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Original Article

Agro-bioeconomic feasibility in beet and cowpea strip-intercropping under green manuring and cowpea population density[1]

Viabilidade agrobioeconômica em consórcio de beterraba × feijão-caupi em faixas sob adubação verde e densidade do feijão-caupi

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HIGHLIGHTS:

The 49.96 t ha^{-1} green manures amount at 142,000 plants ha^{-1} cowpea density provides higher beet-cowpea intercrop efficiency.
Beet was the dominant crop with positive aggressivity while cowpea dominated with negative values, regardless of factors.
Merremia aegyptia *and* Calotropis procera *as green manures prove a viable technology for beet-cowpea producers in semi-arid.*

ABSTRACT: Proper management of the types and quantities of green manures from the Caatinga biome and crop densities has been a prerequisite for the agroecological success of intercropping in the semi-arid region. Given this, the study goal was to assay the agro-bioeconomic viability of combining beet root with cowpea under different *M. aegyptia* and *C. procera* biomass equal amounts (20, 36, 52, and 68 t ha^{-1} dry weight) at various cowpea plant densities (80, 120, 160, and 200,000 plants ha^{-1}), combined with 500,000 plants per hectare of beet over two cultivation years. The experimental procedure of randomized complete blocks was used in the field experiments, in a 4x4 factorial array with four replications. The first factor comprised *M. aegyptia* and *C. procera* biomass in equal amounts, while the second comprised different cowpea population densities. In each block, two plots with beet and cowpea monocropping optimized by regional research were sown for obtaining the indices. The cowpea and beet intercropping showed high agro-bioeconomic viability when adequately fertilized with green manures biomass amounts of 65.00, 68.00, 49.96, and 49.46 t ha^{-1} at the cowpea density of 142,000 plants per hectare, respectively, yielding a land equivalent ratio of 1.27, a canonical variate score of 3.60, a net income of BRL 52,392.71 per hectare, and a rate of return of BRL 2.72 per real invested.

Key words: *Beta vulgaris*, *Vigna unguiculata*, *Merremia aegyptia*, *Calotropis procera*, associated-cropping revenues

RESUMO: O manejo adequado dos tipos e quantidades de adubos verdes do bioma Caatinga, bem como das densidades das culturas tem sido um pré-requisito para o sucesso agroecológico do consórcio na região semiárida. Diante disso, o propósito deste estudo foi avaliar a viabilidade agrobioeconômica da combinação de beterraba com feijão-caupi sob diferentes quantidades de biomassa equivalentes de *M. aegyptia* e *C. procera* (20, 36, 52 e 68 t ha^{-1} de peso seco) em várias densidades de plantas de feijão-caupi (80, 120, 160 e 200.000 plantas ha^{-1}), combinadas com 500.000 plantas por hectare de beterraba ao longo de dois anos de cultivo. Nos experimentos de campo, utilizou-se o procedimento experimental de blocos completos ao acaso, em disposição fatorial 4x4, com quatro repetições. O primeiro fator foi composto por quantidades iguais de biomassa de *M. aegyptia* e *C. procera*, enquanto o segundo fator consistiu em diferentes densidades populacionais de feijão-caupi. Em cada bloco, foram semeadas duas parcelas com monocultivos de beterraba e feijão-caupi otimizados por pesquisas na região para obtenção dos índices. O consórcio de feijão-caupi e beterraba apresentou alta viabilidade agrobioeconômica quando adequadamente fertilizado com quantidades de biomassa dos adubos verdes de 65,00, 68,00, 49,96 e 49,46 t ha^{-1} na densidade de feijão-caupi de 142.000 plantas por hectare, respectivamente, produzindo uma razão de equivalente de terra de 1,27, um escore da variável canônica de 3,60, uma renda líquida de R$ 52.392,71 por hectare e uma taxa de retorno de R$ 2,72 por real investido.

Palavras-chave: *Beta vulgaris*, *Vigna unguiculata*, *Merremia aegyptia*, *Calotropis procera*, receitas em culturas consorciadas

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Introduction

Beet and cowpea are two associable plants of economic, social, and nutritional value for family agriculture of the Brazilian semi-arid region (Chaves et al., 2020). When planted together or in intercropping, they increase production because cowpea, a legume, fixes nitrogen in the soil, enriching it and reducing the need for fertilizers. At the same time, beet has high nutritional and economic value. The cropping practice with these crops also improves the use of water and spatial resources, increasing soil efficiency and overall land productivity.

