

Agrobiological and economic optimization of cowpea-carrot intercropping under green manure management in the semiarid region

Otimização agrobiológica e econômica de feijão-caupi-cenoura consorciado sob manejo de adubação verde no semiárido

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ABSTRACT - Appropriate management of the types and amounts of green manure from the Caatinga biome and population densities of component crops is required for the agroecological success of intercropping in the semi-arid region. This study evaluated cowpea-carrot intercropping under the application of different amounts of *Merremia aegyptia* and *Calotropis procera* biomass. The experiment was conducted in a randomized block design, arranged in a 4 × 4 factorial scheme with 4 replicates, during two cropping seasons in a semi-arid environment. The factors consisted of green manure of *M. aegyptia* and *C. procera* biomass amounts (20, 36, 52, and 68 t ha⁻¹, dry basis) and cowpea population densities (80, 120, 160, and 200 thousand plants ha⁻¹). The highest agro-bioeconomic returns of cowpea-carrot intercropping were obtained with a land equivalent ratio of 1.83, productive efficiency index of 0.97, Z canonical variable score of 2.90, competitive ratio of 2.43, actual yield loss of 1.71, gross income of 165,657.79 BRL ha⁻¹, net income of 138,016.67 BRL ha⁻¹, and rate of return of 6.64 for each real invested in the combinations of green manure biomass input and cowpea population densities of 47.12 and 156; 68.00 and 124; 48.62 and 145; 52.48 and 188; 47.93 and 150; 43.99 and 164; 38.02 and 141; and 42.56 t ha⁻¹ and 165 thousand cowpea plants per hectare, respectively.

RESUMO - O manejo correto dos tipos, das quantidades de adubos verdes do bioma Caatinga e das densidades populacionais das culturas componentes tem sido um requisito para o sucesso agroecológico da prática de consórcio na região semiárida. Este estudo avaliou o consórcio de feijão-caupi e cenoura sob diferentes quantidades de biomassa de *Merremia aegyptia* e *Calotropis procera*. O experimento foi conduzido em um delineamento em blocos casualizados, organizado em um esquema fatorial 4×4 com quatro repetições, durante dois cultivos em ambiente semiárido. Os fatores consistiram nas quantidades de adubo verde de *M. aegyptia* e *C. procera* (20, 36, 52 e 68 t ha⁻¹, em base seca) e densidades populacionais de feijão-caupi (80, 120, 160 e 200 mil plantas ha⁻¹). Os maiores retornos agro-bioeconômicos do consórcio feijão-caupi-cenoura foram obtidos com uma relação de equivalência de terra (RET) de 1,83, índice de eficiência produtiva (IEP) de 0,97, escore da variável canônica Z de 2,90, razão competitiva (RC) de 2,43, perda de rendimento real (PRR) de 1,71, renda bruta (RB) de R\$ 165.657,79 ha⁻¹, renda líquida (RL) de R\$ 138.016,67 ha⁻¹ e taxa de retorno (TR) de 6,64 para cada real investido nas combinações de doses de biomassa de adubos verdes e densidades populacionais de feijão-caupi de 47,12 e 156; 68,00 e 124; 48,62 e 145; 52,48 e 188; 47,93 e 150; 43,99 e 164; 38,02 e 141 e 42,56 t ha⁻¹ e 165 mil plantas de feijão por hectare, nesta ordem.

Keywords: *Daucus carota*. *Vigna unguiculata*. *Merremia aegyptia*. *Calotropis procera*. Associated-cropping revenues.

Palavras-chave: *Daucus carota*. *Vigna unguiculata*. *Merremia aegyptia*. *Calotropis procera*. Receitas de culturas consorciadas.

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INTRODUCTION

Producers who utilize intercropping systems with tuberous vegetables and food crops, such as cowpea, generally seek systems that provide high productivity, greater production diversification, higher product quality, and above all, agro-bioeconomic returns (GUERRA et al., 2021). System efficiency is based on complementarity between crops and the mitigation of adverse impacts of one culture on another. Therefore, careful crop selection is fundamentally important for maximizing economic yield (CECÍLIO FILHO et al., 2021). Thus, intercropping with companion plants optimizes resource management, including water, nutrients, light, space, and solar radiation, since the crops that make up the system are of different sizes and growth cycles (ANDRADE FILHO et al., 2020). Cowpea and carrot satisfy the requirements of intercropping efficiency, as one crop complements the other (SILVA et al., 2020).

Appropriate management of the types and quantities of green fertilizer applied in the Caatinga biome and the planting densities of component crops is required for the agroecological success of intercropping practices in semi-arid regions (GUERRA et al., 2022). Hairy woodrose and roostertree are among the types of green fertilizer that stand out as green manure in the Caatinga (SÁ et al., 2021). Hairy woodrose is an herbaceous plant that produces 36 and 4 t ha⁻¹ of

green and dry mass, respectively, with a nitrogen content of 26.2 g kg^{-1} of dry matter and a carbon to nitrogen (C:N) ratio of 18:1 (LINHARES et al., 2021). Roostertree is a shrubby plant with an average phytomass production of 3 t ha^{-1} per cut (at 120 days), which can reach 9 t ha^{-1} per year on a dry basis, nitrogen content of 18.4 g kg^{-1} of dry matter, and a C:N ratio of 25:1 (DJIMTOINGAR et al., 2022).

Population density management in intercropping systems involves the determination of the number of plants in the system, considering the total population and that of each component crop. In general, increasing the population density increases productivity up to a certain limit, and resource competition (space, light, and nutrients) intensifies, negatively affecting crop growth and development and, consequently, system productivity, as a result of intraspecific and interspecific competitive interactions. Analyses of intercropping systems have shown the viability of this system through agro-biological indexes and economic indicators. The following indexes and indicators have been used: land equivalent ratio (LER) (BEZERRA NETO et al., 2023), actual yield loss (AYL) (CHAVES et al., 2022), productive efficiency index (PEI), Z canonical variable score (SILVA et al., 2024), intercropping advantage (IA), crop aggressivity (A), competitive ratio (CR) (CECILIO FILHO et al., 2022), gross and net incomes (GI and NI, respectively), rate of return (RR), and profit margin (PM) (SILVA et al., 2021b).

