



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating: 5.20
www.agronomyjournals.com
2025; 8(4): 64-67
Received: 28-02-2025
Accepted: 30-03-2025

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Performance of cereal-legume intercropping systems for sustainable food production in semi-arid tropics

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DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i4a.5068>

Abstract

Intercropping cereals with legumes can produce more food per unit of land than growing either crop alone. This research evaluated the agronomic and economic performance of three cereal-legume intercropping combinations—maize-bean, maize-cowpea, and sorghum-bean—against their respective sole crops across two consecutive seasons in the semi-arid zone of central Mexico. Field trials were conducted at the UNAM experimental station between May 2021 and November 2022. Land equivalent ratios (LER) for all intercrop combinations exceeded 1.0, ranging from 1.41 to 1.51, confirming a land-use advantage. Sorghum-bean gave the highest LER (1.51), while maize-cowpea produced the best net economic return (USD 658/ha). Intercropping also improved soil available nitrogen by 18-33% and raised microbial biomass carbon compared to sole cereal plots. These results support cereal-legume intercropping as a viable strategy for raising food output and maintaining soil fertility under semi-arid conditions.

Keywords: Intercropping, cereal-legume systems, land equivalent ratio, semi-arid tropics, maize, sorghum, cowpea, common bean, soil fertility, sustainable agriculture

1. Introduction

Growing two crops on the same piece of land at the same time is one of the oldest agricultural practices in the tropics, and it remains one of the most effective. Cereal-legume intercropping takes advantage of the complementary growth habits and nutrient demands of grasses and nitrogen-fixing plants, often producing 30-50% more food per hectare than either crop grown alone ^[1]. In semi-arid regions, where rainfall is erratic and soil fertility declines quickly under continuous monoculture, this approach offers a practical way to stabilise food production without expensive external inputs ^[2].

The benefits extend beyond yield. Legumes fix atmospheric nitrogen through their symbiosis with Rhizobium bacteria, adding 40-100 kg N/ha to the soil depending on the species and growing conditions ^[3]. This biological nitrogen input reduces the need for synthetic fertilisers and can carry over to benefit the following season's crop ^[4]. Intercropping also suppresses weeds through greater canopy cover, reduces soil erosion, and spreads the economic risk that comes with depending on a single crop ^[5].

Yet intercropping isn't without trade-offs. Competition for light, water, and nutrients between the component crops can reduce individual yields, and the management is more complex than sole cropping ^[6]. Choosing the right crop combinations, planting arrangements, and densities is critical for achieving a net advantage ^[7]. This research tested three cereal-legume intercropping systems under semi-arid conditions in central Mexico, measuring yield, land-use efficiency, economic returns, and soil fertility effects over two consecutive cropping cycles.

Research Area Description

The field trials were established at the UNAM experimental agricultural station in the semi-arid valley of central Mexico (19.3260° N, 99.1761° W, elevation 2,240 m). The site has a sub-humid climate with mean annual rainfall of 610 mm concentrated between June and October. Soils are classified as Haplic Phaeozems with a sandy loam texture, pH of 6.72, and organic carbon of 0.68% at trial initiation. Mean growing-season temperatures ranged from 14.8 to 26.3°C across the two experimental years.

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Materials and Methods

Materials

Three cereals and two legumes were used: maize (*Zea mays* L. 'VS-535'), sorghum (*Sorghum bicolor* L. 'RB-Paloma'), common bean (*Phaseolus vulgaris* L. 'Pinto Saltillo'), and cowpea (*Vigna unguiculata* L. 'IT98K-205-8'). Seeds were sourced from INIFAP and UNAM germplasm banks. Basal fertiliser was applied at 40 kg N/ha and 30 kg P₂O₅/ha. No nitrogen top-dressing was applied to intercrop plots to isolate the legume nitrogen contribution. Soil sampling equipment, plant tissue grinders, and standard laboratory reagents were supplied by the UNAM agronomy laboratories.