In this cropping system, there are still several challenges related to the success of intercropping beet with legume crop cowpea regarding the interactions between production factors, such as green manures types, green manures amounts, crop population densities, crop cultivars suitable for the cultivation system, spatial arrangements between crops, among others, that improve complementarity or even minimize intra- or interspecific competition, optimizing the productive potential of the crops present in the system. One such interaction that has not yet been studied in a semi-arid environment is between the types of green manures, their appropriate amounts, and crop population densities in the intercropping system of beet with cowpea.

The green manures successfully used in the cultivation of vegetables and food crops are hairy woodrose and rooster tree, spontaneous plants of Caatinga (Lino et al., 2021a; Sá et al., 2021). Some benefits of using these species include increased soil organic matter content, improved soil physical, chemical, and biological properties, improved nutrient concentration at the soil surface, increased soil effective cation retention capacity, improved microbial biomass activity, and root-knot nematode control, among others.

The hairy woodrose is a herbaceous plant with green and dry phytomass yield of 36 and 4 t ha^{-1}, with a high nitrogen content of 26.2 g kg^{-1} in dry matter and a C/N ratio of 18/1 (Linhares et al., 2012). The rooster tree, a shrubby species with a mean production of dry phytomass of 3 t ha^{-1} per cut (at 120 days), yielding 9 t ha^{-1} per year (EMPARN, 2004), with a nitrogen content of 18.4 g kg^{-1} in dry matter and a C/N ratio of 25/1 (Nunes et al., 2018).

Regarding the interaction between the treatment factors (green manure amounts and planting density), attempts have been made to intercrop beetroot with leafy crops, resulting in high yield and system economic efficiency. Guerra et al. (2022), evaluating the beet and lettuce intercrop under *M. aegyptia* and *C. procera* equal amounts in diverse lettuce populations, observed higher agro-economic returns in the blending of 65 t ha^{-1} of green manure biomass in the lettuce density of 300,000 plants per hectare.

In this context of the interaction of treatment-factors, the study objective was to assay the agro-bioeconomic viability of combining beetroot with the cowpea legume crop under different biomass equitable amounts of *M. aegyptia* and *C. procera* (20, 36, 52, and 68 t ha^{-1} dry weight) at various cowpea plant densities (80, 120, 160, and 200,000 plants ha^{-1}), combined with 500,000 plants per hectare of beet over two years of cultivation in a semi-arid environment.

Material and Methods

Two field experiments were performed; the first from September to December 2022 and the second from September to December 2023 in the Rafael Fernandes Experimental Farm of the Universidade Federal Rural do Semi-Árido (UFERSA). This farm is 20 km from Mossoró, RN, Brazil, at 5° 03' 37" S and 37° 23' 50" W, and at an altitude of 80 m.

The climate of the region is BShw – dry and hot, with two distinct seasons (Beck et al., 2018). The maximum temperatures averaged 35.1 and 36.3 °C, and the relative humidity was 72.2 and 70.9% during the research conduction in 2022 and 2023 (LABIMC, 2023). The average monthly values of maximum and minimum temperatures and average relative air humidity in each cultivation year of the beet × cowpea intercropping are displayed in Figure 1.

The soils in the different areas were classified as Ultisols (United States, 2014), corresponding to Red Argisols in the Brazilian Soil Classification System (EMBRAPA, 2018). Simple soil samples were withdrawals from each cultivation area in the 0-20 cm deep layer and homogenized to obtain a compounded sample. The results are displayed in Table 1.

The experimental procedure used in both experiments was a randomized complete block design, with treatments displayed in a factorial arrangement (4 × 4), with four replications. The first factor was composed of the biomass amounts of *M. aegyptia* and *C. procera* (20, 36, 52, and 68 t ha^{-1} dry weight), while the second factor was composed of cowpea populations (80, 120, 160, and 200 thousand plants ha^{-1}). In each block, two additional plots were established as monocultures of beet and cowpea. These plots were fertilized with 49.87 and 50.48 t ha^{-1} of green manure biomass from *hairy wood-rose* (*Merremia aegyptia*) and *rooster tree* (*Calotropis procera*), respectively, selected based on previous research in the region to optimize agro-bioeconomic performance (Lino et al., 2021a; Desravines et al., 2022).

The beet-cowpea intercropping was settled in alternating strips, where each crop occupied 50% of the area cultivated. In each experimental parcel, the alternating strips were composed of four rows of each crop, edged by two rows of cowpea on one side and two rows of beetroot on the other side. The total area of each parcel was 3.60 m² (3.00 × 1.20 m), and the useful area was 2.00 m² (2.00 × 1.00 m).

