm (0.82 in 2M2S and 0.79 in 2M3S) was considerably higher than the pWERs (0.54 in 2M2S and 0.66 in 2M3S) (Table 6).

3.6. Economic analysis

Crop yield had a direct impact on the net profit of the different planting patterns (Table 7). The maximum net profit (1056 US \$ ha⁻¹ in 2018, 1636 US \$ ha⁻¹ in 2019, and 1323 US \$ ha⁻¹ in 2020) was obtained in planting pattern 2M3S, while the minimum net profit (559 US \$ ha⁻¹ in 2018, 868 US \$ ha⁻¹ in 2019, and 683 US \$ ha⁻¹ in 2020) was recorded in planting pattern SS (Table 7). On average, the net profit was increased by 27% and 79% in 2M2S and by 36% and 90% in 2M3S, compared to SM and SS, respectively.

4. Discussion

This study verified our hypothesis that a maize-soybean strip

Table 5

Grain yield and land equivalent ratio of maize and soybean for different planting patterns during the summer season of 2018, 2019, and 2020.

Year	Planting patterns	Grain yield (kg ha ⁻¹)		Total grain yield (kg ha ⁻¹)	Partial LER		Total LER
		Maize	Soybean		Maize	Soybean	
2018	2M2S	7817.3 ± 461.1b	1028.5 ± 63.1b	8845.8 ± 478.2 ^{NS}	0.79 ± 0.1 ^{NS}	0.51 ± 0.1 ^{NS}	1.31 ± 0.1 ^{NS}
	2M3S	7349.6 ± 372.7b	1259.8 ± 88.9b	8609.4 ± 455.6	0.74 ± 0.0	0.63 ± 0.1	1.37 ± 0.1
	SM	9898.1 ± 527.2a	–	–	–	–	–
	SS	–	2024.3 ± 94.1a	–	–	–	–
	LSD	1346.7	374.88	–	0.05	0.19	0.17
2019	2M2S	8941.4 ± 471.3b	1282.1 ± 100.3b	10223.5 ± 571.3 ^{NS}	0.84 ± 0.0 ^{NS}	0.55 ± 0.1b	1.39 ± 0.1 ^{NS}
	2M3S	8495.3 ± 562.1c	1515.6 ± 100.1b	10010.9 ± 659.9	0.80 ± 0.0	0.65 ± 0.1a	1.45 ± 0.1
	SM	10603.9 ± 601.4a	–	–	–	–	–
	SS	–	2352.7 ± 104.9a	–	–	–	–
	LSD	297.2	413.54	–	0.05	0.07	0.07
2020	2M2S	8410.3 ± 343.4b	1200.9 ± 40.3c	9611.3 ± 322.6 ^{NS}	0.78 ± 0.1a	0.52 ± 0.0b	1.30 ± 0.1b
	2M3S	8078.6 ± 357.3b	1474.7 ± 68.0b	9553.3 ± 312.7	0.75 ± 0.1b	0.64 ± 0.0a	1.39 ± 0.1a
	SM	10915.2 ± 623.4a	–	–	–	–	–
	SS	–	2314.1 ± 121.4a	–	–	–	–
	LSD	2137.2	185.40	–	0.01	0.04	0.03

Means are averages over three replicates ± standard error of the mean. Means that do not share the same letters in a column differ significantly at $p < 0.05$ using least significant differences (LSD), calculated separately for each year; NS= Non-significant.

Table 6

Water use efficiency (WUE) and water equivalent ratio (WER) of maize and soybean for different planting patterns during the summer season of 2018, 2019, and 2020.

