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Performance of maize, soybean, and mung bean intercropping systems in East Java, Indonesia

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ABSTRACT

Context: Maize (*Zea mays* L.)-soybean (*Glycine max* L. (Merr.)) intercropping can enhance land and resource use efficiency, but its performance depends on species interactions, environmental conditions, and management. There is little information on intercrop performance under different configurations without major resource deficits in a tropical climate.
Objectives: We determined the land use efficency of simultaneously sown, flood irrigated maize-soybean intercropping systems comprising maize, soybean and mung bean in the tropical climate of East Java with moderate fertilizer input, and evaluated how narrow-wide row systems and incorporation of mung bean changed the land use efficiency and productivity.
Methods: Experiments were done during four growing seasons. Two replacement systems used two maize and four soybean rows in alternating strips at local standard spacing or at reduced maize inter-row distances to improve soybean radiation interception (narrow-wide row system). Two additive systems introduced mung bean (*Vigna radiata* L.) or additional soybean rows.
Results: Additive intercrops had higher land use efficiency (average LER ≈ 1.10) than sole crops or replacement systems (LER = 0.93). The narrow-wide row system improved soybean performance and overall LER without significantly affecting maize yield. Soybean outperformed mung bean in additive systems, while mung bean struggled near maize rows.
Synthesis and implications: Simultaneously sown maize-soybean replacement intercropping systems with recommended fertilizer inputs and sufficient water did not have a land use advantage in East Java. Additive systems provided marginal benefits. These findings align with emerging evidence that yield benefits of intercropping are small under simultaneous sowing and adequate resource inputs.

1. Introduction

Maize-soybean intercropping is recognized as a system with yield advantages and complementary resource utilization (Raza et al., 2022; Xia et al., 2022; Xu et al., 2020; Zhang et al., 2022). Xu reported an average LER of 1.32 ± 0.02 across 90 studies conducted under various growing conditions from 1980 till 2018. However, some studies have reported no or only small yield advantages, particularly when the species were sown simultaneously (Li et al., 2020a, 2021; Zhang et al., 2022). Additionally, high nitrogen input has been found to reduce the yield advantage attained in maize-legume intercropping systems (Mudare et al., 2022). Hence, there is uncertainty about the performance of maize-soybean intercropping when sowing is simultaneous and crops are managed to avoid shortages of nutrients.

Simultaneous intercropping (i.e. with the same or similar sowing time for both crop species and a similar time of maturity) has a lower

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yield advantage than relay intercropping (i.e. with substantial, planned, differences in sowing and harvesting times between the species to create temporal complementarity; Yu et al., 2015). However, relay intercropping is not always practically feasible. For instance, in some areas of Southeast Asia, such as the lowlands of Java, Indonesia, farmers grow three crops per year in a year-round system, including one or two paddy rice crops (Supplementary Fig. S1). Engaging in relay intercropping would mean that one of the three seasons would have to be foregone. Hence, under such conditions, simultaneous intercropping is the most suitable intercropping option.

Shading effects of maize on soybean are a key challenge in maize-soybean intercropping (Su et al., 2014; Yao et al., 2017). To address this shading problem, a narrow-wide row system was developed in Sichuan, China (Yang et al., 2014, 2016; Raza et al., 2019). This system involves narrowing the distance between the maize rows to create wider spacing between maize and soybean, thereby reducing shading on the soybean plants. While this approach increases soybean yields, it may reduce maize production due to increased intra-specific competition among maize plants (Raza et al., 2019). In East Java, Indonesia, the latitude is much lower than in Sichuan, China (7.80°S at our site versus 30°N in Sichuan). Due to the higher solar elevation, the shading effect in maize-soybean intercropping is likely to be smaller in East Java than in Sichuan. Accordingly, there might be less of a need to use narrow-wide planting systems under the high light conditions of East Java. However, this has not been investigated.

Plant density is a key factor driving crop yields, and positive relationships have been found between plant density and yield in intercrops (Helenius and Jokinen, 1994; Osiru and Willey, 1972; Willey and Osiru, 1972). Yu et al. (2015) found that additive intercrops (defined in their study as intercrops with a relative density total greater than one; see also van der Werf et al., 2021) had a greater LER than replacement intercrops with a relative density total equal to one. In growers' practice, additive intercropping often entails adding a second species to an existing crop stand without lowering the density of the existing crop, but potentially modifying its planting pattern. In a narrow-wide row system, applied to mitigate shading effects on the soybean canopy, there is some empty space between maize and soybean. Therefore, there is room to add extra rows of a species (Fig. 1). This may increase productivity (Yu et al., 2015). Mung bean is a food crop that is commonly cultivated, consumed, and sold by farmers in East Java. It is typically grown during the same season as soybean and maize but it matures earlier than soybean and it may therefore suffer less than soybean from shading during the later growth stages of maize if it is intercropped with maize.

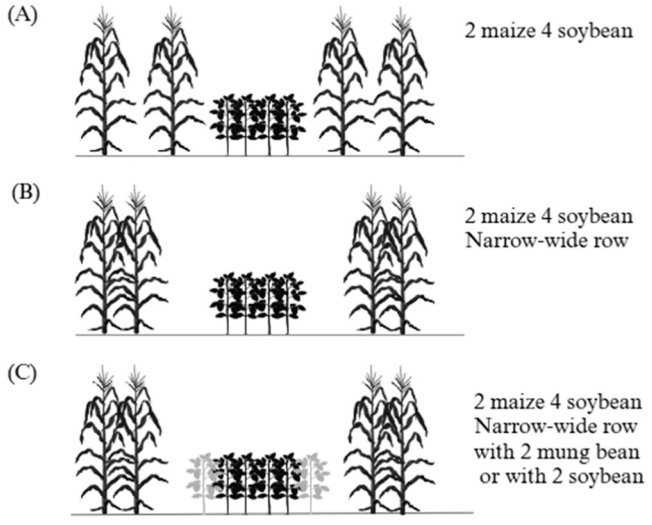


Fig. 1. Maize-bean intercropping systems tested in this study (A) replacement 2:4 maize-soybean intercropping configuration. (B) 2:4 narrow-wide row replacement intercropping configuration. (C) 2:4:2 narrow-wide row additive maize-soybean-mung bean intercropping configuration or 2:6 narrow-wide row additive maize-soybean intercropping configuration. The additive rows are indicated in a lighter grey.

