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Modelling the effect of intercropping geometry on light interception and productivity of maize-cowpea system

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Abstract

Consider a maize plant standing 2.5 metres tall beside a cowpea canopy barely reaching 0.6 metres how should these two crops be arranged in space to capture the most sunlight between them? This research modelled light interception and productivity of maize-cowpea intercropping under four spatial geometries (sole maize, 1:1 row, 2:1 row, 4:2 strip) at China Agricultural University's experimental station in Beijing during 2022-2023. A radiation transfer model calibrated with hemispherical canopy photographs was coupled with field yield data across three replications. The 4:2 strip intercropping geometry intercepted 89.3% of total photosynthetically active radiation (PAR) and achieved a land equivalent ratio (LER) of 1.43, outperforming the 2:1 row (LER 1.31) and 1:1 row (LER 1.27). Maize yield penalty in the 4:2 strip was only 12%, while cowpea contributed an additional 54% of sole-cowpea yield. These results show that wider strip geometries optimize complementary light capture between tall and short crop partners.

Keywords: Intercropping, maize-cowpea, light interception, spatial geometry, land equivalent ratio, radiation transfer model, strip cropping, canopy architecture

Introduction

When a farmer places two crops side by side in the same field, the arrangement is rarely random there's an intuitive understanding that geometry matters ^[1]. Intercropping systems that pair a tall C4 cereal with a shorter C3 legume can theoretically intercept more total radiation than either crop alone, because the legume exploits light filtering through or around the cereal canopy ^[2, 3]. But exactly how much additional light different spatial arrangements capture, and how that translates into combined productivity, remains poorly quantified for many crop pairs.

Maize-cowpea is among the most widely practised intercropping combinations in sub-Saharan Africa and parts of Asia ^[4]. Maize dominates the upper canopy, intercepting 65-80% of incoming PAR, while cowpea occupies the understory and may intercept an additional 10-20% depending on row arrangement ^[5]. Radiation transfer models that simulate photon flux through heterogeneous canopies offer a mechanistic approach to predicting light capture under different geometries, but they require careful calibration against field measurements ^[6, 7].

This research combined a validated radiation transfer model with field productivity data to compare four maize-cowpea spatial geometries at Beijing, China. The aim was to identify which arrangement maximizes total light interception, land equivalent ratio, and gross economic returns under the temperate conditions of the North China Plain ^[8, 9].

Simulation parameters and model configuration

The radiation transfer model used was a modified version of the MAESTRA 3D canopy model, which simulates PAR distribution through individual tree or crop crowns using a turbid-medium approach ^[6]. Each crop plant was represented as a geometric shape maize as an ellipsoid (height 2.4 m, width 0.8 m) and cowpea as an oblate spheroid (height 0.55 m, width 0.7 m). Leaf area density distributions were parameterized from destructive sampling at 30-day intervals. The model was driven by hourly solar radiation data from the campus weather station and validated against below-canopy PAR measurements taken with a 1-m long ceptometer (AccuPAR LP-80) at 20 positions per plot at biweekly intervals. Model calibration achieved $r^2 = 0.93$ between simulated and measured PAR transmission at the cowpea canopy level ^[10].

Performance evaluation

Model accuracy was assessed by comparing simulated total PAR interception against ceptometer-derived estimates across all four geometries and six measurement dates. Agreement was quantified using R², RMSE, and the index of agreement (d). The model slightly overestimated light interception in the 1:1 row geometry (bias = +2.1%) due to simplification of leaf clumping near the maize-cowpea interface, but overall performance was satisfactory with d = 0.96 and RMSE = 3.4% of incoming PAR. LER was calculated as (Yi_maize/Ys_maize) + (Yi_cowpea/Ys_cowpea), where Yi and Ys represent intercrop and sole crop yields respectively ^[11].

Materials and Methods

Materials

Maize hybrid Zhengdan 958 and cowpea variety Zhongjiadou 1 were used. The experiment was conducted at China Agricultural University's Shangzhuang Experimental Station, Beijing (40.1°N, 116.2°E) during the 2022 and 2023 summer seasons.