Year	Planting patterns	WUE (kg ha ⁻¹ mm ⁻¹)		Partial WER		Total WER
		Maize	Soybean	Maize	Soybean	
2018	2M2S	13.7 ± 0.8b	1.8 ± 0.1b	0.80 ± 0.1b	0.52 ± 0.1 ^{NS}	1.33 ± 0.1 ^{NS}
	2M3S	13.2 ± 0.7b	2.3 ± 0.2b	0.77 ± 0.0a	0.66 ± 0.1	1.43 ± 0.1
	SM	17.1 ± 0.9a	–	–	–	–
	SS	–	3.5 ± 0.2a	–	–	–
	LSD	2.18	0.65	0.03	0.19	0.18
2019	2M2S	17.3 ± 0.9b	2.5 ± 0.2b	0.85 ± 0.0 ^{NS}	0.56 ± 0.1b	1.41 ± 0.1 ^{NS}
	2M3S	16.7 ± 1.2b	3.0 ± 0.2b	0.82 ± 0.0	0.67 ± 0.1a	1.49 ± 0.1
	SM	20.4 ± 1.1a	–	–	–	–
	SS	–	4.5 ± 0.2a	–	–	–
	LSD	0.74	0.82	0.05	0.10	0.12
2020	2M2S	12.8 ± 0.5b	1.8 ± 0.1c	0.79 ± 0.1 ^{NS}	0.53 ± 0.0b	1.32 ± 0.1b
	2M3S	12.4 ± 0.6b	2.3 ± 0.1b	0.76 ± 0.1	0.65 ± 0.0a	1.42 ± 0.1a
	SM	16.4 ± 0.9a	–	–	–	–
	SS	–	3.5 ± 0.2a	–	–	–
	LSD	3.16	0.27	0.01	0.03	0.04

Means are averages over three replicates ± standard error of the mean. Means that do not share the same letters in a column differ significantly at $p < 0.05$ using least significant differences (LSD), calculated separately for each year; NS= Non-significant.

intercropping system could enhance water and land use efficiencies; it would be a reliable agronomic and economic measure in the areas of limited resources. It achieved land equivalent ratios greater than one in all experimental years, indicating that the yield per hectare of the intercropping systems 2M2S and 2M3S was equivalent to the sole yield of crops on 1.33 and 1.40 ha, respectively. Compared to sole cropping systems, intercropping systems used less water to produce more grains, showed a complementarity effect in utilizing the available water. Overall, these results suggest that intercropping systems are more profitable in obtaining a higher net income with fewer inputs.

The data demonstrate that a maize-soybean strip-intercropping system is suitable to produce maize and soybean in irrigated areas. The considerably high LER values of intercropping systems indicate the efficient use of available land (Gitari et al., 2020; Liu et al., 2018), water (Rahman et al., 2017), and nutrient resources (Raza et al., 2020b). The observed higher production under intercropping systems than pure stand could further be attributed to increased radiation use efficiency as it was followed by a high LAI (Raza et al., 2019a). Although the individual LAI values of maize and soybean were lower under intercropping, the overall index was relatively higher than pure stands. This could have resulted in increased light interception, which consequently increased the TDM and partitioning to grain production in maize and soybean plants. This is consistent with previous findings (Feng et al., 2019), in which they observed increased crop yield under intercropping and associated it with an increased light interception (Liu et al., 2018).

Our findings agree with the common observation in intercropping systems (Li et al., 2020) that maize was the dominant crop species with a higher pLERm than pLERs in intercropping systems, indicating the competitive advantage of maize over soybean in using the available resources in intercropping systems (Raza et al., 2020a). This study shows that changing row ratio and the associated modification in strip width have a significant effect on the relative yields of maize and soybean in intercropping systems. The relative yield of soybean increased from 0.53 (grown in 2M2S, where both crops used the same land, i. e.,

100 cm of the cropped area was used by maize and 100 cm of the cropped area was used by soybean) to 0.64 (planted in 2M3S, where soybean covered 140 cm of the cropped area). Whereas, the relative yield of maize slightly decreased (by 5%) in 2M3S (wider-strips) than 2M2S (narrower-strips). The slight yield loss of intercropped maize in the plots with wider-strips of soybean was compensated by a substantial yield gain of intercropped soybean (21%), which resulted in an increased total yield. This was an implication of the facilitative effect, i. e., wider-strips reduced maize shading on soybean rows, which considerably increased the soybean yield while maintaining the maize yield (Raza et al., 2020a). Nevertheless, the total yield (9,560 kg ha⁻¹ in 2M2S and 9,391 kg ha⁻¹ in 2M3S) at the system level was non-significantly changed by strip width due to an apparent reduced maize shading effect on soybean in 2M3S. Improved LAI and TDM of soybean ultimately enhanced the competitive ability of soybean by maintaining the competitive ability of maize in 2M3S than 2M2S. Wider-strips in intercropping systems tends to have fewer shading effects from tall crop species such as maize on inner short crop species such as soybean because the inner rows of soybean were farthest from the tall border rows of maize in 2M3S than 2M2S (Wang et al., 2020). Furthermore, in wider-strips, the intra-specific competition for available resources was eased due to the increased plant-to-plant spacing between soybean plants, resulting in a spatial niche differentiation and relative yield advantage of soybean. Thus, changing row ratio and strip width are the main factors that affect the micro-environment, above and below ground interspecific interactions, and crop yields in intercropping systems.