Given this background, we investigated the following research questions:

1. Does simultaneous maize-soybean intercropping, with government-recommended fertilizer levels under irrigated conditions, improve land-use efficiency in East Java, Indonesia?
2. Does a narrow-wide row system in simultaneous maize-soybean intercropping improve soybean productivity and the land equivalent ratio of the intercropping system as a whole?
3. Does adding extra rows in a narrow-wide row system improve land-use efficiency?
4. Is mung bean a more efficient intercrop in additive systems than soybean ?

2. Materials and methods

2.1. Experimental site

We conducted four field experiments at the Ministry of Agriculture's experimental station (Instalasi Penelitian dan Pengkajian Teknologi Pertanian/IP2TP) in Muneng district, Probolinggo Regency, East Java province, Indonesia (7.80°S, 113.16°E; Supplementary Fig. S2). The experiments were conducted in two growing seasons each in 2022 and 2023 on sandy clay soil (detailed in Supplementary Table S1).

The region has a tropical monsoon climate (climate type Am in the Köppen-Geiger climate classification; Kottek et al., 2006, Haizea analytics., n.d.). Farmers in this area typically divide the year into three cropping seasons, each lasting approximately four months (Supplementary Fig. S1). The rainy season (November-April) and dry season (May-October) vary slightly each year. For total seasonal rainfall, see Supplementary Table S2.

In each of the years, the first experiment (sown February/March and harvested May/June) started in the rainy season and ended in the dry season. The second experiment (sown June/July and harvested October/November) started during the dry season and ended in the rainy season. No experiments were done between November and February, during the core of the rainy season when rice is the most suitable crop in the study area (cf. Supplementary Fig. S1).

Local farmers typically irrigate maize frequently, while soybean and mung bean are usually only irrigated at the start of and half-way their growing season. At the experimental site, flood irrigation was used: water was pumped into the field until the plots were fully flooded, after which the evacuation gate was opened to allow the water to drain away. The exact water quantity retained in the soil was not measured. Temperature trends in both seasons were similar, but rainfall was lower in 2023, which was compensated for by irrigating more frequently (Fig. 2).

2.2. Experimental setup

Field experiments were conducted with maize (cultivar Bisi 18), soybean (cultivars Grobogan and OSOYA 1 Agritan, hereafter OSOYA) and mung bean (cultivar Vima 2) in different intercropping configurations. In the second year of the trials we included treatments with the newly released soybean cultivar OSOYA, a derivative of Grobogan,to assess the performance of this new cultivar in intercropping and compare its performance in intercropping to that of Grobogan. In 2022, plot sizes were 7.5 × 11 m for sole maize, 5.1 × 11 m for sole soybean and mung bean, and 9.6 × 11 m for all intercropping configurations. In 2023, plot sizes were 6 × 7 m for sole maize, 4.5 × 7 m for sole soybean and mung bean, and 8.1 × 7 m for all intercrops.

In 2022, three intercropping treatments were tested (Fig. 3):