The beet spacing in the intercropped treatments was 0.25 × 0.04 m, in a planting density of 500 thousand plants ha^{-1}. Each useful area of the intercrop plot contained 100 beet plants. Cowpea spacings in the evaluated treatments were 0.25 × 0.10 m, 0.25 × 0.125 m, 0.25 × 0.166 m, and 0.25 × 0.25 m, providing plant populations of 80, 120, 160, and 200 thousand plants ha^{-1}, respectively (Table 2). The number of cowpea plants in the useful area in these evaluated spacings was 16, 24, 32, and 40, respectively.

The beet monocropping was settled in a total area of 1.44 m² (1.20 × 1.20 m), containing six rows, and a useful area of 0.80 m² (0.80 × 1.00 m), and containing four rows in the planting spacing of 0.20 × 0.10 m. On the other hand, cowpea monocropping was implemented in a total area of 3.60 m² (3.00 × 1.20 m), containing six rows, and a useful area of 2.00 m²

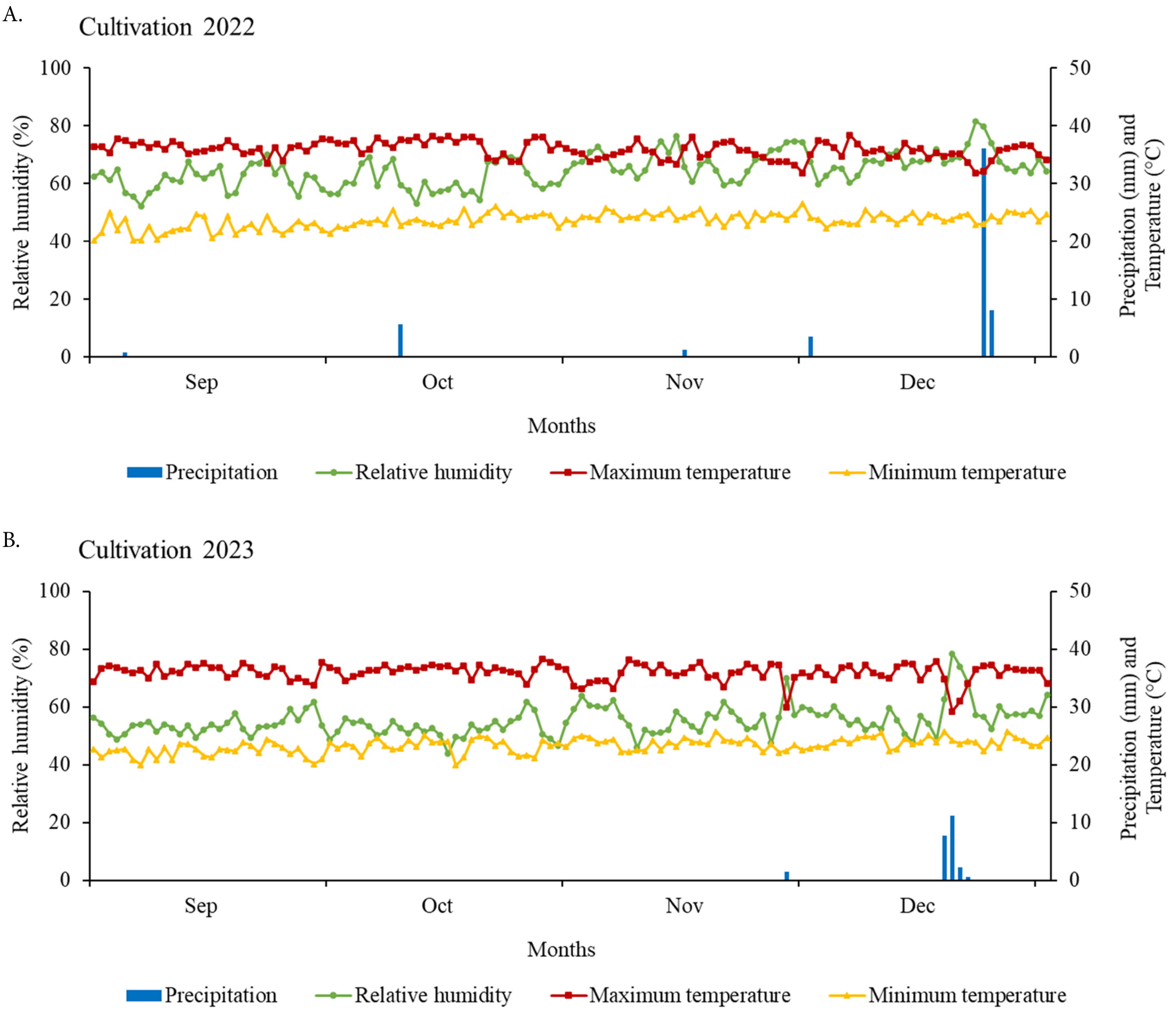


Figure 1. Average monthly climate data of maximum and minimum temperatures and relative humidity of air in each cultivation year of beet × cowpea intercropping

Table 1. Results of soil chemical analysis of the study area before incorporating green manures in the 2022 and 2023 crops

Attributes		Years of cultivation	
		2022	2023
pH	H_2O	7.40	5.80
EC	dS m^{-1}	0.34	0.41
OM	g kg^{-1}	7.84	13.25
K	$mmol_c$ dm^{-3}	1.35	1.77
Mg	$mmol_c$ dm^{-3}	5.90	2.70
Ca	$mmol_c$ dm^{-3}	3.28	8.40
Na	$mmol_c$ dm^{-3}	1.74	1.49
P	mg dm^{-3}	6.00	7.00
Cu	mg dm^{-3}	0.20	0.22
Fe	mg dm^{-3}	5.20	18.70
Mn	mg dm^{-3}	10.80	4.90
Zn	mg dm^{-3}	1.10	0.60
B	mg dm^{-3}	0.34	0.44

pH (H_2O) - Hydrogenionic potential; E.C. - Electrical conductivity; O.M. - Organic matter; K - Potassium; Mg^{2+} - Magnesium; Ca^{2+} - Calcium; Na - Sodium; P - Phosphorus; Cu - Copper; Fe - Iron; Mn - Manganese; Zn - Zinc; B - boron.

(2.00 × 1.00 m), containing four rows, at a spacing of 0.50 × 0.10 m. Crop harvesting in the intercropped and monocropping systems was performed in the four central rows, excluding the lateral rows and the first and last plants of each crop row, considered border plants.