The aim of this study was to assess the viability of intercropping green cowpea and carrot in balanced biomass

amounts of *Merremia aegyptia* and *Calotropis procera* applied to cowpea with population densities during two years of cultivation in a semi-arid region through agro-biological indexes and economic indicators.

MATERIAL AND METHODS

Field research was accomplished from July to December in 2022 and 2023 at the Experimental Station 'Rafael Fernandes' of the Universidade Federal Rural do Semi-Árido, 20 km from the city of Mossoró, RN, Brazil, at $5^{\circ} 03' 37'' \text{ S}$, $37^{\circ} 23' 50'' \text{ W}$, at an altitude of 80 m.

The region's climate is classified as BShw with two seasons: a dry season and a rainy season (OLIVEIRA JÚNIOR et al., 2021). The experiments were carried out in 2022 and 2023, with average maximum temperatures of 35.1 and 36.3°C , relative humidity of 72.2 and 70.9%, and rainfall of 107.4 and 94 mm.

The soil from the research site was classified as dystrophic red-yellow, with a sandy loam texture (SANTOS et al., 2025), and representative composite samples were collected from the 0–20-cm layer. These samples were sent to the Water, Soil and Plant Tissue Analysis Laboratory of the Federal Institute of Science and Technology of Ceará, Limoeiro do Norte Campus, to determine their chemical attributes (Table 1).

Table 1. Chemical analyses of soils in experimental areas before incorporation of green manure for the 2022 and 2023 crops.

Soil	C	OM	pH (H ₂ O)	EC	P	K	Ca	Mg	Na	Cu	Fe	Mn	Zn	B
	--- g kg ⁻¹ ---		----- dSm ⁻¹ -----		--- mg dm ⁻³ ---		----- cmoldm ⁻³ -----					----- mg dm ⁻³ -----		
1	7.20	12.41	7.10	0.19	7.00	1.16	20.10	6.10	0.43	0.20	6.80	12.70	7.70	0.48
2	7.68	13.25	5.80	0.41	6.00	1.77	8.40	2.70	1.49	0.20	18.70	4.90	0.60	0.44

C: carbon; OM: organic matter; pH (H₂O): hydrogen ionic potential; EC: electrical conductivity; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; B: boron.

The experiment was set up in a randomized block design with a factorial scheme (4×4) and four replications. The first factor was the balanced biomass amount of *M. aegyptia* and *C. procera* of 20, 36, 52, and 68 t ha^{-1} on a dry basis, and the second factor was the cowpea population density (80, 120, 160 and 200 thousand plants ha^{-1}). Experiments were performed in two cultivation areas in a semiarid environment. In each block, two plots were planted with monocrops of carrot and cowpea, fertilized with 49.87 and 50.48 t ha^{-1} of the green manure biomass, hairy woodrose and roostertree, which was optimized by research in the region and evaluated to calculate the agro-bioeconomic indexes (DESRVINES et al., 2022; FREITAS et al., 2023).

The experimental plots with cowpea-carrot intercropping were sown in two alternating strips, in which each crop occupied 50% of the cultivated area. In each plot, the alternating bands were composed of four rows of each crop, flanked by two carrot rows on one side and two cowpea rows on the other, which were used as borders. Each plot had a total area of 3.60 m^2 ($3.00 \text{ m} \times 1.20 \text{ m}$) and useful area of 2.00 m^2 ($2.00 \text{ m} \times 1.00 \text{ m}$).

The useful area of the intercropped plots was comprised of two central strips of plants of each crop, excluding the two outer rows of the crops on each side and the last two plants of each row in the strips, which were used as borders. The carrot spacing in the intercropped treatments was $0.25 \text{ m} \times 0.04 \text{ m}$ for a density of 500 thousand plants ha^{-1} . Each harvest area in the intercropping plots contained 100 carrot plants. Cowpea spacing was $0.25 \text{ m} \times 0.10 \text{ m}$, $0.25 \text{ m} \times 0.125 \text{ m}$, $0.25 \text{ m} \times 0.166 \text{ m}$, and $0.25 \text{ m} \times 0.25 \text{ m}$ in the evaluated treatments, providing plant populations of 80, 120, 160, and 200 thousand plants ha^{-1} , respectively. There were 16, 24, 32, and 40 cowpea plants in the harvest area at the evaluated spacings, respectively.

Carrot monocropping plots were sown in a total area of 1.44 m^2 ($1.20 \text{ m} \times 1.20 \text{ m}$), containing 6 rows, with a useful area of 0.80 m^2 ($0.80 \text{ m} \times 1.00 \text{ m}$), which had 4 rows in a planting space of $0.20 \text{ m} \times 0.10 \text{ m}$. Cowpea monocropping was implemented in a total area of 3.60 m^2 ($3.00 \text{ m} \times 1.20 \text{ m}$), containing 6 rows, with a useful area of 2.00 m^2 ($2.00 \text{ m} \times 1.00 \text{ m}$), which had 4 rows in a plant space of $0.50 \text{ m} \times 0.10 \text{ m}$. In both the intercropped and monocropped systems,

crops were harvested in the four central crop rows, excluding the lateral rows, as well as the first and the last plants of each row, which were considered borders.

Green fertilizer was comprised of hairy woodrose (*M. aegyptia*) and roostertree (*C. procera*), which were collected from native vegetation at sites near the rural area of Mossoró,

RN, before flowering began. After collecting green manure, it was crushed in a conventional forager to obtain fragments of 2-3 cm. It was then dehydrated at room temperature until reaching 10% humidity and subsequently subjected to laboratory analysis (Table 2).

Table 2. Chemical analysis of macronutrients in dry biomass from *Merremia aegyptia* and *Calotropis procera* incorporated into the soil in a carrot-cowpea intercropping system over two growing seasons.