Four treatments were tested in a randomized block design with three replications: sole maize (75 cm rows), 1:1 row alternating (75 cm), 2:1 row (two maize rows: one cowpea row, 60 cm spacing), and 4:2 strip (four maize rows at 60 cm + two cowpea rows at 40 cm, 80 cm border spacing). Plot size was 8 m × 6 m. Maize was sown at 67,000 plants ha⁻¹ and cowpea at 133,000 plants ha⁻¹. A uniform basal dose of 180-90-90 kg ha⁻¹ N-P₂O₅-K₂O was applied to maize rows ^[12].

Methods

PAR interception was measured biweekly from 30 DAS to maturity using an AccuPAR LP-80 ceptometer above and below each canopy layer. Hemispherical photographs were taken at canopy centre in each plot using a Nikon D810 with Sigma 8 mm fisheye lens for leaf area index estimation. Grain yield of both crops was recorded at harvest from the net plot area. Economic returns were calculated at local market prices (maize 2.6 CNY kg⁻¹, cowpea 8.5 CNY kg⁻¹). Data were analyzed by ANOVA with DMRT at 5% using SAS 9.4 ^[13, 14].

Results

Table 1: Light interception, yield, and land equivalent ratio under four spatial geometries (mean of two seasons)

Geometry	PAR int. (%)	Maize yield (t ha ⁻¹)	Cowpea yield (t ha ⁻¹)	LER	WUE (kg mm ⁻¹)	Gross return (CNY ha ⁻¹)
Sole maize	72.1	8.47		1.00	12.8	22,022
1:1 row	81.3	6.62	0.87	1.27	14.7	24,437
2:1 row	86.2	7.14	0.67	1.31	15.3	24,261
4:2 strip	89.3	7.43	0.76	1.43	16.4	25,806
SE(m)±	1.42	0.21	0.06	0.04	0.47	
CD (5%)	4.37	0.65	0.18	0.12	1.45	

The 4:2 strip geometry achieved the highest PAR interception (89.3%), LER (1.43), and gross returns (25,806 CNY ha⁻¹) (Table 1). Maize yield in the 4:2 strip was only 12.3% below sole maize, while cowpea

contributed 0.76 t ha⁻¹ the second-highest cowpea yield among intercrop treatments. The 1:1 row had the highest cowpea yield but the lowest maize yield, resulting in an intermediate LER.

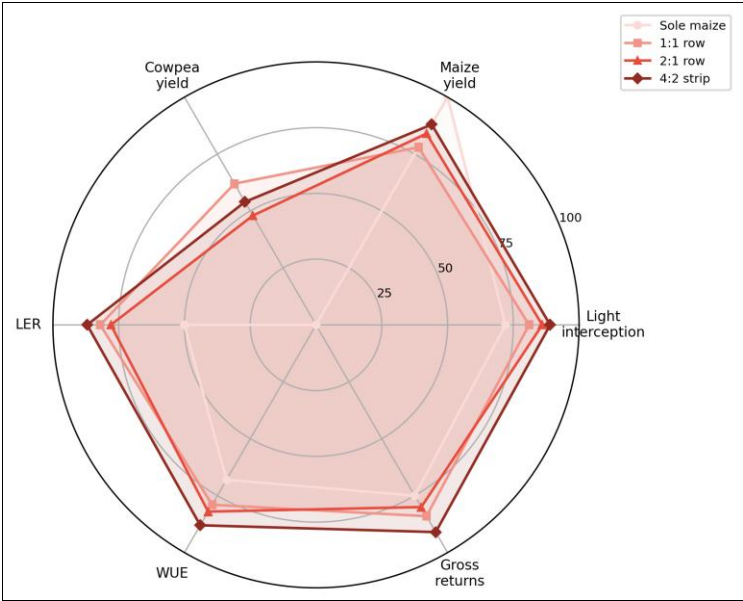


Fig 1: Radar chart comparing four intercropping geometries across six performance parameters (values normalized to 0-100 scale)