Before installing the experiments, the soils in the research areas were mechanically cleaned using a tractor, where, later, a harrowing and formation of planting beds were carried out. Then, pre-planting solarization was performed on these beds using a 30-µm Vulca Brilho BrilFlex® plastic film for 30 days to control harmful soil microorganisms (Pereira et al., 2016).

After the solarization period, the green manure biomasses collected in rural areas were incorporated into the soil using hoes in two stages. In the first stage, 50% of the doses assessed in each experimental plot were incorporated. At 20 days after this first incorporation, the crops were planted, which took place in the first cultivation on October 11, 2022, and in the second cultivation on September 27, 2023, respectively. Twenty days after sowing (DAS), the second incorporation was performed with the remaining 50% of the green manure doses, through the grooves between the planting rows.

The cowpea cultivar sown was BRS Tumucumaque, and the beet cultivar was Early Wonder. Both were sown in holes

Table 2. Description of beet and cowpea populations used in the intercropped systems and monocropping, in the respective spacing

Populations of intercropped crops (thousand plants ha^{-1})		Spacings (m)	
Beetroot	Cowpea	Beetroot	Cowpea
500	80	0.25 × 0.04	0.25 × 0.250
500	120	0.25 × 0.04	0.25 × 0.166
500	160	0.25 × 0.04	0.25 × 0.125
500	200	0.25 × 0.04	0.25 × 0.100
Crop populations in monocrop (thousand plants ha^{-1})			
Beet	500	0.20 × 0.10	
Cowpea	200		0.50 × 0.10

3 cm deep, with 3 to 4 seeds per hole, capped with commercial substrate for germination. Thinning in cowpea and beetroot crops was executed seven and fourteen days after sowing. Only one plant per hole was left after thinning for both crops in the intercrop and monocrop systems.

The green manures, hairy woodrose and rooster tree, were collected in the rural area of Mossoró city, before flowering began. After collecting, they were crushed in a conventional forager to obtain 2 to 3 cm fragments, dried under ambient conditions until they reached 10% moisture, and then submitted to laboratory analyses.