Green manure	N	P	K	Mg	Ca	C:N
	g kg ⁻¹					
	Cropping season 2022 (S1)					
<i>M. aegyptia</i>	20.56	2.83	37.08	7.07	19.35	25:1
<i>C. procera</i>	15.14	2.96	24.84	9.20	17.00	27:1
	Cropping season 2023 (S2)					
<i>M. aegyptia</i>	18.56	2.58	32.80	4.48	17.88	25:1
<i>C. procera</i>	14.66	1.27	31.00	5.40	11.60	27:1

Before installing the experiments in the experimental area, the soil was mechanically cleaned using a tractor, followed by harrowing to form planting beds. Pre-planting solarization was carried out in these beds using Vulca Brilho Bril Flex® plastic (30 microns) for 30 days to reduce the population of harmful microorganisms present in the soil (SÁ et al., 2021).

After the solarization period, the biomass used as green manure was incorporated into the soil using hoes in two stages. In the first stage, 30% of the tested dose was incorporated into each experimental plot. At 20 days after this first incorporation, the crops were planted, with the first sowing on August 16, 2022, and the second on August 05, 2023. At 30 days after sowing, the second incorporation used the remaining 70% of the green fertilizer dose on September 31, 2022 in the first season and on September 04, 2023 in the second season; it was applied through grooves opened in the space between the rows.

Cowpea cultivar 'BRS Tumucumaque' and carrot cultivar 'Brasília' were sown in holes of 3-cm deep, and the seeds were covered with commercial substrate for germination. Cowpea and carrot were thinned at 5 and 10 days after sowing, respectively. Only one plant per hole was left after thinning in both crops in the intercropped and monocropped systems. During the periods in which the experiments were conducted, carrot was manually weeded and hilled whenever necessary. No chemical pest or disease control was applied.

Irrigation was carried out daily using a microsprinkler irrigation system, divided into two shifts. The supplied water amount was based on the carrot cultivation coefficient (main crop) obtained in the region (average Kc of 0.965) (SANTOS et al., 2021), with a water depth of 8 mm per day. In cowpea, harvest was carried out three times in each year of cultivation. In the first year, the first harvest occurred on October 25, 2022, and in the second year, it was on October 13, 2023. Subsequent harvests occurred 3 days after the first harvest. In the first year, the first cowpea harvest occurred 70 days after sowing, and in the second year, it occurred 69 days after

sowing. For carrot, harvest occurred on November 22, 2022, in the first year and November 3, 2023, in the second year at 98 and 90 days after sowing, respectively.

The following crop characteristics were evaluated: carrot root commercial productivity, determined by the weight of the fresh mass of the roots in the useful area with a minimum size of 5 cm in length and greater than 1 cm in diameter, free from deformations (SILVA et al., 2021a), expressed in t ha⁻¹; and cowpea productivity of green grains, quantified by the fresh mass of all green grains harvested from green pods in the harvest area, expressed in t ha⁻¹ (DESRUVINES et al., 2022). The agro-bioeconomic efficiencies of carrot and cowpea intercrops were assessed through agronomic and competition indices and economic indicators:

LER was estimated as described by Bezerra Neto et al. (2023), (Equation 1):

$$LER = \frac{Y_{cco}}{Y_c} + \frac{Y_{coc}}{Y_{co}} \quad (1)$$

where LER represents the land equivalent ratio; Y_{cco} is the productivity of commercial carrot roots intercropped with cowpea; Y_{coc} is the green grain productivity of cowpea intercropped with carrot; Y_c is the productivity of commercial carrot roots in the monocropping system; and, Y_{co} is the green grain productivity of monocropped cowpea.

This index is described as the relative land area under the monocropping conditions required to provide the productivities obtained under intercropping conditions. If LER is greater than 1, intercropping favors crop development and growth and, consequently, culture productivity. If LER is less than 1, intercropping of the component crops is negatively affected, impairing crop development, growth, and productivity.

IA was assessed through the formulation described by Chaves et al. (2022) (Equations 2, 3 and 4):

$$IA = IA_c + IA_{co} \quad (2)$$

$$IA_c = AYL_c + P_c \quad (3)$$

$$IA_{co} = AYL_{co} + P_c \quad (4)$$

where IA is the intercropping advantage; IA_c is the intercropping advantage of carrot with cowpea; IA_{co} is the intercropping advantage of cowpea with carrot; AYL_c and AYL_{co} describe the actual yield loss index; P_c is the price of carrot roots in BRL kg^{-1} ; and P_{co} is the price of cowpea green grains in BRL kg^{-1} .

PEI was estimated in each treatment utilizing the Data Envelopment Analysis model with constant returns to scale since there was not any evidence of significant differences in scale. The Data Envelopment Analysis model was derived as follows (Equations 5, 6 and 7):

$$MAX_z = \sum_{j=1}^r \mu_j x_{jo} \quad (5)$$

subject to restrictions:

$$\sum_{i=1}^s v_i w_{io} = 1 \quad (6)$$

$$\sum_{j=1}^r \mu_j x_{jk} - \sum_{i=1}^s v_i w_{ik} \leq 0 \quad (7)$$

$$k = 1 \dots n; \mu_j, v_i \geq 0, i = 1 \dots s, j = 1 \dots r,$$

where MAX_z means the maximum measure of z efficiency of the treatment; X_{jo} represents the value of resource j in the plot under analysis; X_{jk} is the value of product j in plot k ; r is the product value; S is the resource value; n is the number of plots; w_{ik} is input value i ($i = 1 \dots s$) for treatment k ($k = 1 \dots n$); v_i and μ_j are weights set up to inputs and outputs, respectively; and o is the treatment under analysis (SILVA et al., 2024). In measuring the efficiency of each treatment, unitary inputs were assumed for all units.

The 16 treatments were used as evaluation units. The productivity of commercial carrot roots and cowpea green grains were used as outputs. To evaluate the performance of each intercropping treatment, each one was considered a single resource at a unitary level since the outputs incorporated the possible inputs. The closer the PEI value to 1, the more advantageous the intercropping treatment in terms of production.