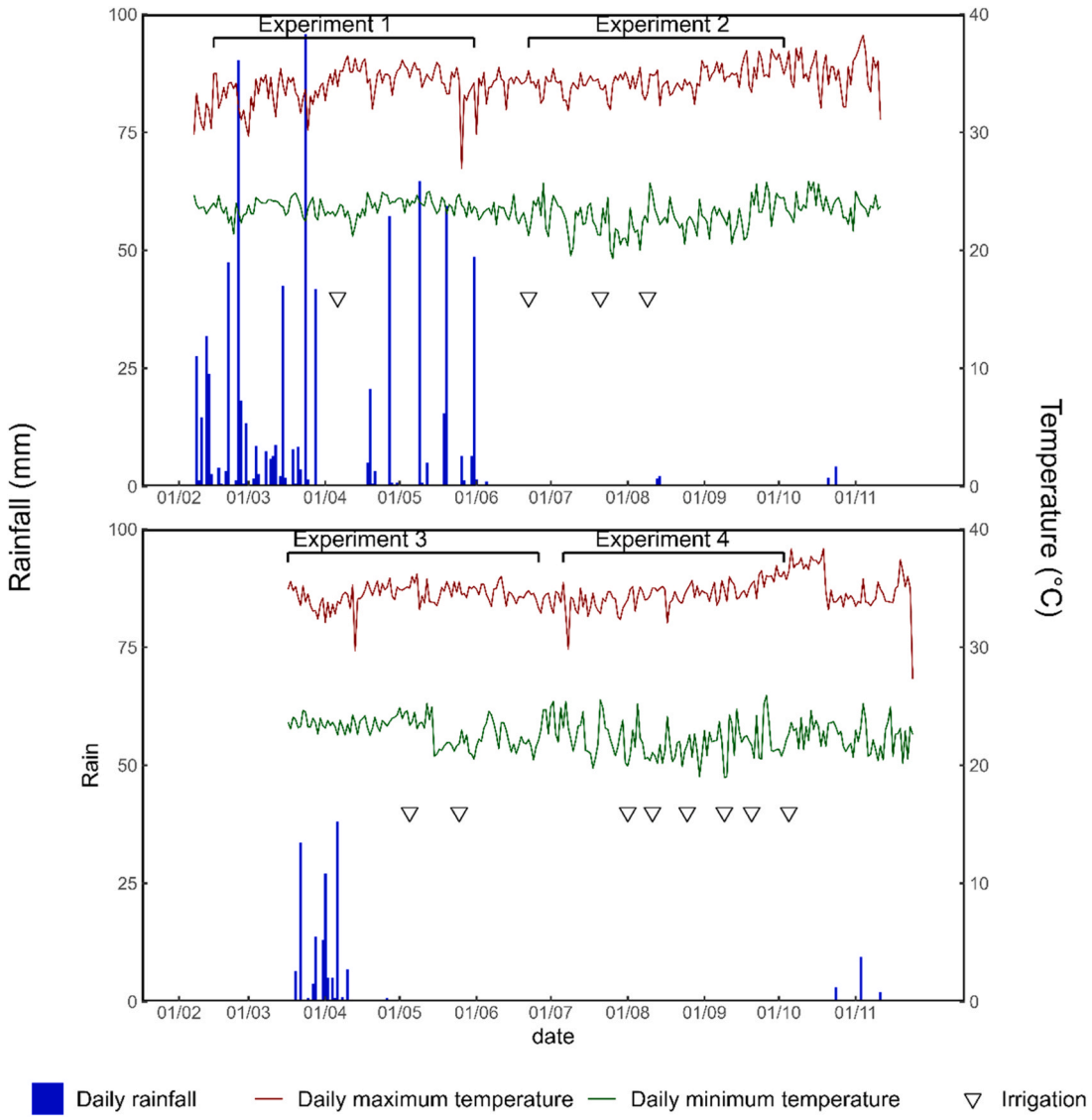


Fig. 2. Daily minimum temperature, maximum temperature, rainfall, and timing of irrigation during the experimental seasons 1 and 2, from February to November 2022 (A) and 3 and 4, from March to November 2023 (B). Weather data were collected using a weather station (HOBO U30 USB Weather Station, Onset, USA) at the experimental site. No measurements were made during the rainy season from December 2022 to February 2023.

1) Replacement intercrop: Two rows of maize and four rows of soybean, both at standard row distances.

2) Narrow-wide row intercrop: Two rows of maize and four rows of soybean, but maize rows are planted narrower to increase light availability for soybean and reduce below-ground competition.

3) Additive intercrop: Two narrow-spaced maize rows, four soybean rows, and two rows of mung bean planted between maize and soybean, utilizing the wider space between maize and soybean.

In 2023, based on results from the first year and the introduction of the soybean cultivar OSOYA, three additional treatments were added:

4) Replacement intercrop with OSOYA.

5) Additive intercrop with two maize rows and six soybean rows (Grobogan).

6) Additive intercrop with two maize rows and six soybean rows (OSOYA).

Sole crops of maize, soybean (Grobogan and OSOYA), and mung bean were included in each experiment as a reference. In the fourth season, due to the poor establishment of Grobogan, data were collected only from OSOYA-based treatments: sole OSOYA, sole maize, and the replacement and additive intercrops. Treatments for each season are described in Supplementary Table S3. All experiments followed a randomized complete block design with four blocks. The within-row spacing was 20 cm for all crop species in all configurations including sole crops and intercrops. The inter-row spaces of sole maize, sole soybean, and sole mung bean were 75 cm, 30 cm, and 30 cm, respectively, while in the narrow-row spacing for maize, the row distance was 20 cm. Further details are in Supplementary Table S4.

2.3. Crop management

Sowing dates for maize and soybean varied across experiments: 15–16 February 2022 (Expt 1), 22–20 June (Expt 2), 17–25 March 2023 (Expt 3), and 6–14 July 2023 (Expt 4). Due to intermittent rainfall, sowing was extended over several days, with resowing performed in cases of poor seedling emergence. Crops were manually sown at two seeds per hole. Thinning, initially omitted in Expt 1, was conducted in subsequent experiments to maintain uniform plant density. The planned plant density is described in supplementary Table S4. Weeding, pesticide spraying, and irrigation were carried out throughout all experiments as necessary and customary in the area (see details in Supplementary Tables S5, S6, S7, and S8). In Expt 2, maize plants suffered feeding damage from *Spodoptera litura* and *Valanga nigricornis* from 5 weeks after sowing,