The WER data suggested that intercropping systems substantially enhanced WUE. Considering that the intercropping systems had the 100% planting density of maize and 100% planting density of soybean, the intercropped maize and soybean produced more grains per mm of water because the water was halved for maize and soybean each. The maize plants produced more grains per mm of water than intercropped soybean plants because maize had a competitive advantage over

Table 7

Economic analysis for the effects of different planting patterns on maize and soybean production in 2018, 2019, and 2020.

Planting patterns	Total expenditure (US \$ ha ⁻¹)			Gross income (US \$ ha ⁻¹)			Net income (US \$ ha ⁻¹)		
	2018	2019	2020	2018	2019	2020	2018	2019	2020
2M2S	1542	1220	1131	2524	2787	2351	982	1566	1220
2M3S	1542	1220	1131	2597	2857	2454	1056	1636	1323
SM	1415	1120	1038	2197	2236	2100	782	1116	1062
SS	993	786	728	1552	1654	1411	559	868	683

The 2M2S (two-rows of maize intercropped with two-rows of soybean) and 2M3S (two-rows of maize intercropped with three rows of soybean) refer to two different maize-soybean strip intercropping systems. The SM and SS represent the sole cropping system of maize and soybean, respectively.

soybean with respect to water uptake and use. Remarkably, despite this asymmetry in available water use between intercropped species, intercropping systems are still advantageous in water and land use, as indicated by water equivalent and land equivalent ratio values, and net profit. Taken together, for water use in the intercropping systems, we conclude that (a) the WUE of intercropped species depends on the strip width and row ratio arrangement in intercropping systems (Mao et al., 2012); (b) wider-strips increased the WUE of soybean and maintained the WUE of maize; (c) intercropping systems used the same amount of irrigation water as sole maize and sole soybean, but produced greater economic returns. In contrast to our results, some previous studies reported that the strip intercropping systems decreased the WUE (Gao et al., 2009; Szumigalski and Van Acker, 2008), due to increased competition between intercrops, which reduced the final crop yields and WUE. A factor that could have played an important role in improving the WER of 2M2S and 2M3S is reduced evaporation from the soil surface due to greater canopy closure in intercropping systems (Cooper et al., 1987; Wallace, 2000). The higher planting densities of the 2M2S and 2M3S planting patterns appeared to overcome evaporation loss from the soil surface (Mao et al., 2012). Another reason may have been a complementarity in water acquisition from the upper and lower depths of the soil (Bai et al., 2016) by soybean and maize, respectively; however, further investigation is required to fully understand complementarity in water uptake from different soil depths.

Earlier studies revealed that intercropping with narrower-strips produced the greater yields, and that wider-strips reduced the benefits of intercropping (Raza et al., 2020b; van Oort et al., 2020). However, in the present study, the wider-strips (2M3S) had greater crop yields and net profit than narrower-strips (2M2S). Greater economic returns obtained under intercropping indicated that maize and soybean could be grown together with a minimal overall yield penalty. The improvement in net profit largely ascribed to a higher yield of soybean with a maintained maize yield, which finally increased the net profit of 2M3S over 2M2S because soybean is valued at five times the value of maize in the local market. Crop yield stability is the primary consideration when judging any planting pattern option (Piepho, 1998). Agreeing with the results of other studies (Du et al., 2017; Li et al., 2020), the overall results of this study exhibit yield stability, resource use advantages, and net profit of the intercropping system over the sole cropping system under the irrigated conditions. Therefore, intercropping systems are the better planting method, especially in irrigated conditions, to obtain high yields with limited resources. However, further research is required to understand the resource capture mechanism of intercrop species in intercropping systems under the contrasting climates. For example, in high-temperature regions, the intercropping system may perform differently because of increased water demands in the production of cereals and legumes, in addition to the impact of different growing environments.