The efficiency of the intercropping system was assessed by agronomic index Z (score of the canonical variable), obtained through bivariate analysis of variance (ANDRADE FILHO et al., 2020) of the productivity of cowpea green grains and commercial carrot roots. The higher and more positive the Z value, the more agronomically efficient the assessed intercropping system. The competition indexes assessed in the intercropping treatments were the cultures' A , CR , and AYL .

The A index indicates how much the relative production increase in the r culture (carrot, in this case) is greater than that of the l culture (cowpea) in the intercropping treatment. This index was calculated as described by Jiao et

al. (2024) (Equations 8 and 9).

$$A_c = \left(\frac{Y_{cco}}{Y_c Z_{cco}} \right) - \left(\frac{Y_{coc}}{Y_{co} Z_{coc}} \right) \quad (8)$$

$$A_{co} = \left(\frac{Y_{coc}}{Y_{co} Z_{coc}} \right) - \left(\frac{Y_{cco}}{Y_c Z_{cco}} \right) \quad (9)$$

where A_c and A_{co} are aggressivity of intercropped carrot and cowpea, respectively; Y_{cco} is the commercial productivity of carrot roots intercropped with cowpea; Y_c is the commercial productivity of monocropped carrot roots; Z_{cco} is the proportion of the area planted with carrot that was intercropped with cowpea; Y_{coc} is the productivity of cowpea green grains when intercropped with carrot; Y_{co} is the productivity of monocropped cowpea green grains; and Z_{coc} is the proportion of the area planted with cowpea that was intercropped with carrot. If A is positive, the culture is formulated as a dominant one, and that with a negative value is formulated as the dominated culture. If A has a value of zero, then both cultures are equally competitive.

CR of the intercrop was determined as described by Cecílio Filho et al. (2022) (Equations 10, 11 and 12), as follows:

$$CR = CR_c + CR_{co} \quad (10)$$

$$CR_c = \left[\left(\frac{LER_c}{LER_{co}} \right) \times \left(\frac{Z_{coc}}{Z_{cco}} \right) \right] \quad (11)$$

$$CR_{co} = \left[\left(\frac{LER_{co}}{LER_c} \right) + \left(\frac{Z_{coc}}{Z_{cco}} \right) \right] \quad (12)$$

where CR_c is the competitive ratio of carrot intercropped with cowpea; CR_{co} is the competitive ratio of cowpea intercropped with carrot; LER_c is the land equivalent ratio of carrot; and LER_{co} is the land equivalent ratio of cowpea. Terms Z_{coc} and Z_{cco} were calculated previously.

According to the same author, CR represents the number of times the dominant culture was more competitive than that dominated. The crop with a higher CR has better resource utilization.

AYL of the intercrop was assessed through the formulation described by Silva et al. (2021b) (Equations 13, 14 and 15).

$$AYL = AYL_c + AYL_{co} \quad (13)$$

$$AYL_c = \left[\left\{ \left(\frac{Y_{cco}}{Z_{cco}} \right) \div \left(\frac{Y_c}{Z_c} \right) \right\} - 1 \right] \quad (14)$$

$$AYL_{co} = \left[\left\{ \left(\frac{Y_{coc}}{Z_{coc}} \right) \div \left(\frac{Y_{co}}{Z_{co}} \right) \right\} - 1 \right] \quad (15)$$

where AYL_c is the actual yield loss of carrot; AYL_{co} is the actual yield loss of cowpea; Y_{cco} is the productivity of commercial carrot roots intercropped with cowpea; Z_{cco} is the proportion of carrot intercropped with cowpea; Y_c is the productivity of commercial carrot roots in the monocropping system; Z_c is the proportion of monocropped carrot; Y_{coc} is the productivity of cowpea intercropped with carrot; Z_{coc} is the proportion of cowpea intercropped with carrot; Y_{co} is the

productivity of monocropped cowpea; and Z_{co} is the proportion of monocropped cowpea. If AYL is greater than zero, intercropping has an advantage over monocropping; if AYL is less than zero, intercropping has a disadvantage.

The following economic efficiency indicators were assessed in the intercrops: GI, NI, RR, and PM. GI was estimated through the product of agricultural production and the price paid to the producer in the regional market in 2022 and 2023. The average prices paid were 11.00 BRL kg⁻¹ for cowpea green grains and 6.35 BRL kg⁻¹ for carrot roots. This indicator does not consider the total costs (TC) of production of the products involved. The TC of intercropping was obtained as the total expenditure per hectare with the services provided by stable capital, input prices, and the value of the alternative costs, as described by Lino et al. (2023).

NI was determined by subtracting the TC of intercropping per hectare from GI. RR was determined as the ratio between GI and TC, corresponding to the value in BRL obtained for each BRL invested in the application of the carrot-cowpea intercropping treatment. PM was calculated as the ratio between NI and GI, expressed as a percentage.

Univariate analysis of variance was carried out on the

indices and indicators under study. Homogeneity of variance was determined between the years of cultivation. Therefore, the average between these years was calculated for each treatment. Regression analysis was carried out for each index and indicator, and a response surface was fitted as a function of balanced biomass amounts of *M. aegyptia* and *C. procera* and population densities of cowpea using Table Curve 3D software (SYSTAT SOFTWARE, 2021).

RESULTS AND DISCUSSION

Table 3 presents the results of univariate analysis of variance and regression of the agro-biological and competition indices evaluated in carrot-cowpea intercropping with different balanced biomass amounts of *M. aegyptia* and *C. procera* and different cowpea population densities. No significant interaction was observed in the agronomic and competition indexes, namely LER, IA, PEI, A_c , A_{co} , CR, and AYL, among the tested treatments in the cowpea-carrot intercropping systems (Table 3).

Table 3. F values for land equivalent ratio (LER), intercropping advantage (IA), actual yield loss (AYL), productive efficiency index (PEI), Z canonical variable score, aggressivity of carrot over cowpea (A_c), aggressivity of cowpea over carrot (A_{co}), competitive ratio (CR), and regressions of these indexes in cowpea-carrot intercropping with different balanced biomass amounts of *Merremia aegyptia* and *Calotropis procera* and different cowpea planting densities.