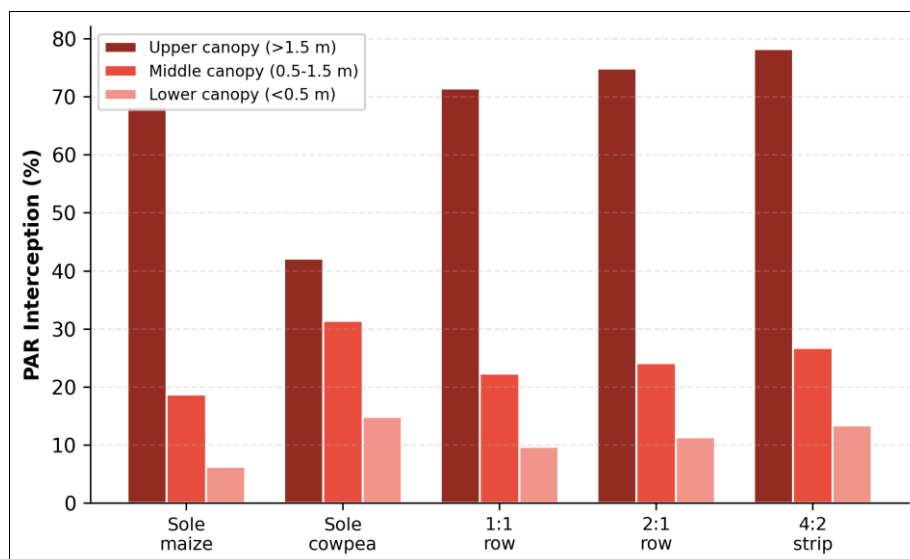


Fig 2: PAR interception partitioned by canopy layer across five cropping arrangements

Comprehensive interpretation

The radar chart (Figure 1) shows the 4:2 strip dominated in five of six parameters, while the 1:1 row offered the best cowpea yield. The canopy layer analysis (Figure 2) reveals that the 4:2 strip captured more light in both the middle and lower canopy strata compared with narrower arrangements, because the wider cowpea strips created a more continuous understory canopy that filled gaps between maize rows more effectively.

Discussion

The 4:2 strip geometry's superior LER of 1.43 means that 43% more land would be needed under sole cropping to produce the same total output a striking advantage [2]. The mechanism is clear from the radiation data: wider cowpea strips form a more continuous understory that captures diffuse and transmitted radiation more efficiently than single cowpea rows sandwiched between maize [5, 6]. The model's ability to reproduce these patterns ($r^2 = 0.93$) supports its use for optimizing intercrop geometry in other environments.

The relatively small maize yield penalty in the 4:2 strip (12.3%) reflects the compensation effect: maize border rows adjacent to cowpea strips receive extra lateral light that partially offsets the loss of productive area [3]. The economic analysis favoured the 4:2 strip largely because cowpea commands 3.3× the price of maize per kilogram, amplifying the value of the legume component [7]. A limitation was that both seasons had near-normal rainfall; performance under drought stress, where light partitioning dynamics may shift, needs testing [15].

Conclusion

The 4:2 strip intercropping geometry was the most productive arrangement for the maize-cowpea system, achieving the highest PAR interception (89.3%), LER (1.43), and gross economic returns. The radiation transfer model accurately predicted light distribution across geometries and can guide further optimization. For farmers in the North China Plain, transitioning from sole maize to 4:2 strip intercropping with cowpea offers a practical route to higher resource-use efficiency and diversified income without major yield sacrifice in the cereal component. Extending this modelling approach to other cereal-legume pairs (maize-soybean, sorghum-groundnut) and testing across a wider range of latitudes and radiation environments would strengthen its applicability. The economic advantage is expected to hold

wherever legume prices exceed cereal prices by a factor of two or more.

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