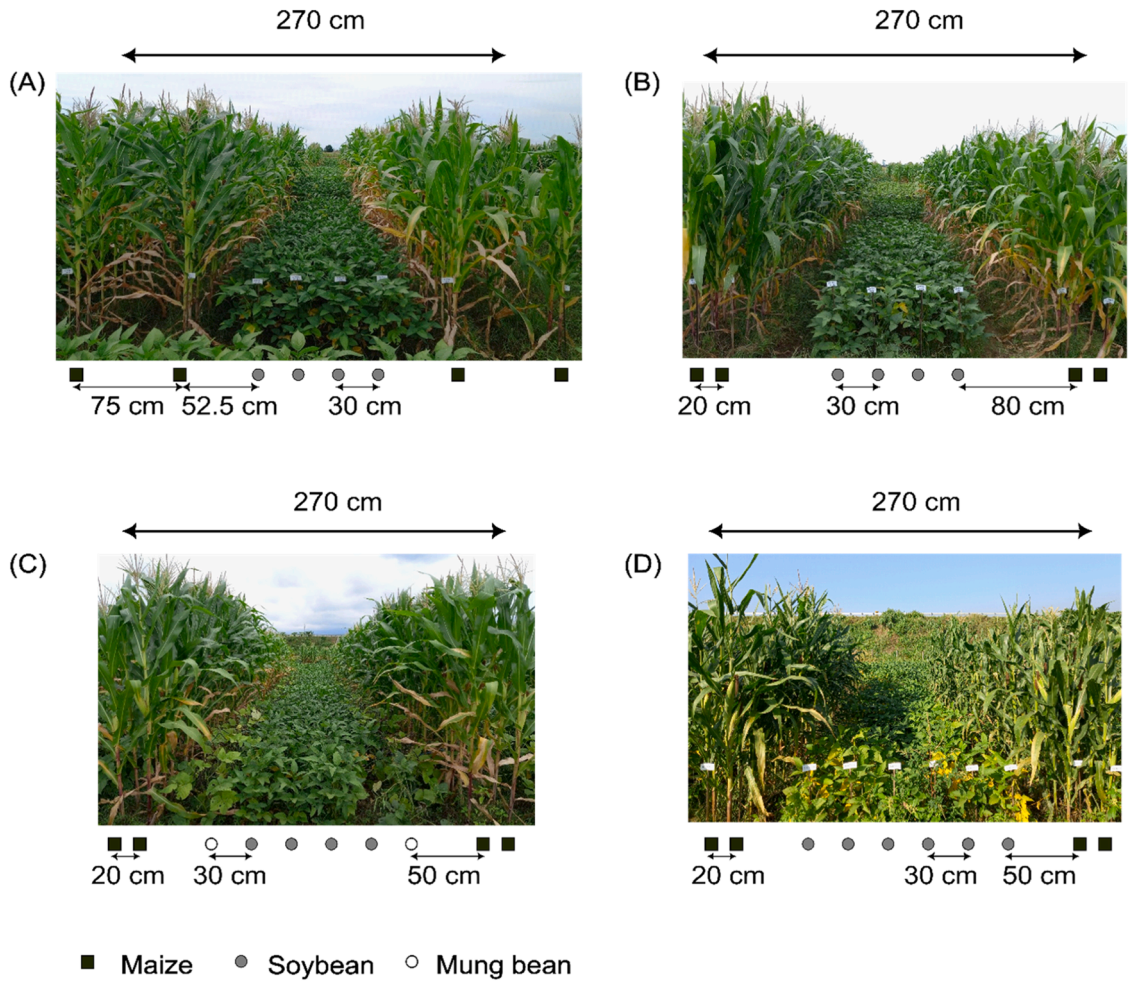


Fig. 3. Four intercrop configurations in the field. (A) Maize-soybean 2:4 replacement intercropping; (B) Maize-soybean 2:4 narrow-wide row intercropping; (C) Maize-soybean-mung bean additive intercropping, with mung bean rows inserted at the position of the maize-soybean gap in the maize-soybean 2:4 narrow-wide row intercropping; (D) Maize-soybean 2:6 additive intercropping, with soybean rows inserted at the position of the maize-soybean gap in the maize-soybean 2:4 narrow-wide row intercropping.

resulting in delayed maize flowering.

In each experiment, maize received 16.1 g m^{-2} of nitrogen (N), 5.5 g m^{-2} of phosphorus (P), and 2.6 g m^{-2} of potassium (K). Soybean received 2.3 g m^{-2} of N, 3.3 g m^{-2} of P, and 2.6 g m^{-2} of K, while mung bean received 2.3 g m^{-2} of N, 3.3 g m^{-2} of P, and 3.9 g m^{-2} of K. Fertilizer application in intercropping systems was applied per row, ensuring that rows with the same crop species received the same amount of fertilizer across all systems. Consequently, additive systems received more fertilizer overall than replacement systems due to the additional crop rows in the former. Fertilizer rates per m row are provided in Supplementary Table S9. Soybean and mung bean received fertilizer at the time of sowing, whereas maize received its nitrogen as split gifts at 10 and 20 days after sowing at rates of 14 g and 2.1 g N m^{-2} respectively. Phosphorus and potassium were applied at 10 days after sowing.

In the four experiments, the growth duration was 102 –117 days for maize, 85 –90 days for soybean, and 63 –70 days for mung bean

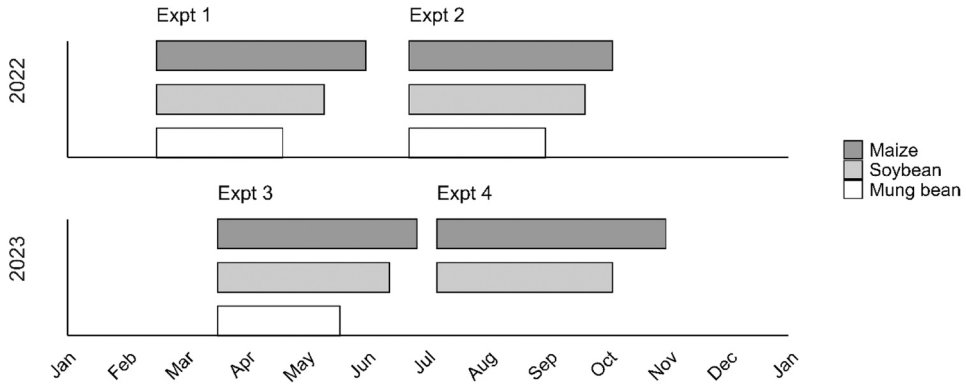


Fig. 4. Growing periods of maize, soybean, and mung bean in experiments 1–4.

(Fig. 4). All crops were sown simultaneously, so the species initially overlapped in growth, but competition was diminished when mung bean and soybean matured. We defined this simultaneous sowing system as "simultaneous intercropping" even though there is some temporal complementarity due to the difference in growth duration. Details are given in Supplementary Tables S5, S6, S7 and S8.

2.4. Measurements

Crops were cut at approximately 2 cm from the soil surface when mature. In Expts 1 and 2, the harvest area of sole maize and soybean was 13.5 m^2, and that of sole mung bean and intercrops was 19.8 m^2 (3 m row length for all intercrops: 4 rows of maize and 12 rows of soybean for the replacement system, and 4 rows of maize, 12 rows of soybean, and 6 rows of mung bean for mung bean additive system). In Expts 3 and 4, the harvest area of sole maize was 15 m^2, that of sole soybean and sole mung bean was 9.9 m^2, and that of intercrops was 27 m^2 (5 m row length for all intercrops: 4 rows of maize and 8 rows of soybean for replacement system, 4 rows of maize, 8 rows of soybean, and 4 rows of mung bean for mung bean additive system, and 4 rows of maize and 12 rows of soybean for soybean additive system).

Each soybean row was harvested separately and categorized into different row positions to determine whether there was a border row effect on yield in intercrops (Supplementary Fig. S3). Border row effects give useful information on interspecific competition (Zhang et al., 2007; Gou et al., 2016).

Harvested crop samples were weighted in full, with sub-samples collected based on row positions for further analysis. All samples were sun-dried for one week before being separated into seeds (soybean, mung bean), cobs (maize), and stover for weighing. To determine dry matter content, sub-samples were oven-dried at 70°C for 48 hours. The obtained dry matter percentage was then used to adjust sun-dried weights to standardized oven-dried weights.