Sources of variation	DF	Agronomic indexes				Competition indexes			
		LER	IA	PEI	Z	A_c	A_{co}	CR	AYL
Blocks	3	3.19*	4.01*	3.05 ^{ns}	2.66 ^{ns}	0.34 ^{ns}	0.34 ^{ns}	1.73 ^{ns}	3.75*
Amounts of <i>M. aegyptia</i> and <i>C. procera</i> biomass (A)	3	3.04*	3.62*	28.44**	2.40 ^{ns}	7.45**	7.45**	8.37**	2.62 ^{ns}
Cowpea population densities (D)	3	2.69 ^{ns}	2.11 ^{ns}	2.46 ^{ns}	3.65*	2.31 ^{ns}	2.31 ^{ns}	5.10**	3.51*
A × D	9	0.22 ^{ns}	0.30 ^{ns}	0.76 ^{ns}	0.57 ^{ns}	0.13 ^{ns}	0.13 ^{ns}	1.51 ^{ns}	0.35 ^{ns}
Regression		8.50*	9.52**	36.84**	8.53*	27.42**	29.27**	16.51**	8.82**
Error	45	0.0082	2.3609	0.0017	0.0301	0.0171	0.0171	0.0046	0.0322
CV (%)		5.11	13.05	4.67	6.30	25.27	-25.27	3.26	11.81

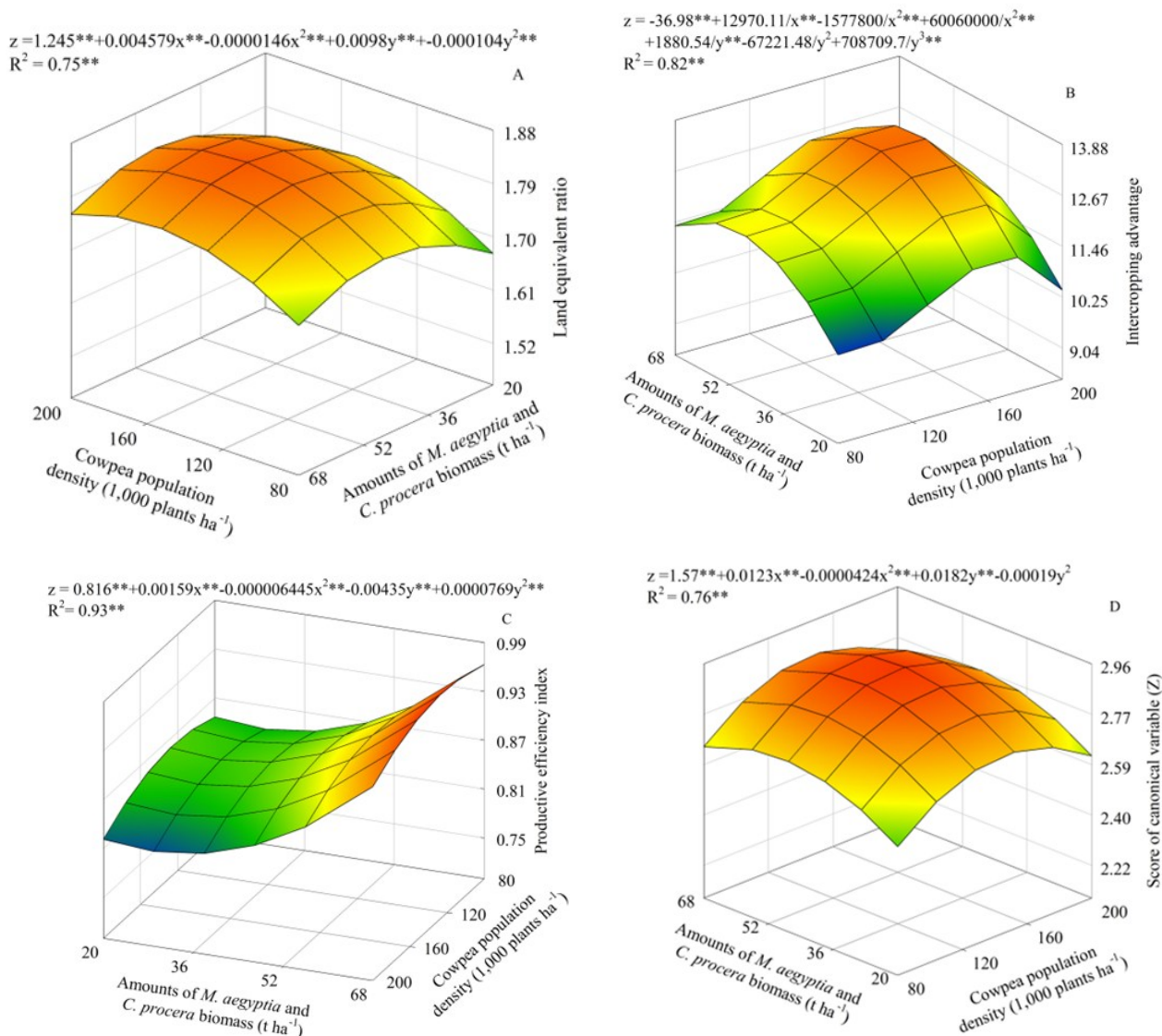
** – $p < 0.01$; * – $p < 0.05$; ns – $p > 0.05$; CV – coefficient of variation; DF – degrees of freedom.

A response surface was adapted to the studied agronomic and competition indices as a function of treatments, *M. aegyptia* and *C. procera* amounts, and cowpea population density when intercropped with carrot. For the agronomic indices, the highest values obtained for LER, IA, PEI, and Z were 1.83, 13.57, 0.97, and 2.90 when of 47.12, 47.88, 68.00, and 48.62 t ha⁻¹ of green manure was incorporated into the soil with cowpea population densities of 156, 152, 124, and 145 thousand plants ha⁻¹, respectively (Figures 1A, 1B, 1C and 1D). These results are attributed to the utilization of green manure by the crops and the low competition between carrot and cowpea, even with the increase in population density.