5. Conclusion

The higher water equivalent and land equivalent ratios in this study suggest that an intercropping system may save 35%–40% of water and farmland, achieving similar yields in comparison to sole maize and sole soybean. Notably, the net incomes from 2M2S (1256 US \$ ha⁻¹) and 2M3S (1338 US \$ ha⁻¹) were considerably higher than the net incomes from sole maize (987 US \$ ha⁻¹) and sole soybean (703 US \$ ha⁻¹). Therefore, the intercropping system would be a promising cropping system for sustaining crop productivity and improving water and land-use efficiency. In addition, a combination of narrow maize strips with wide soybean strips, e. g., two maize rows with three soybean rows, would be a reasonable planting arrangement because it allows machine operations by smaller-scale equipment specially designed for maize-soybean strip-intercropping systems in China. However, further research is required to understand the resource capture mechanism of intercrop species in intercropping systems under the changing climate

(high-temperature regions where farmers are using extra water to produce cereals and legumes). Particularly, a series of comprehensive studies to develop best management practices regarding fertilization, irrigation, and pest control would support the sustainability of intercropping systems and grower adoption. The successful adoption of the intercropping system will play a vital role in meeting the food requirements of the increasing population, especially in developing countries that are facing challenges in resource limitation.

CRediT authorship contribution statement

Muhammad Ali Raza: Investigation, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization, Writing – review & editing. **Hina Gul:** Investigation, Methodology, Writing – original draft. **Jun Wang:** Formal analysis, Writing – review & editing. **Hassan Shehryar Yasin:** Investigation, Methodology. **Ruijun Qin:** Formal analysis, performed the statistical . **Muhammad Hayder Bin Khalid:** Investigation, Methodology. **Muhammd Naeem:** Investigation, Methodology. **Ling Yang Feng:** Visualization, Writing – review & editing. **Nasir Iqbal:** Writing – review & editing. **Harun Gitari:** Data curation, Writing – review & editing. **Shakeel Ahmad:** Investigation, Methodology. **Martin Battaglia:** Writing – review & editing. **Muhammad Ansar:** Investigation, Methodology, conducted the field experiment and collected all data in all the study years. **Feng Yang:** Conceptualization, Resources, Funding acquisition, Supervision, Writing – review & editing. **Wenyu Yang:** Conceptualization, Resources, Funding acquisition, Supervision, conceived the study, secured the .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Abendroth, L., Elmore, R., Boyer, M., Marlay, S.J.C.E.S., Ames, 2011. Corn Growth and Development. PMR 1009. Iowa State Univ.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao. Rome* 300 (9), D05109.
- Bai, W., Sun, Z., Zheng, J., Du, G., Feng, L., Cai, Q., Yang, N., Feng, C., Zhang, Z., Evers, J. B., 2016. Mixing trees and crops increases land and water use efficiencies in a semi-arid area. *Agric. Water Manag.* 178, 281–290.
- Barona, E., Ramankutty, N., Hyman, G., Coomes, O.T., 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environ. Res. Lett.* 5 (2), 024002.
- Battaglia, M., Groover, G.E., Thomason, W.E., 2017. Value and Implications of Corn Stover Removal from Virginia Fields.
- Battaglia, M., Thomason, W., Fike, J.H., Evanylo, G.K., von Cossel, M., Babur, E., Iqbal, Y., Diatta, A.A.J.G.B., 2020. The Broad Impacts of Corn Stover and Wheat Straw Removal for Biofuel Production on Crop Productivity, Soil Health and Greenhouse Gas Emissions: A Review.
- Cai, H., Ma, W., Zhang, X., Ping, J., Yan, X., Liu, J., Yuan, J., Wang, L., Ren, J., 2014. Effect of subsoil tillage depth on nutrient accumulation, root distribution, and grain yield in spring maize. *The Crop Journal* 2 (5), 297–307.
- Chai, Q., Gan, Y., Turner, N.C., Zhang, R.-Z., Yang, C., Niu, Y., Siddique, K.H., 2014. Water-saving innovations in Chinese agriculture. *Advances in Agronomy*. Elsevier 149–201.
- Chen, G., Kong, X., Gan, Y., Zhang, R., Feng, F., Yu, A., Zhao, C., Wan, S., Chai, Q., 2018. Enhancing the systems productivity and water use efficiency through coordinated soil water sharing and compensation in strip-intercropping. *Sci. Rep.* 8 (1), 1–11.