2.5. Data analysis

The Land Equivalent Ratio (LER) was used to assess the land use efficiency of each intercropping treatment as (Mead and Willey, 1980):

$$LER = pLER_m + pLER_s + pLER_{mu} = Y_m/M_m + Y_s/M_s + Y_{mu}/M_{mu} \quad (1)$$

Where Y_m, Y_s, and Y_{mu} are the yields per unit area for each crop in the intercrop (kg ha^{-1}); M_m, M_s and M_{mu} are yields per unit area for each crop when grown as sole crop (kg ha^{-1}); and $pLER_m$, $pLER_s$ and $pLER_u$ are partial LER for each species. A LER of 1.0 indicates the same land productivity for intercrops and sole crops, whereas a LER greater than 1.0 indicates a land use advantage for intercrops and a LER smaller than 1.0 indicates a land use disadvantage.

The expected pLER was calculated using the scaled relative density of different crop species in intercropping (Eq. 2, Table 1), where the scaled relative density represents a theoretical proportion of area allocated per species (van der Werf et al., 2021). The scaled relative density in replacement intercropping is equal to the relative density, while the scaled relative density in additive intercropping is the relative density divided by the relative density total (Eq. 3). Relative density (RD) is dimensionless as it is the ratio of the density for a particular species in the mixture and its density in the sole crop (van der Werf et al., 2021) (Details in Supplementary Method S1).

$$Scaled\ relative\ density = \frac{Relative\ density}{Relative\ density\ total} \quad (2)$$

$$Relative\ density\ total = RD_m + RD_s + RD_{mu} \quad (3)$$

Where RD_m, RD_s, RD_{mu} are the partial relative density for maize, soybean and mungbean respectively.

Statistical analyses were performed using R (R Core Team, 2021). Grain yield per unit area (kg ha^{-1}), biomass yield per unit area (kg ha^{-1}), grain yield per m row length (g m^{-1}), biomass yield per m row length (g m^{-1}), harvest index, and LER were analyzed by fitting three models (Supplementary Table S10), and model selection was conducted using the anova function. When no significant differences were found between the mixed-effects and linear models, linear models were employed to avoid overfitting. When there was no significant interaction between different fixed effects in the linear models these interactions were removed. The results were shown as marginal means using the "emmeans" package (Lenth, 2024). Data visualization was conducted using the "ggplot2" package (Wickham, 2016). ANOVA and pairwise comparisons using Fisher's LSD test were applied to assess differences among configurations.

3. Results

3.1. Yield

Across the four experiments, average yields in sole cropping systems were 6016 ± 132 kg ha^{-1} for maize, 1638 ± 85.2 kg ha^{-1} for soybean cultivar Grobogan, 2209 ± 121 kg ha^{-1} for soybean cultivar OSOYA, and 1062 ± 40.6 kg ha^{-1} for mung bean (Table 2).

In replacement intercropping systems, maize yield was lowest in the narrow-wide row configuration (3151 ± 123 kg ha^{-1}). In ordinary replacement intercrops, maize yielded 3390 ± 123 kg ha^{-1} when combined with Grobogan and 3596 ± 160 kg ha^{-1} when combined with OSOYA. There was no significant difference in maize yield between the two soybean cultivars in the replacement configuration. In the additive intercropping system with OSOYA, maize yield further declined to 2912 ± 160 kg ha^{-1} . In the three-species intercrop with mung bean, maize yield was 3075 ± 123 kg ha^{-1}, which was similar to that in the soybean additive intercrop (3104 ± 210 kg ha^{-1} with Grobogan and 3012 ± 210 kg ha^{-1} with OSOYA).

Soybean yields also varied across intercropping configurations. For the cultivar Grobogan, the yield was 742 ± 28.3 kg ha^{-1} in the narrow-wide row configuration, which was higher than in the ordinary replacement intercrop (651 ± 28.3 kg ha^{-1}). When mung bean rows were added in the created space between maize and soybean, the average soybean yield (686 ± 28.3 kg ha^{-1}) did not differ from that in

Table 1
Relative densities, relative density total, and scaled relative density in different intercropping configurations.

Intercropping configurations	Relative density			Relative density Total	Scaled relative density		
	Maize	Soybean	Mung bean		Maize	Soybean	Mung bean
Replacement							
Replacement cv. Grobogan	0.56	0.44		1	0.56	0.44	
Replacement cv. OSOYA	0.56	0.44		1	0.56	0.44	
Narrow-Wide Row cv. Grobogan	0.56	0.44		1	0.56	0.44	
Additive							
Mung bean Additive cv. Grobogan	0.56	0.44	0.22	1.22	0.46	0.36	0.18
Soybean Additive cv. Grobogan	0.56	0.67		1.23	0.46	0.54	
Soybean Additive cv. OSOYA	0.56	0.67		1.23	0.46	0.54	

Table 2
Marginal means (± standard error) of grain yield (kg ha^{-1}), biomass yield (kg ha^{-1}), and harvest index (HI) of maize, soybean, and mung bean.

Configurations	Maize			Soybean			Mung bean		
	Grain	Biomass	HI	Grain	Biomass	HI	Grain	Biomass	HI
Sole stands									
Maize	6016 ± 132	14174 ± 338	0.43 ± 0.01						
Soybean$_G$				1638 ± 85.2	4257 ± 218	0.39 ± 0.01			
Soybean$_O$				2209 ± 121	5980 ± 308	0.40 ± 0.01			
Mung bean							1062 ± 40.6	3873 ± 210	0.29 ± 0.01
Replacement									
Replacement$_G$	3390 ± 123^{bc}	8453 ± 257^{c}	0.40 ± 0.01^{a}	651 ± 28.3^{a}	1577 ± 74.7^{a}	0.42 ± 0.01^{a}			
Replacement$_O$	3596 ± 160^{c}	8218 ± 333^{bc}	0.43 ± 0.02^{ab}	725 ± 36.6^{ab}	1790 ± 96.8^{a}	0.40 ± 0.01^{a}			
Narrow-Wide Row$_G$	3151 ± 123^{ab}	7158 ± 257^{a}	0.44 ± 0.01^{b}	742 ± 28.3^{b}	1769 ± 74.7^{a}	0.42 ± 0.01^{a}			
Additive									
Mung bean Additive$_G$	3075 ± 123^{ab}	6970 ± 257^{a}	0.44 ± 0.01^{b}	686 ± 28.3^{ab}	1718 ± 74.7^{a}	0.41 ± 0.01^{a}	159 ± 6.64	683 ± 37.5	0.25 ± 0.01
Soybean Additive$_G$	3104 ± 210^{abc}	7382 ± 438^{ab}	0.42 ± 0.02^{ab}	1021 ± 48.2^{c}	2584 ± 127^{b}	0.42 ± 0.01^{a}			
Soybean Additive$_O$	2912 ± 160^{a}	6621 ± 333^{a}	0.44 ± 0.01^{b}	1191 ± 36.6^{d}	3166 ± 96.8^{c}	0.42 ± 0.01^{a}			