One of the challenges in intercropping a tuberous vegetable, such as carrot, with a legume, such as cowpea, is determining whether there is an agronomic-biological benefit in the intercropping system. The maximum values obtained for LER (1.83), IA (13.57), PEI (0.97), and Z (2.90) show that the assessed intercropping of carrot and cowpea was

beneficial. These benefits were determined by the degree of complementarity between the crops in the use of environmental resources (GUERRA et al., 2022) and these advantages can be converted into profit for the producer.

Since LER was greater than 1, intercropping favored the development, growth, and productivity of the crops in the system, providing an advantage to the intercrop. The higher the value above 1, the more advantageous the intercropped system. The higher and more positive the IA and Z indices, the more agronomically advantageous the intercrops (SILVA et al., 2021b). In addition to indicating the agronomic advantage, IA can also be considered an economic feasibility indicator of the intercropping system (VÁLYI-NAGY et al., 2024). The results obtained for these indices showed that all intercrops were beneficial. However, the closer PEI (0.97) is to 1, the more agronomically advantageous the evaluated intercropping system (SILVA et al., 2024). From the results obtained, all evaluated intercropping systems were advantageous.



*, ** – Significant at $p \leq 0.05$ and $p \leq 0.01$ according to the F-test

Figure 1. Land equivalent ratio (LER) (A), intercropping advantage (IA) (B), productive efficiency index (PEI) (C), and Z canonical variable score of carrot intercropped with cowpea when different balanced biomass amounts of *Merromia aegyptia* and *Calotropis procera* were applied with different cowpea planting densities.

These agronomic indexes confirm that organic fertilization with *M. aegyptia* and *C. procera* bettered the chemical properties of the soil and contributed to the higher yield of the intercrops regardless of the population density of component cultures. This was confirmed by the soil chemical analyses, which indicated that the soil had low fertility, and organic fertilizer addition increased the intercrop yields, as shown by the indexes and indicators (SILVA et al., 2024).

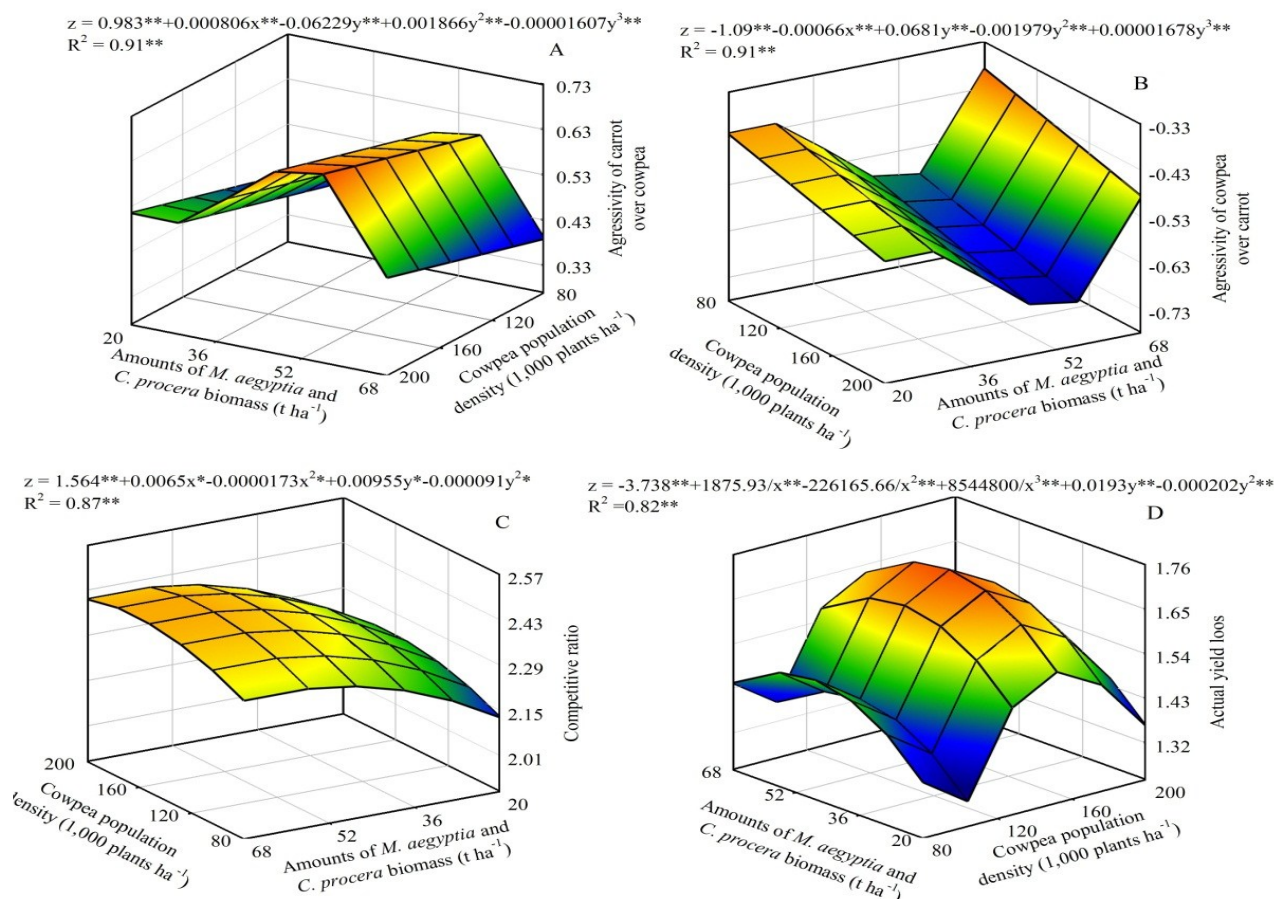
Moreover, it is also known that organic fertilization has some benefits for the soil, such as increased penetration and water retention, improved structure, aeration, and porosity, increased microbial populations, and increased nutrient availability and absorption to fit culture demand (XING et al., 2025). The maximum agronomic efficiency indicated by these indexes enable carrot and cowpea producers to choose the ideal quantity of green manure for incorporation at the ideal planting density of the component crop based on the agronomic indicator that best suits them in

terms of agronomic yield of the intercrop (CHAVES et al., 2022).