- Cooper, P., Gregory, P., Keatinge, J., Brown, S., 1987. Effects of fertilizer, variety and location on barley production under rainfed conditions in Northern Syria 2. Soil water dynamics and crop water use. *Field Crop. Res.* 16 (1), 67–84.
- Du, J.-b., Han, T.-f., Gai, J.-y., Yong, T.-w., Sun, X., Wang, X.-c., Yang, F., Liu, J., Shu, K., Liu, W.-g., 2017. Maize-soybean strip intercropping: achieved a balance between high productivity and sustainability. *Journal of Integrative Agriculture* 16, 60345–60347.
- Fan, Z., Chai, Q., Huang, G., Yu, A., Huang, P., Yang, C., Tao, Z., Liu, H., 2013. Yield and water consumption characteristics of wheat/maize intercropping with reduced tillage in an Oasis region. *Eur. J. Agron.* 45, 52–58.
- FAO, 2013. *FAO Statistical Yearbook: World Food and Agriculture*. FAO.
- FAO, 2018. *FAO statistical yearbook: world food and agriculture*. <http://www.fao.org/faostat/en/#data/QC>.
- Feng, L.Y., Raza, M.A., Chen, Y., Khalid, M.H.B., Meraj, T.A., Ahsan, F., Fan, Y., Du, J., Wu, X., Song, C., 2019. Narrow-wide row planting pattern improves the light environment and seed yields of intercrop species in relay intercropping system. *PLoS One* 14 (2), e0212885.
- Feng, L.Y., Raza, M.A., Shi, J., Ansar, M., Titriku, J.K., Meraj, T.A., Shah, G.A., Ahmed, Z., Saleem, A., Liu, W., 2020. Delayed maize leaf senescence increases the land equivalent ratio of maize soybean relay intercropping system. *Eur. J. Agron.* 118, 126092.
- Gao, Y., Duan, A., Qiu, X., Sun, J., Zhang, J., Liu, H., Wang, H., 2010. Distribution and use efficiency of photosynthetically active radiation in strip intercropping of maize and soybean. *Agron. J.* 102 (4), 1149–1157.
- Gao, Y., Duan, A., Sun, J., Li, F., Liu, Z., Liu, H., Liu, Z., 2009. Crop coefficient and water-use efficiency of winter wheat/spring maize strip intercropping. *Field Crop. Res.* 111 (1–2), 65–73.
- Gitari, H.I., Gachene, C.K., Karanja, N.N., Kamau, S., Nyawade, S., Sharma, K., Schulte-Geldermann, E., 2018. Optimizing yield and economic returns of rain-fed potato (*Solanum tuberosum* L.) through water conservation under potato-legume intercropping systems. *Agric. Water Manag.* 208, 59–66.
- Gitari, H.I., Nyawade, S.O., Kamau, S., Karanja, N.N., Gachene, C.K., Raza, M.A., Maitra, S., Schulte-Geldermann, E., 2020. Revisiting intercropping indices with respect to potato-legume intercropping systems. *Field Crop. Res.* 258, 107957.
- Hu, F., Feng, F., Zhao, C., Chai, Q., Yu, A., Yin, W., Gan, Y., 2017. Integration of wheat-maize intercropping with conservation practices reduces CO₂ emissions and enhances water use in dry areas. *Soil Tillage Res.* 169, 44–53.
- Iqbal, N., Hussain, S., Ahmed, Z., Yang, F., Wang, X., Liu, W., Yong, T., Du, J., Shu, K., Yang, W., 2018. Comparative analysis of maize-soybean strip intercropping systems. *A review*. *Plant Production Science(just-accepted)* 22 (2), 131–142.
- James, L.G., 1988. *Principles of Farm Irrigation Systems Design*. John Wiley and Sons Limited.
- Kang, S., Shi, W., Zhang, J., 2000. An improved water-use efficiency for maize grown under regulated deficit irrigation. *Field Crop. Res.* 67 (3), 207–214.