Subscript G is for cultivar Grobogan, subscript O is for cultivar OSOYA
No shared letters in the same column denotes statistically significant differences (p = 0.05) among different intercrop configurations based on Fisher LSD tests. Means (± standard error) of grain and biomass yield (kg ha^{-1}) for each experiment are shown in Supplementary Table S11.

the ordinary replacement and narrow-wide row systems. However, when soybean rows were added in the created space between maize and soybean, soybean yields increased substantially to 1021 ± 48.2 kg ha^{-1} for Grobogan and 1191 ± 36.6 kg ha^{-1} for OSOYA. While cultivar OSOYA yielded more than Grobogan in the soybean additive system, their yields were similar in the ordinary replacement system (Table 2).

Biomass production showed patterns similar to grain yield across treatments (Table 2). The harvest index (HI) ranged from 0.40 to 0.44 for maize, 0.24–0.39 for soybean, and 0.25–0.29 for mung bean. A small but significant treatment effect on HI was observed only for maize, where the narrow-wide row intercropping configuration had a higher HI (0.44 ± 0.01) than the ordinary replacement system (0.40 ± 0.01).

3.2. Land use efficiency

Additive intercropping consistently resulted in LER values above one (Fig. 5), indicating higher land-use efficiency than in sole cropping. In contrast, replacement intercrops had LER values near or below one, ranging from 0.89 ± 0.03 in the maize-OSOYA replacement system to 0.97 ± 0.03 in the narrow-wide row intercropping with Grobogan. The lower LER in the maize-OSOYA replacement system was primarily due to the poor relative performance of intercropped OSOYA (pLER = 0.30 ± 0.02, substantially below the expected value of 0.44 based on its relative density). While maize had an acceptable pLER of 0.59 ± 0.03, it was insufficient to offset the low performance of OSOYA in the mixture.

Maize had pLERs greater than the expected values of 0.56 in replacement intercrops and 0.46 in additive intercrops, but the differences between replacement and additive intercrops were not significant. Soybean pLERs were generally below expected in replacement systems (0.40 ± 0.02 for Grobogan and 0.30 ± 0.02 for OSOYA), but the differences with the expected relative soybean pLER were not significant, except in the case of ordinary replacement intercropping with OSOYA. The pLER of mung bean (0.15 ± 0.01) was significantly below the expected value of 0.18.

Two additive intercrops had a total LER that was significantly above one: the 2:6 configuration of maize with Grobogan (LER = 1.16 ± 0.04) and the 2:4:2 maize-Grobogan-mung bean configuration (LER = 1.08 ± 0.03; Fig. 5). The higher LER values in additive systems resulted from the additional rows of beans; the pLER of maize was somewhat lower than in replacement systems, but it was still sufficiently high for an overall good system performance with LER above one (Fig. 5). There was

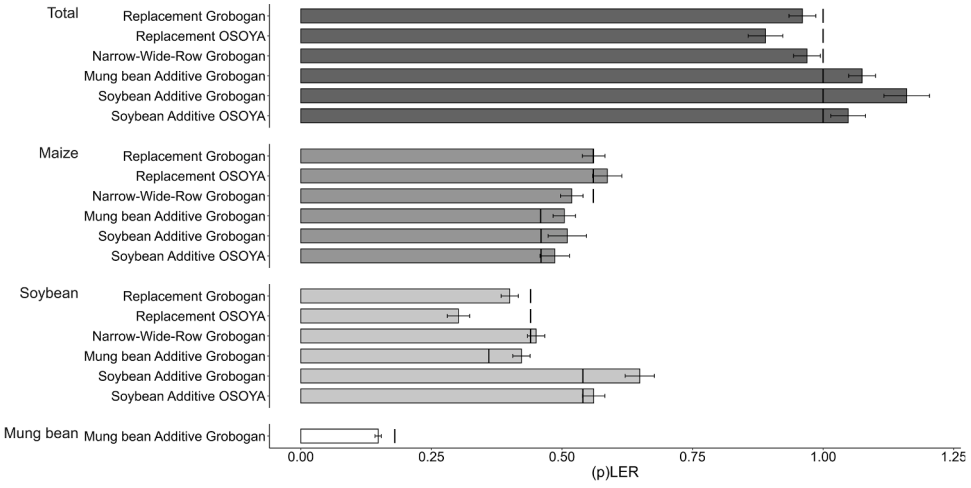


Fig. 5. Marginal means of the partial Land Equivalent Ratio (pLER) for soybean, maize, and mung bean, as well as the total Land Equivalent Ratio (LER) for grain yield in different configurations. The bars indicate means ± standard error. Different letters indicate statistically significant differences (p = 0.05) among configurations in the pLER of soybean, maize, mung bean, and the total LER, as determined by Fisher's LSD test. Solid lines indicate the scaled relative density (Table 1), which shows the expected pLER or LER for each configuration. Means (± standard error) of grain and biomass LER for each experiment are shown in Supplementary Table S12.