When investigating the production and benefits of carrot–cowpea intercropping under different amounts of *M. aegyptia* biomass and different spatial arrangements, Silva et al. (2020) observed that the best results in terms of agronomic efficiency of the crops were achieved with the incorporation of 32.69 and 50.17 t ha⁻¹ of *M. aegyptia* biomass, respectively. Similarly, when evaluating the agronomic effectiveness of cowpea–radish intercropping under different amounts of *C. procera* and with different planting arrangements, Nunes et al. (2021) recorded higher agronomic efficiencies when incorporating 62 t ha⁻¹ of *C. procera* biomass into the soil. In both studies, the use of green manure improved the soil conditions and increased the physiological performance of the associated crops, highlighting the role of organic matter in promoting sustainability and productivity in intercropping systems.

Regarding the competition indices between crops that make up the intercropping system, A_c increased with the amount of green manure applied and with the increase in the

cowpea population density, reaching a maximum value of 0.69 in the combination with 53.08 t ha⁻¹ of the green manure and 200 thousand cowpea plants ha⁻¹ (Figure 2A).



** – Significant at $p \leq 0.05$ and $p \leq 0.01$ according to the F-test

Figure 2. Aggressivity of carrot over cowpea (A_c) (A), aggressivity of cowpea over carrot (A_{co}) (B), competitive ratio (CR) (C), and actual yield loss (AYL) (D) of carrot intercropped with cowpea at different balanced biomass amounts of *Merremia aegyptia* and *Calotropis procera* and different cowpea planting densities.

The positive A_c under intercropping indicates that the tuberous crop was dominant, and cowpea was the dominated crop in the system. In other words, carrots were the most competitive crop, as the amount of the green manure and cowpea planting density increased up to the highest value. This behavior can be attributed to factors related to the morphology, physiology, and nutritional needs of the crops (MAITRA et al., 2021). The competitiveness of a crop is proportional to the population density in the planted area (LI et al., 2025). Thus, with the increase in the cowpea population density and the increase in the amount of green manure, the competitive capacity of carrot increased and that of cowpea decreased.

A_{co} increased with increasing amounts of green manure and the decreasing cowpea population density, reaching a maximum value of -0.39 in the combination with 68 t ha⁻¹ of green manure incorporated into the soil and 80,000 cowpea

plants ha⁻¹. The negative value of cowpea aggressivity over carrot indicate that this legume is the dominated crop, as the green manure amount increased and the cowpea population density decreased. These results indicate that cowpea has a lower interspecific competition capacity than carrot, regardless of the number of plants in the area. In general, the planting density and relative proportion of component crops are essential for determining the efficiency of intercropping. According to Zheng et al. (2021), differences in plant architecture, especially of root crops, determine how they access and utilize soil nutrients.

The competition indexes, CR and AYL, as observed herein, showed an ascending polynomial behavior as a function of the increase in the treatment-factors, that is, they increased with the increase in the amount of green manure applied and the increase in the cowpea population density, reaching maximum values of 2.43 for CR and 1.71 for AYL

with balanced biomass amounts of *M. aegyptia* and *C. procera* of 52.48 and 47.93 t ha⁻¹ and cowpea population densities of 188 and 150 thousand plants ha⁻¹, respectively (Figures 2C and 2D).

CR and AYL were greater than 1, resulting from the increase in the amount of green manure and cowpea population density, which positively influenced the intra- and interspecific competition of carrot and cowpea cultures due to the better use of environmental resources, providing a more advantageous intercropping system compared to monocropping. CR indicates the degree of competition by determining the number of times the dominant species is more competitive than the dominated species (MAITRA et al., 2021). CR and AYL values provide information on the intra- and interspecific competition between companion crops in intercropping systems (CHAVES et al., 2022). Thus, the

values obtained for these competitive relationships show the ability to use resources more efficiently (SILVA et al., 2024).

Superior result 1 reinforces the complementarity between the component crops, showing that they overcame both intra- and interspecific competition, having advantages for the intercropping system compared to monocropping. From these indexes, the appropriate degree of competitiveness was determined between the species, indicating the number of times that the dominant species was more efficient than the dominated species in using the available environmental resources.

For economic indicators GI, RL, TR, and PM, no significant interactions were observed among the balanced biomass amounts of *M. aegyptia* and *C. procera* and the cowpea planting density (Table 4).

Table 4. F values for gross income (GI), net income (NI), rate of return (RR), and profit margin (PM) of carrot intercropped with cowpea and regressions of these indicators in cowpea-carrot intercropping under different balanced biomass amounts of *Merromia aegyptia* and *Calotropis procera* and different cowpea planting densities.

Sources of variation	DF	GI	NI	RR	PM
Blocks	3	5.02**	2.90*	0.96*	4.91**
Amounts of <i>M. aegyptia</i> and <i>C. procera</i> biomass (A)	3	2.01 ^{ns}	8.69**	74.08**	233.1**
Coriander population densities (D)	3	5.72**	9.20**	3.21*	6.48**
A x D	9	0.13 ^{ns}	0.58 ^{ns}	0.68 ^{ns}	1.03 ^{ns}
Regression		19.72**	15.23**	83.18**	271.24**
Error	45	60625124	33929724	0.12882264	0.8115866
CV (%)		4.98	4.50	6.15	1.09