The chemical attributes of green manures in the 2022 cultivation were for hairy woodrose: N = 18.98 g kg^{-1}, P = 2.65 g kg^{-1}, K = 34.6 g kg^{-1}, Mg = 5.18 g kg^{-1}, Ca = 18.43 g kg^{-1} and C:N = 25:1 and for rooster tree: N = 15.35 g kg^{-1}, P = 1.25 g kg^{-1}, K = 33.0 g kg^{-1}, Mg = 5.29 g kg^{-1}; Ca = 10.28 g kg^{-1} and C:N = 27:1. In the 2023 cultivation, the chemical attributes were for hairy woodrose: N = 18.56 g kg^{-1}, P = 2.58 g kg^{-1}, K = 32.8 g kg^{-1}, Mg = 4.48 g kg^{-1}; Ca = 17.88 g kg^{-1} and C:N = 24:1, and for rooster tree: N = 14.66 g kg^{-1}, P = 1.27 g kg^{-1}, K = 31, 0 g kg^{-1}, Mg = 5.4 g kg^{-1}; Ca = 11.6 g kg^{-1} and C:N = 28:1.

Manual weeding and hilling of the beet were conducted as required during the experimental period. Any pests and diseases in the crops were controlled using the bio-insecticide Azamax.

The experiments were irrigated using a micro-sprinkler system, with two irrigation shifts (morning and afternoon), with the water requirements of the main crop, beetroot, as a reference (Oliveira Neto et al., 2011). For each shift, half the predicted water depth was applied. The water volume was calculated based on the application rate of the emitters (64 L h^{-1}), spaced 2.0 m apart, installed in two hose rows positioned laterally in each bed, to ensure greater uniformity in distribution and maintenance of adequate moisture.

The beet was harvested at 65 DAS in the first cultivation, and at 69 DAS in the second. Cowpea harvests were carried out at 57 and 60 DAS, in the first cultivation, and in the second cultivation, harvests were carried out at 48, 51, and 56 DAS.

The crops characteristics assessed in the cropping systems were: commercial yield of beet roots (Y_b), estimated through fresh mass of roots in the useful area with a minimum size of 4 cm, free from deformations (Lino et al., 2021b), expressed in t ha^{-1} and the grain yield of cowpea (Y_c), estimated through fresh mass of all green grains harvested from green pods in the useful area, expressed in t ha^{-1} (Desravines et al., 2022).

The agro-bioeconomic efficiencies of the beet-cowpea intercropping systems were determined using agronomic and competition indices and economic indicators:

a) The land equivalent ratio (LER) (Eq. 1) was calculated by the expression:

$$\mathrm{LER} = \frac{Y_{bc}}{Y_b} + \frac{Y_{cb}}{Y_c} \tag{1}$$

where:

LER - land equivalent ratio;

Y_{bc} - yield of commercial beet roots intercropped with cowpea (t ha^{-1});

Y_{lr} - yield of cowpea green grains intercropped with beet (t ha^{-1});

Y_b - yield of commercial beet roots (t ha^{-1}) in monocropping; and,

Y_c - yield of cowpea green grains (t ha^{-1}) in monocropping.

This agronomic index represents the relative land area under sole cropping required to produce the yields obtained in intercropping. When the LER value is greater than 1, intercropping enhances the growth, development, and yield of the component crops. In contrast, when the LER is less than 1, intercropping negatively affects crop growth and yield performance.

b) The intercropping advantage (IA) was determined by Eq. 2 used by Lino et al. (2023):

$$\mathrm{IA} = \mathrm{IA}_b + \mathrm{IA}_c \tag{2}$$

where:

IA - intercropping advantage;

IA_b - intercropping advantage of beet with cowpea (Eq. 3);

IA_c - intercropping advantage of cowpea with beet (Eq. 4);

$$\mathrm{IA}_b = \mathrm{AYL}_b \times P_b \tag{3}$$

$$\mathrm{IA}_c = \mathrm{AYL}_c \times P_c \tag{4}$$

AYL_b and AYL_c - defined in the description of the actual yield loss (AYL);

P_b - price of beet roots in BRL kg^{-1}; and P_c - price of cowpea green grains in BRL kg^{-1}.

c) The productive efficiency index (PEI) (Eq. 5) was estimated for each treatment through the DEA (Data Envelopment Analysis) model with constant returns to scale. This model formulation is:

$$MAXz = \sum_{j=1}^{r} \mu_j x_{jo} \tag{5}$$

subject to restrictions:

$$\sum_{i=1}^{S} \upsilon_i w_{io} = 1$$

$$\sum_{j=1}^{r} \mu_j x_{jk} - \sum_{i=1}^{S} \upsilon_i w_{ik} \leq 0$$

$$k = 1, \ldots, n;\ \mu j, \nu i \geq 0;\ i = 1, \ldots, s;\ j = 1, \ldots r$$

where:

MAX z - maximum measure of z efficiency of the treatment;

X_{jo} - value of resource j for the plot under analysis 0;

X_{jk} - value of product j for plot k;

r - value of product;

S - value of resource;

n - number of plots; w_{ik} - input value i (i = 1 ... s), for treatment k (k = 1 ... n);

ν_i and μ_j - weights assigned to inputs and outputs, respectively; and,

o - treatment under analysis (Bezerra Neto et al., 2012; Silva et al., 2018).

To measure the efficiency of each experimental parcel (treatment), unitary inputs were assumed for all units.

The sixteen treatments were used as evaluation units. The yields of beet commercial roots and cowpea green grains were used as outputs. The performance of each plot was evaluated assuming a single resource utilized at a unit level, since the outputs already accounted for the corresponding inputs. The closer the PEI value is to 1, the more agronomically advantageous the intercropping system assessed is.

d) The efficiency of the intercropping system was also assessed by the agronomic index, score of the canonical variable (Z), obtained by multivariate analysis of variance (Andrade Filho et al., 2020) of the productivities of cowpea green grains and of the beet commercial roots. The higher and more positive the Z value, the more agronomically efficient the intercropping system evaluated.

The competition indices evaluated in the intercrops were: crop aggressivity (A_b and A_c), competitive ratio (CR), and actual yield loss of the system (AYL), Eqs 6, 7, 8, 9, 10, and 11, respectively.

e) The aggressivity (A) is an index that indicates how much of the relative increase in production of component crop b (beet in this case) (Eq. 6) is greater than that of component crop c (cowpea) (Eq. 7) in intercropping. This index was estimated by expressions used by Cecílio Filho et al. (2015).

$$A_b = \left(\frac{Y_{bc}}{Y_b Z_{bc}}\right) - \left(\frac{Y_{cb}}{Y_c Z_{cb}}\right) \tag{6}$$

$$A_c = \left(\frac{Y_{cb}}{Y_c Z_{cb}}\right) - \left(\frac{Y_{bc}}{Y_b Z_{bc}}\right) \tag{7}$$

where:

A_b and A_c - aggressivity of the beet and cowpea in intercropping;

Y_{bc} - commercial yield of beet roots (t ha^{-1}) intercropped with cowpea;

Y_b - commercial yield of beet roots (t ha^{-1}) in monocropping;

Z_{bc} - proportion of beet planted area intercropped with cowpea;

Y_{cb} - yield of cowpea green grains (t ha^{-1}) intercropped with beet;

Y_c - yield of cowpea green grains (t ha^{-1}) in monocropping; and,

Z_{cb} - proportion of the area planted with cowpea intercropped with beet.

If A is positive, the component crop with a positive sign is dominant, and the one with a negative sign is the dominated crop. If A is zero, then both crops are equally competitive.

f) The competitive ratio (CR) (Eq. 8) was also obtained through the formula used by Cecílio Filho et al. (2015), where:

$$CR = CR_b + CR_c \tag{8}$$

where:

CR_b - competitive ratio of the beet in intercropping with cowpea (Eq. 9);

CR_c - competitive ratio of the cowpea in intercropping with beet (Eq. 10);

LER_b - land equivalent ratio in beet; and,

LER_c - land equivalent ratio in cowpea. The terms Z_{cb} and Z_{bc} are defined earlier.

$$CR_b = \left[\left(\frac{LER_b}{LER_c} \times \frac{Z_{cb}}{Z_{bc}}\right)\right] \tag{9}$$

$$CR_c = \left[\left(\frac{LER_c}{LER_b} \times \frac{Z_{bc}}{Z_{cb}}\right)\right] \tag{10}$$

The competitive ratio indicates the number of times the dominant species is more competitive than the dominated species, revealing the exact degree of competition (Eskandari & Ghanbari, 2010). The crop with higher CR makes better use of environmental resources.

g) The actual yield loss (AYL) (Eq. 11) was determined by the expression used by Silva et al. (2021):

$$AYL = AYL_b + AYL_c \tag{11}$$

where:

AYL_b - actual yield loss of the beetroot (Eq. 12);

AYL_c - cowpea's actual yield loss (Eq. 13);

Y_{bc} - yield of commercial roots of beet (t ha^{-1}) intercropped with cowpea;