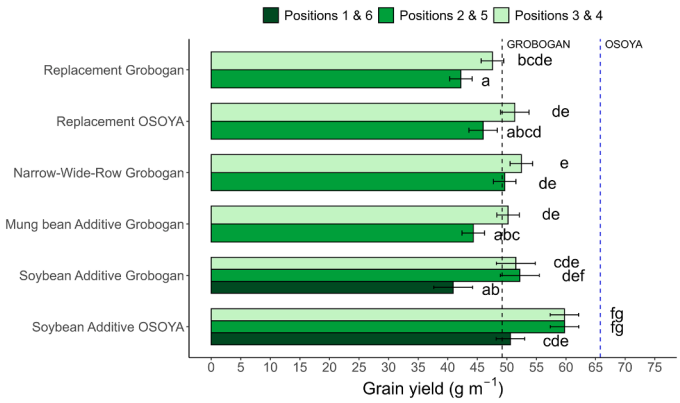


Fig. 6. Grain yield (g m^{-1}) of soybean in different row positions and configurations. Bars indicate means ± standard error. Row positions 1 and 6 are the rows next to maize for the soybean additive system. Row positions 2 and 5 are the rows next to maize for replacement systems and next to mung bean for the mung bean additive configuration (Supplementary Fig. S3). Dashed lines indicate the grain yield (g m^{-1}) of sole soybean, which is higher for the cultivar OSOYA than for Grobogan. A same letter behind a bar indicates no statistically significant differences (LSD, p = 0.05) among all configurations and row positions. Means (± standard error) of grain and biomass yield of soybean (g m^{-1}) for each experiment are shown in Supplementary Table S13.

no significant difference in maize performance between the narrow-wide row configuration (0.52 ± 0.02) and the additive configurations (from 0.49 ± 0.03–0.51 ± 0.04). In contrast, soybean in the narrow-wide row configuration had a slightly higher pLER of 0.45 ± 0.02 compared to 0.40 ± 0.02 in the ordinary replacement configuration.

3.3. Border row effects

Border rows of soybean are closer to the maize and hence subject to greater shading and competition for belowground resources with maize than inner rows. Narrowing the distances between maize rows widens the gap between maize and soybean, reducing these competitive effects on soybean. Border rows performed worse than inner rows in most systems, but not in the 2:4 narrow-wide row configuration in which border and inner rows had similar yields (Fig. 6). The four inner rows of the soybean strip performed well in the 2:6 additive systems (six soybean rows and maize planted in narrow rows). Notably, in the 2:6 soybean additive system with Grobogan, row positions 2 and 5 yielded significantly higher than the same positions in the mung bean additive system with the same soybean cultivar (Fig. 6).

4. Discussion

This study examined intercropping strategies to improve land productivity in tropical conditions in East Java, Indonesia. We evaluated three different intercropping configurations: (1) replacement intercropping, (2) narrow-wide row intercropping to reduce shading of soybean by maize, and (3) additive intercropping with additional mung bean or soybean rows. The study was conducted over two years, with two growing seasons per year, and used two soybean cultivars.

Narrowing the maize row spacing to reduce competition with soybean improved the partial LER of soybean but had a minimal effect on maize. However, overall LER values of replacement systems remained around or below one. Additive intercropping with extra soybean rows resulted in a clear yield advantage, primarily due to increased bean yields. These trends were consistent across respective growing seasons. A land use advantage was also found when mung bean was added rather than soybean, but the advantage was less than with soybean.

4.1. Replacement intercropping under simultaneous sowing

We found that simultaneous maize-soybean replacement intercropping with irrigation and fertilization did not have a land-use advantage in East Java. This finding align with a meta-analysis by Yu et al. (2015) and experiments by Li et al. (2020a) which show that intercropping of maize and legumes becomes less advantageous at higher nutrient levels when there is no temporal complementarity between the species, as was largely, even if not fully, the case in our study. In contrast, studies conducted in tropical regions of Africa (Tsujimoto et al., 2015; MacLaren et al., 2023; Kermah et al., 2017, 2018) reported significant land-use advantages, as indicated by high land equivalent ratios (LER) under simultaneous maize-soybean replacement intercropping. These African studies used lower nitrogen inputs (0–8 g m^{-2} in Tsujimoto et al., 2015; 12 g m^{-2} in MacLaren et al., (2023); and 5 g m^{-2} in Kermah et al., 2017, 2018) than we used in our study (16.1 g m^{-2}). Our findings, therefore, fit in a broader pattern that land use advantages of intercropping are less likely to occur if there is limited temporal complementarity and the plants are fertilized at the locally recommended amounts and fully irrigated (Li et al., 2020a; Wang et al., 2022).

4.2. Narrow-wide row replacement configuration

The partial LER of soybean was higher in the narrow-wide row configuration than in the ordinary replacement system (Fig. 5), mainly due to better performance in the border rows (Fig. 6). Similar results were reported in relay intercropping systems in Sichuan, China (Yang et al., 2014; 2016; Raza et al., 2019).

In Sichuan, soybean yield increased by 23–36 % and maize yield decreased by 13–18 % in narrow-wide row configurations compared to wide maize inter-row spacing, depending on the distance between maize and soybean. In our study in East Java, the increase in soybean yield was smaller (14 %), and maize yield decreased by only 7 % (Table 2). The soybean harvest index also increased in Sichuan but remained unchanged in our case.

Two main differences could underly these contrasting results. First, the Sichuan system used relay intercropping, with maize sown 75 days earlier than soybean. The two crops overlapped for only 48 days, after which soybean grew alone for 91 days. In East Java, both crops were sown at the same time and overlapped for 85 days, with soybean under continuous shading from the taller maize. This likely explains the more modest yield responses (Ahmed et al., 2020) and the lack of response in the harvest index of soybean.

Second, the Sichuan system used an additive design with high plant density (relative density total close to 2). Our system used a replacement design (relative density total of 1), resulting in 38 % lower maize density and 26 % lower soybean density than in the Sichuan studies. The lower maize density may have reduced competition among maize plants and thus limited the yield loss of maize in narrow rows. However, the soybean density may have been too low to use the extra space fully. Adding soybean rows in the gap in the narrow-wide row system showed good performance of the soybean in the gap (Fig. 6) and an increase in pLER above the expected value based on the scaled relative density (Fig. 5).

Therefore, in our system, which uses simultaneous sowing and a narrow-wide row configuration, the tested maize plant density appears to be adequate, as the yield remained within an acceptable range compared to the sole crop. In contrast, there seems to be potential to increase the soybean plant density to achieve the maximum achievable population and yield under simultaneous intercropping.