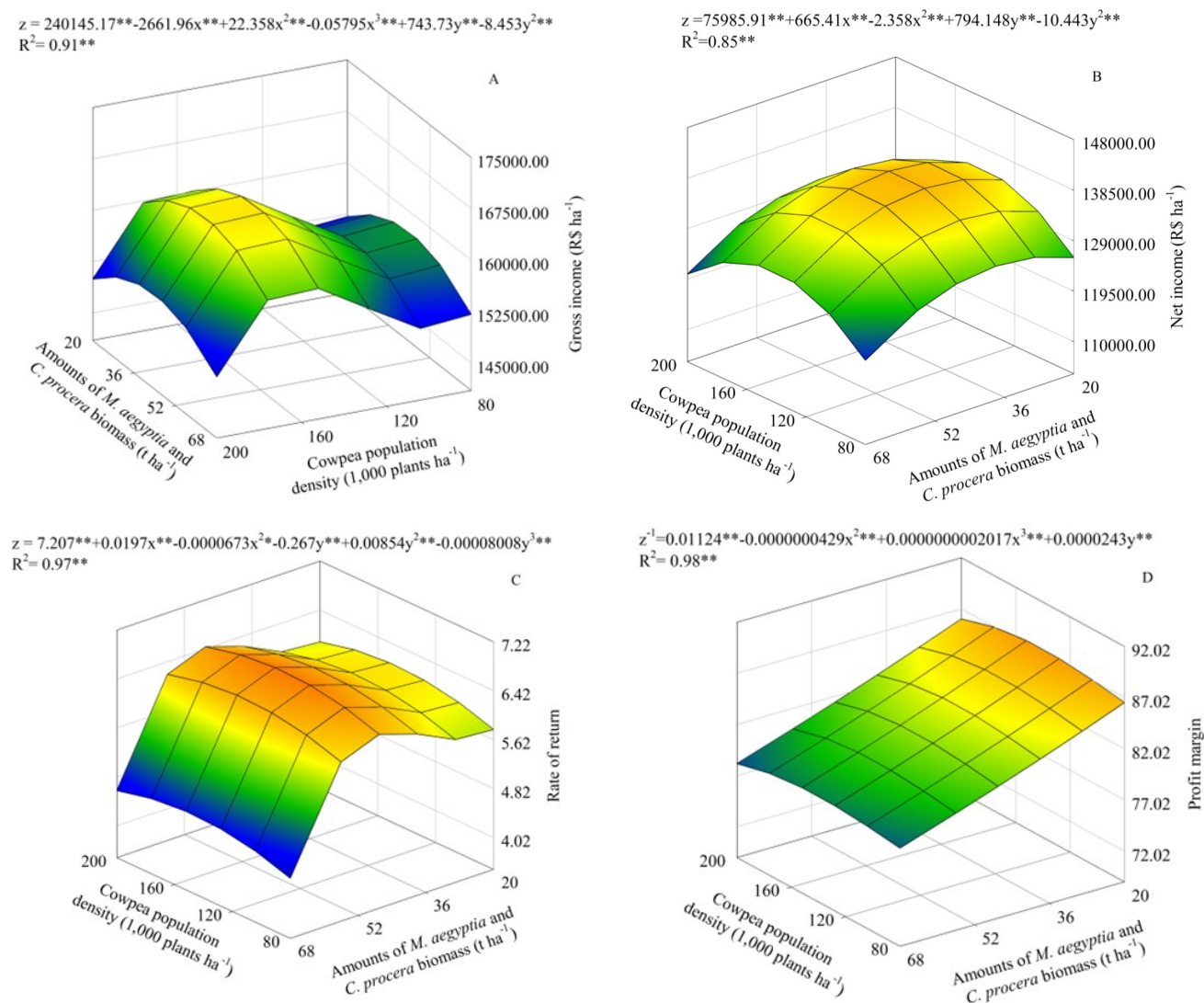
** – $p < 0.01$; * – $p < 0.05$; ns – $p > 0.05$; CV – coefficient of variation; DF – degree of freedom.

The response surface was adjusted for each economic indicator as a function of the treatment-factors, balanced biomass amounts of *M. aegyptia* and *C. procera*, and cowpea population density, presenting a maximum GI and NI values of 165,657.79 and 138,016.67 BRL ha⁻¹ obtained in the combination of 43.99 and 38.02 t ha⁻¹ of green manure biomass at population densities of 164 and 141 thousand cowpea plants ha⁻¹, respectively (Figures 3A and 3B). The highest RR and PM indicators were 6.64 BRL for each real invested and 87.42% profit when equitable amounts of 42.56 and 20 t ha⁻¹ of green manure were added to the soil at cowpea population densities of 165 and 142 thousand plants ha⁻¹, respectively (Figures 3C and 4D).

In this study, GI, NI, RR, and PM increased with the amount of the green manure and cowpea planting density. This harmony in behavior is likely due to the TC of each treatment. Economic analyses in intercropping systems aims to complement the assessment of agronomic and competition indices since, in addition to the physical production of the crops that make up the intercropping system, it considers the price of the products based on their commercial classification,

quality, and cropping season (CHAVES et al., 2022). It is an important tool for producers of tuberous vegetables (such as carrot) and legumes (such as cowpea) to consider when implementing and evaluating their intercropping systems (SILVA et al., 2025). The economic indicators, NI, RR, and PM are of capital importance in the assessment of intercropping systems since they depend on the TC, that is, they are standardized and estimated in terms of TC (NUNES et al., 2021). The higher their values, the greater the agro-bioeconomic benefits of the assessed intercropping system.

Based on the results obtained in this study, the evaluated economic indicators show that intercropping the tuberous vegetable carrot and the legume cowpea and fertilizing with the spontaneous species of the Caatinga biome *M. aegyptia* and *C. procera* at an adequate cowpea crop density is promising for the semiarid region, as it converts agro-biological benefits into economic efficiency. Thus, this intercropping system is an efficient and highly economical production system, increasing the production per unit area and improving the environmental resource use efficiency (BEZERRA NETO et al., 2023; SILVA et al., 2025).



*, ** - Significant at $p \leq 0.05$ and $p \leq 0.01$ by the F-test

Figure 3. Gross income GI (A), net income NI (B), rate of return RR (C), and profit margin PM (D) of carrot intercropped with cowpea at different balanced biomass amounts of *Merromia aegyptia* and *Calotropis procera* and different cowpea planting densities.

CONCLUSIONS

Intercropping cowpea and carrot and fertilizing with *M. aegyptia* and *C. procera* is highly viable under semi-arid conditions, showing a high agronomic efficiency (LER > 1 and positive Z values) and economic return. Carrot was the dominant crop.

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