Z_{bc} - proportion of beet planting intercropped with cowpea;
Y_b - yield of beet commercial roots (t ha^{-1}) in monocropping;
Z_b - proportion of beet planting in monocropping;
Y_{cb} - yield of cowpea (t ha^{-1}) intercropped with beet;
Z_{cb} - planting proportion of cowpea intercropped with beet;
Y_c - yield of cowpea (t ha^{-1}) in monocropping; and,
Z_c - proportion of cowpea planting in monocropping.

$$AYL_b = \left\{ \left[\left(\frac{Y_{bc}}{Z_{bc}} \right) / \left(\frac{Y_b}{Z_b} \right) \right] - 1 \right\} \tag{12}$$

$$AYL_c = \left\{ \left[\left(\frac{Y_{cb}}{Z_{cb}} \right) / \left(\frac{Y_c}{Z_c} \right) \right] - 1 \right\} \tag{13}$$

If AYL > 0, it indicates an advantage of intercrop over monocrop; if AYL < 0, it indicates a disadvantage of the intercropped system.

The economic efficiency indicators assessed in the intercrops were: gross income (GI), net income (NI), rate of return (RR), and profit margin (PM). The GI was set by the product of agricultural yield per hectare and the price paid to the producer in the regional market in December 2023. The average prices were 13.00 BRL kg^{-1} for cowpea green grains and 3.25 BRL kg^{-1} for beet roots. This indicator does not consider the total costs (TC) of production of the products involved.

The total production costs of an intercrop, based on Cecílio Filho et al. (2010), are acquired through the total expenditure (total costs) per hectare with the crops that are part of the system at an experimental level, which includes the services provided by stable capital (depreciation, fixed labor and costs associated with working capital), input prices and the value of alternative costs (also called opportunity costs).

The NI was acquired by subtracting the total production costs (TC) of the system per hectare from the gross income (GI). The RR was acquired from the ratio between gross income (RB) and total costs (CT), i.e., RR = GI/CT, corresponding to the value in Reais (BRL) acquired for each Real (BRL) invested in the application of the beetroot and cowpea intercropping treatment. The PM was acquired from the ratio between net income (NI) and gross income (GI), expressed as a percentage.

Analyses of variance on all indices and indicators evaluated were executed through SAS software (SAS, 2002). Because the effects of years were not significant, an average was acquired between years for each treatment.

A regression analysis was executed on each index or indicator as a function of the equal biomass amounts of green manures incorporated into the soil and cowpea plant populations tested using the Table Curve 3D software, adjusting a response surface to these treatment factors' interaction. A discriminant function analysis or canonical variable analysis was performed, which consisted of finding a linear combination of p original variables (Y_i) as follows: $Z = E_1Y_1 + E_2Y_2 + ... + E_pY_p$. Then proceeded to the extraction of eigenvalues and autovectors of the matrix HE^{-1} (H = SSCP - Sum of Squares and Cross-Products matrix for Treatment; Error SSCP matrix), being the coefficients of the autovectors matrix the solution to the coefficients E_i with i = 1, 2, . . ., p of the linear combination in Z. After that, they were obtained the scores of the function $Z_1 = E_1Y_1 + E_2Y_2$ from the vector observation of each experimental unit, reducing to a single value.

Results and Discussion

It was registered in the score of the canonical variable Z that a significant interaction between biomass amounts of *M. aegyptia* and *C. procera* added to the soil and cowpea populations (Table 3). In contrast, for land equivalent ratio (LER), intercropping advantage (IA), productive efficiency index (PEI), aggressivity of the beet over cowpea (A_b), aggressivity of cowpea over beet (A_c), competitive ratio (CR) and actual yield loss (AYL) in the evaluated beet-cowpea intercrops were not observed significant interactions between these factors-treatments assessed (Table 3).