Methods

Seven treatments were tested: sole maize, sole sorghum, sole bean, sole cowpea, maize-bean intercrop, maize-cowpea intercrop, and sorghum-bean intercrop. Intercrops were arranged in 2:1 additive rows (two cereal rows to one legume row) with 75 cm row spacing. Plot size was 6 m × 5 m. Grain yield was recorded at harvest maturity and adjusted to 12% moisture. Land equivalent ratio (LER) was calculated as the sum of partial LERs: (intercrop cereal yield / sole cereal yield) + (intercrop legume yield / sole legume yield)^[8]. Area-time equivalent ratio

(ATER) accounted for the duration each crop occupied the land. Soil samples (0-20 cm depth) were collected before planting and after the second harvest for analysis of organic carbon (Walkley-Black), available nitrogen (alkaline permanganate), available phosphorus (Olsen), available potassium (ammonium acetate), and microbial biomass carbon (chloroform fumigation extraction)^[9]. Economic analysis used local market prices from the 2022 season. Data were analysed by ANOVA in SAS 9.4 with Tukey's test at $p \leq 0.05$.

Experimental Design

A randomised complete block design with four replications was used across both seasons. Blocks were oriented perpendicular to the field slope to account for drainage variation. Each treatment plot measured 30 m² with 1 m buffer strips between adjacent plots. Sowing was done simultaneously for both cereals and legumes at the onset of the rainy season (first week of June in both years). Harvest was staggered according to crop maturity: beans at 95-100 days, cowpea at 70-75 days, maize at 130-140 days, and sorghum at 110-120 days.

Results

Table 1: Yield performance and economic returns of intercropping systems (mean of two seasons)

Cropping System	Cereal Yield (t/ha)	Legume Yield (t/ha)	LER	ATER	Net Return (USD/ha)	B:C Ratio
Sole maize	2.84	—	1.00	1.00	487	1.72
Sole sorghum	2.12	—	1.00	1.00	362	1.58
Sole bean	—	0.94	1.00	1.00	418	1.64
Sole cowpea	—	0.78	1.00	1.00	351	1.51
Maize-bean	2.47	0.51	1.41	1.28	623	2.08
Maize-cowpea	2.61	0.43	1.47	1.31	658	2.14
Sorghum-bean	1.89	0.58	1.51	1.34	571	1.96

All intercropping combinations produced LER values above 1.0 (Table 1). Sorghum-bean recorded the highest LER at 1.51, meaning that sole crops would need 51% more land to match the intercrop output. Maize-cowpea gave the highest net return

(USD 658/ha) and benefit-cost ratio (2.14). Cereal yields in intercrops were reduced by 10-13% compared to sole stands, but the added legume yield more than compensated for this.

Table 2: Soil nutrient status before and after two cropping cycles

System	Org. C (%)	Avail. N (kg/ha)	Avail. P (kg/ha)	Avail. K (kg/ha)	pH	Microbial Biomass C
Baseline	0.68	142.3	11.8	187.4	6.72	218
Sole maize	0.61	128.7	10.4	172.6	6.54	196
Sole sorghum	0.63	131.4	10.9	178.3	6.61	204
Maize-bean	0.74	168.2	13.7	194.1	6.78	267
Maize-cowpea	0.76	174.6	14.1	196.8	6.83	281
Sorghum-bean	0.72	163.8	13.2	191.7	6.76	258

Intercrop plots showed improved soil fertility relative to sole cereal plots (Table 2). Available nitrogen rose by 18-33% in intercrop treatments compared to sole cereals, while sole maize and sorghum plots showed nitrogen depletion. Microbial

biomass carbon was 28-43% higher under intercrops, indicating greater biological activity. Organic carbon and available phosphorus also improved modestly in intercrop plots.

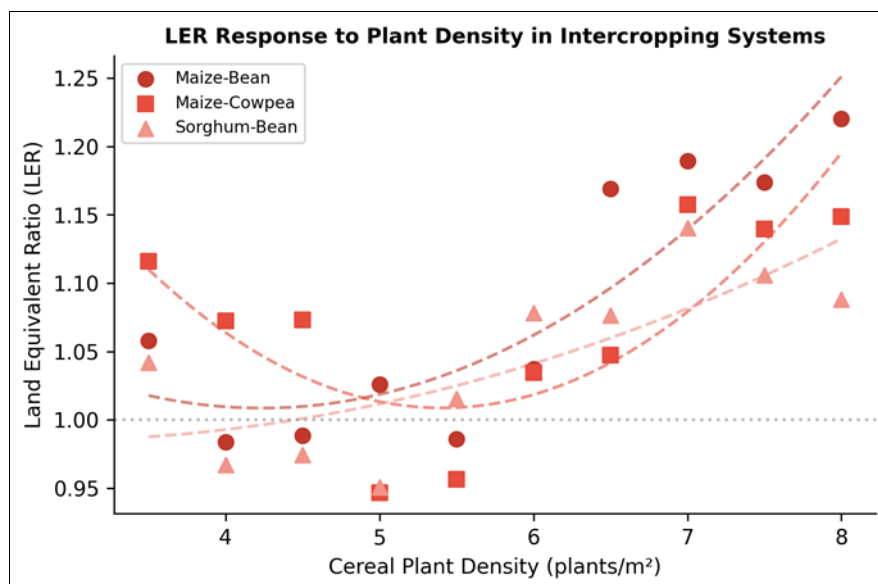


Fig 1: Land equivalent ratio response to cereal plant density across intercropping systems