- Kendy, E., Wang, J., Molden, D.J., Zheng, C., Liu, C., Steenhuis, T.S., 2007. Can urbanization solve inter-sector water conflicts? Insight from a case study in Hebei Province, North China Plain. *Water Pol.* 9 (S1), 75–93.
- Khan, S., Hasan, M.U., 2017. Evapotranspiration distribution and variation of Pakistan (1931–2015). *Annals of Valahia University of Targoviste, Geographical Series* 17 (2), 184–197.
- Khattak, M.S., Ali, S., 2015. Assessment of temperature and rainfall trends in Punjab province of Pakistan for the period 1961–2014. *J. Himal. Earth Sci.* 48 (2).
- Li, C., Hoffland, E., Kuyper, T.W., Yu, Y., Zhang, C., Li, H., Zhang, F., van der Werf, W., 2020. Syndromes of production in intercropping impact yield gains. *Nature Plants* 1–8.
- Lithourgidis, A., Vlachostergios, D., Dordas, C., Damalas, C., 2011. Dry matter yield, nitrogen content, and competition in pea-cereal intercropping systems. *Eur. J. Agron.* 34 (4), 287–294.
- Liu, X., Rahman, T., Song, C., Yang, F., Su, B., Cui, L., Bu, W., Yang, W., 2018. Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping. *Field Crop. Res.* 224, 91–101.
- Mao, L., Zhang, L., Li, W., van der Werf, W., Sun, J., Spiertz, H., Li, L., 2012. Yield advantage and water saving in maize/pea intercrop. *Field Crop. Res.* 138, 11–20.
- Mead, R., Willey, R., 1980. The concept of a 'land equivalent ratio' and advantages in yields from intercropping. *Exp. Agric.* 16 (3), 217–228.
- Payero, J.O., Melvin, S.R., Irmak, S., Tarkalson, D., 2006. Yield response of corn to deficit irrigation in a semiarid climate. *Agric. Water Manag.* 84 (1–2), 101–112.
- Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., 2010. The impacts of climate change on water resources and agriculture in China. *Nature* 467 (7311), 43–51.
- Pielke Sr, R.A., 2013. *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*. Elsevier.
- Piepho, H.P., 1998. Methods for comparing the yield stability of cropping systems. *J. Agron. Crop Sci.* 180 (4), 193–213.
- Poumanyong, P., Kaneko, S., Dhakal, S., 2012. Impacts of urbanization on national transport and road energy use: evidence from low, middle and high income countries. *Energy Pol.* 46, 268–277.
- Rahman, T., Liu, X., Hussain, S., Ahmed, S., Chen, G., Yang, F., Chen, L., Du, J., Liu, W., Yang, W., 2017. Water use efficiency and evapotranspiration in maize-soybean relay strip intercrop systems as affected by planting geometries. *PLoS One* 12 (6), e0178332.
- Raza, M.A., Cui, L., Qin, R., Yang, F., Yang, W.J.S.R., 2020a. Strip-width determines competitive strengths and grain yields of intercrop species in relay intercropping system, 10 (1), 1–12.
- Raza, M.A., Feng, L.Y., van der Werf, W., Cai, G.R., Khalid, M.H.B., Iqbal, N., Hassan, M.J., Meraj, T.A., Naeem, M., Khan, I., 2019a. Narrow-wide-row planting pattern increases the radiation use efficiency and seed yield of intercrop species in relay-intercropping system. *Food and Energy Security*, e170.
- Raza, M.A., Feng, L.Y., Wopke, v.d.W., Iqbal, N., Khan, I., Hassan, M.J., Ansar, M., Chen, Y.K., Xi, Z.J., Shi, J.Y., 2019b. Optimum leaf defoliation: a new agronomic approach for increasing nutrient uptake and land equivalent ratio of maize soybean relay intercropping system. *Field Crop. Res.* 244, 107647.