4.3. Adding mung bean vs adding soybean in narrow-wide row systems

Adding mung bean or soybean to the system increased land-use efficiency (Fig. 5). This finding is consistent with previous studies highlighting the yield advantages of additive systems (Yu et al., 2015; Gu et al., 2021). While the land equivalent ratio (LER) of the mung bean

additive system was not significantly different from that of the soybean additive system, pLER of mung bean was lower than expected (Fig. 5). In the same row positions, soybean in the soybean additive configuration yielded higher than soybean in the mung bean additive configuration (Fig. 6). This suggests that soybean and mung bean do not combine well. Further research is needed to understand the mechanisms behind this.

4.4. Performance of different cultivars under intercropping

The new cultivar OSOYA is valued for its sensory qualities which enhance its value in industrial processing and thereby the market. The cultivar was higher yielding in our trials than its parent and predecessor Grobogan (Table 2, Fig. 6), but intercropping systems with OSOYA had lower LER than intercropping systems with the parent soybean cultivar Grobogan (Fig. 5). The pLERs of OSOYA and maize were lower than the corresponding pLERs of Grobogan and maize in intercrops in which Grobogan was used. OSOYA has a lower protein and fat content than Grobogan, and further research is needed to investigate whether and how these nutritional traits are influenced under intercropping conditions.

4.5. Innovations, weaknesses, and potential implementation by farmers

This study presents four significant innovations.

1. Redefining yield expectations for tropical intercropping: We demonstrate that in tropical high-light environments, simultaneous maize-soybean replacement systems grown with sufficient resources do not give a yield advantage. This aligns with previous studies but provides important new evidence for intercropping performance in tropical environments.

2. Narrow-wide row configuration in simultaneous intercropping systems in tropical environments: We demonstrate that narrowing the maize row distance and, therefore, widening the space between maize and soybean under simultaneous intercropping with sufficient water and recommended fertilization resulted in improved soybean yields and a small yield penalty for maize. This suggests that shading of soybean is important in East Java, regardless of the high level of radiation at the study site. Maize yield penalties were smaller than those observed in subtropical relay intercropping systems in Sichuan, China.

3. Introducing mung bean to enhance land use: We demonstrate that in additive systems with soybean or mung bean, soybean adjacent to soybean performs better than soybean adjacent to mung bean (Fig. 6). This finding suggests that soybean and mungbean do not go well together, and it highlights the importance of species interactions in intercropping. The performance of mung bean was less favorable than expected.

4. We demonstrate that the new soybean cultivar, OSOYA, is less productive in intercropping systems than its parent and predecessor, Grobogan. This suggests potential trade-offs between agronomic traits important for diversified farming systems and quality traits critical for processing and industrial use. While OSOYA offers superior processing qualities and market demands, providing economic benefits for farmers, its performance in intercropping systems may be a limitation.

This study has several limitations, such as overall low plant densities in both pure stands and intercrops, which resulted in the loss of treatments in Experiment 4 and may have led to suboptimal soybean yields in other experiments. Pest damage occurred so the flowering of maize was delayed in Experiment 2 but with no visible differences in severity between sole and intercropped maize.

Maize–soybean intercropping presents a promising opportunity for farmers in East Java. Maize offers greater market stability than soybean, whose price is more volatile due to global fluctuations. Beyond economic benefits, this study highlights the potential to further diversify the region's three crops per year rotation system, typically comprising two paddy crops and one upland crop, or one paddy and two upland crops, by introducing simultaneous intercropping in one or two of the drier growing seasons.

While relay intercropping has shown notable agronomic advantages (Chai et al., 2021; Li et al., 2020a,b, 2023; Yu et al., 2015), our simultaneous intercropping system demonstrated more modest benefits and only when sown as additive systems. Relay systems usually have much greater LER, but may leave portions of the land underutilized during certain times of the year. Relay intercropping is therefore advantageous if season length extends beyond a single crop cycle but is insufficient for multiple crop cycles. In the case of a three crops per year rotation, as is common in East Java, relay intercropping is difficult to implement. By maintaining three seasons per year and using simultaneous intercropping, we preserved year-around productivity while enhancing system diversity.

Diversification strengthens the resilience of food systems (Hertel et al., 2023) and is particularly valuable under increasing climatic instability and increasing frequency of weather extremes. Cereal–legume intercropping systems are thought to be more resilient than the respective sole crops (Liu et al., 2022; Raseduzzaman and Jensen, 2017), so the system might provide more benefit to resource-limited farmers who are located in high-stress environments where either crop may run a chance of failing. In addition, diversification supports long-term soil fertility (Wang et al., 2024, 2015; Cong et al., 2014). Long-term studies are needed to evaluate the effects on soil fertility and soil organic matter of simultaneous intercropping in tropical triple-cropping systems.

Although our findings are based on short-term outcomes, the narrow-wide configuration combined with additive intercropping showed good potential. Engagement and co-design with farmers will be essential to address practical constraints and adapt intercropping systems to the needs, possibilities, constraints and aspirations of the users.

5. Conclusion

In this study, we investigated various intercropping configurations, including narrow-wide row replacement and mung bean or soybean additive systems, as variations on the maize-soybean intercropping theme. Our findings show that replacement intercropping does not offer a yield advantage in East Java, Indonesia, when crops are sown simultaneously and sufficient nutrients and water are provided. The narrow-wide row planting system increased soybean production without significantly reducing maize yield, hence this system had a small land use advantage. Adding additional bean rows in the space freed up by planting maize at a narrow row distance increased the yield advantage. These results highlight the importance of optimizing intercropping designs to achieve productivity gains when crops are sown simultaneously and sufficient resources are provided.

CRediT authorship contribution statement

Narendra Duhita: Supervision, Funding acquisition. **Devi Fitriani:** Investigation, Data curation. **Wopke van der Werf:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Lotte Suzanne Woittiez:** Writing – review & editing, Supervision. **Tjeerd Jan Stomph:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Denis Muba Pandapotan Simanihuruk:** Investigation, Data curation. **Wahyu Muji Laksono:** Investigation, Data curation. **Naoko Kawasaki:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.110015.

Data availability

Data will be made available on request.

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