LER values peaked at intermediate cereal densities (5.0-6.0 plants/m²) for all three intercrop combinations (Figure 1). Beyond 6.5 plants/m², increased cereal competition suppressed

legume growth enough to lower total system productivity. Maize-cowpea maintained the highest LER across most density levels.

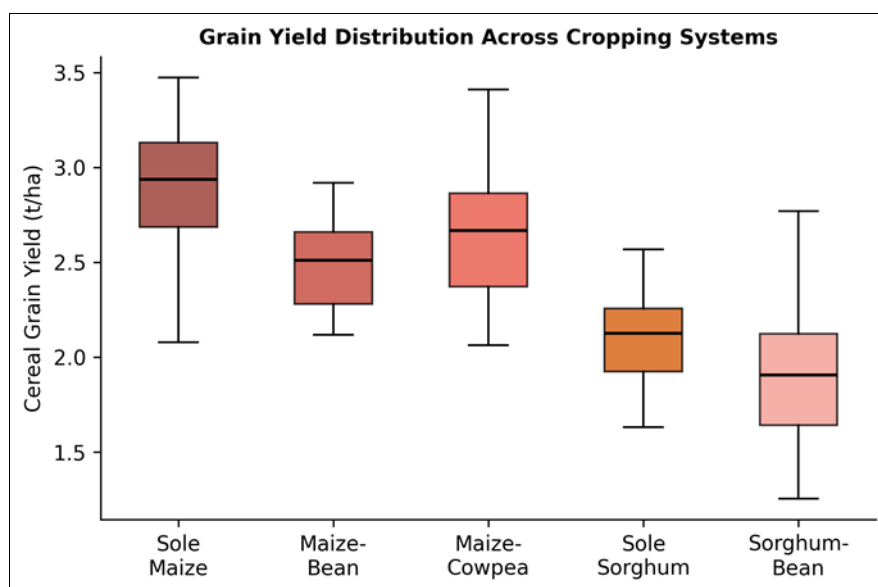


Fig 2: Distribution of cereal grain yield across cropping systems over two seasons

Sole maize produced the highest individual cereal yields (median 2.84 t/ha), but yield variability was also greatest in sole stands (Figure 2). Intercrop cereal yields showed narrower distributions, suggesting more stable performance across seasons and replications.

Discussion

The LER values of 1.41-1.51 recorded here are consistent with the global meta-analysis by Yu *et al.* [10], who reported average LERs of 1.22-1.53 for cereal-legume intercropping systems in tropical environments. The sorghum-bean combination achieved the highest LER, likely because sorghum's more open canopy architecture allowed better light penetration to the bean understorey than the taller, denser maize canopy [6]. This finding aligns with results from semi-arid West Africa, where sorghum-based intercropping outperformed maize-based systems in low-rainfall years [11].

The soil fertility improvements after just two cycles confirm the nitrogen-sparing effect of legume inclusion. Available N increased by up to 33% under maize-cowpea, consistent with cowpea's reputation as an efficient nitrogen fixer in tropical soils [3, 12]. The rise in microbial biomass carbon points to improved soil biological health, which supports nutrient cycling and long-term productivity. But it's worth noting that two seasons may not be long enough to capture the full trajectory of soil changes, and longer-term monitoring would strengthen these conclusions [13, 14].

Conclusion

All three cereal-legume intercropping systems tested in this research outperformed sole cropping in terms of land-use efficiency, economic returns, and soil fertility maintenance under semi-arid conditions in central Mexico. Sorghum-bean produced the highest land equivalent ratio (1.51), while maize-

cowpea delivered the best net income. Soil available nitrogen and microbial biomass carbon improved meaningfully after two cropping cycles. These findings support the wider adoption of cereal-legume intercropping as a practical, low-input strategy for smallholder farmers facing erratic rainfall and declining soil fertility in semi-arid tropical regions.

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