- Raza, M.A., Feng, L.Y., Wopke, v.d.W., Iqbal, N., Khan, I., Khan, A., Din, A.M.U., Naeem, M., Meraj, T.A., Hassan, M.J., 2020b. Optimum strip width increases dry matter, nutrient accumulation, and seed yield of intercrops under the relay intercropping system. *Food and Energy Security* 9 (2), 1–14.
- Raza, M.A., Khalid, M.H.B., Zhang, X., Feng, L.Y., Khan, I., Hassan, M.J., Ahmed, M., Ansar, M., Chen, Y.K., Fan, Y.F., 2019c. Effect of planting patterns on yield, nutrient accumulation and distribution in maize and soybean under relay intercropping systems. *Sci. Rep.* 9 (1), 4947.
- Ren, J., Zhang, L., Duan, Y., Zhang, J., Evers, J.B., Zhang, Y., Su, Z., van der Werf, W., 2019. Intercropping potato (*Solanum tuberosum* L.) with hairy vetch (*Vicia villosa*) increases water use efficiency in dry conditions. *Field Crop. Res.* 240, 168–176.
- Sharma, N., Singh, R.J., Mandal, D., Kumar, A., Alam, N., Keesstra, S., 2017. Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India. *Agric. Ecosyst. Environ.* 247, 43–53.
- Szumigalski, A.R., Van Acker, R.C., 2008. Land equivalent ratios, light interception, and water use in annual intercrops in the presence or absence of in-crop herbicides. *Agron. J.* 100 (4), 1145–1154.
- Terzić, D., Popović, V., Tatić, M., Vasileva, V., Dekić, V., Ugrenović, V., Popović, S., Avdić, P., 2018. In: *Soybean Area, Yield and Production in World, XXII Eco-Conference® 2018, Ecological Movement of Novi Sad*, pp. 136–145.
- van Oort, P., Gou, F., Stomph, T., van der Werf, W., 2020. Effects of strip width on yields in relay-strip intercropping: a simulation study. *Eur. J. Agron.* 112, 125936.
- Vandermeer, J.H., 1992. *The Ecology of Intercropping*. Cambridge University Press.
- Verschelde, M., D'Haese, M., Rayp, G., Vandamme, E., 2013. Challenging small-scale farming: a non-parametric analysis of the (inverse) relationship between farm productivity and farm size in Burundi. *J. Agric. Econ.* 64 (2), 319–342.
- Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. *Agric. Ecosyst. Environ.* 82 (1–3), 105–119.
- Wang, R., Sun, Z., Zhang, L., Yang, N., Feng, L., Bai, W., Zhang, D., Wang, Q., Evers, J.B., Liu, Y., 2020. Border-row proportion determines strength of interspecific interactions and crop yields in maize/peanut strip intercropping. *Field Crop. Res.* 253, 107819.
- Yang, C., Huang, G., Chai, Q., Luo, Z., 2011. Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of northwest China. *Field Crop. Res.* 124 (3), 426–432.
- Yin, W., Yu, A., Chai, Q., Hu, F., Feng, F., Gan, Y., 2015. Wheat and maize relay-planting with straw covering increases water use efficiency up to 46%. *Agron. Sustain. Dev.* 35 (2), 815–825.
- Yuan, M., Zhang, L., Gou, F., Su, Z., Spiertz, J., Van Der Werf, W., 2013. Assessment of crop growth and water productivity for five C3 species in semi-arid Inner Mongolia. *Agric. Water Manag.* 122, 28–38.
- Zhang, H., Oweis, T.Y., Garabet, S., Pala, M., 1998. Water-use efficiency and transpiration efficiency of wheat under rain-fed conditions and supplemental irrigation in a Mediterranean-type environment. *Plant Soil* 201 (2), 295–305.
- Zhang, J., 2007. Barriers to water markets in the Heihe River basin in northwest China. *Agric. Water Manag.* 87 (1), 32–40.