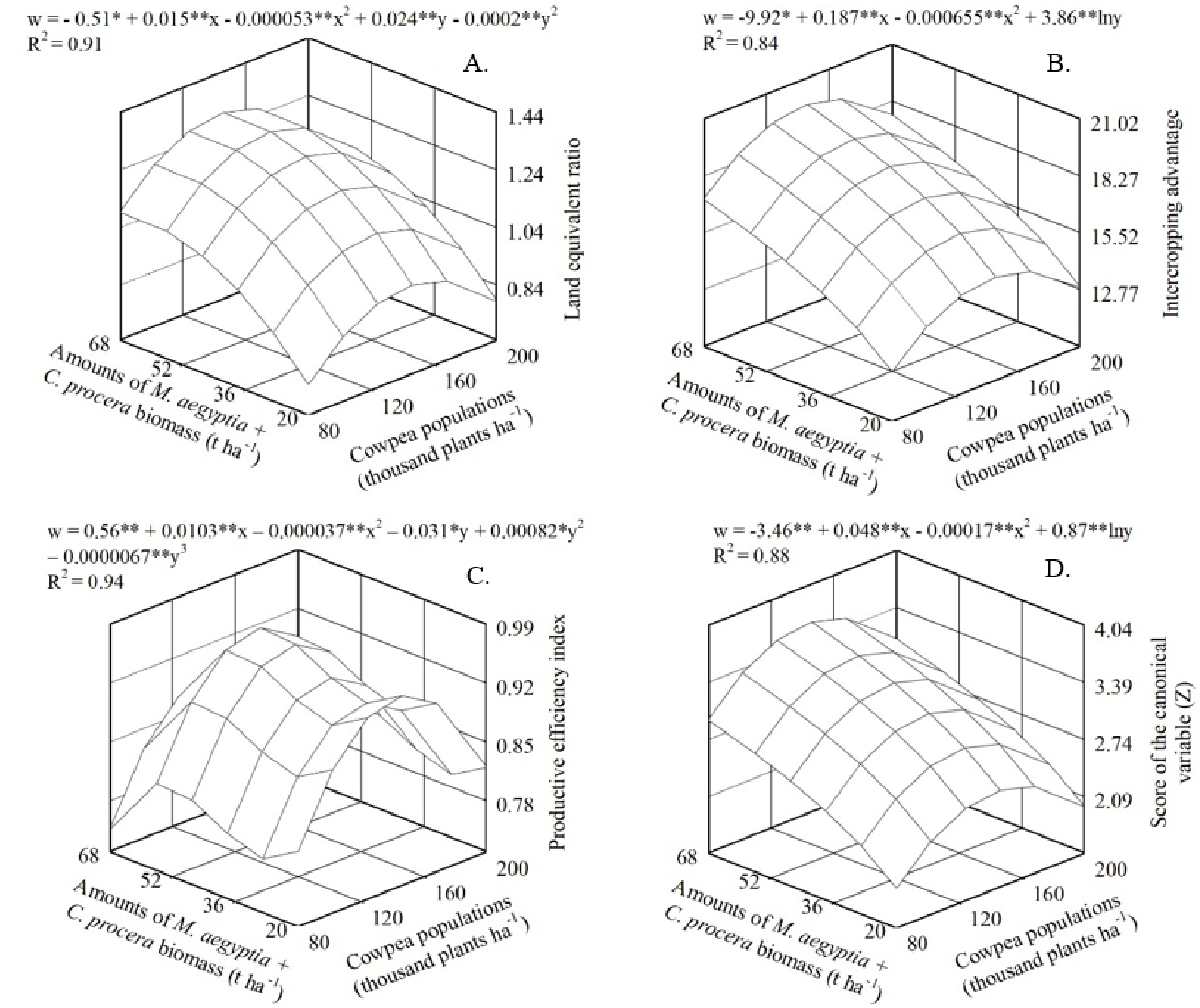
A response surface was fitted for the agronomic indices of the intercrops assessed as a function of the equal biomass amounts of *M. aegyptia* and *C. procera* and cowpea plant populations intercropped with beet. The values of these agronomic indices LER, IA, PEI, and Z increased with the increase of the treatment-factors (green manures and plant populations), reaching the maximum values of 1.27; 19.71; 0.94, and 3.60, respectively, in the combinations of 65 and 142; 68 and 142; 52.55 and 141, and 68 t ha^{-1} of the green manures added to the soil and cowpea populations of 142 thousand cowpea plants per hectare (Figures 2A, B, C, and D).

The obtained maximum values for LER (1.27), IA (19.71), PEI (0.94), and Z (3.60) reveal that the tested beet and cowpea intercropping systems were advantageous, determined by the complementarity in the utilization of environmental resources

Table 3. F-values for land equivalent ratio (LER), intercropping advantage (IA), productive efficiency index (PEI), score of the canonical variable (Z), aggressivity of beet over cowpea (A_b), aggressivity of cowpea over beet (A_c), competitive ratio (CR), and actual yield loss (AYL) of the beet-cowpea intercropping under biomass amounts of *M. aegyptia* and *C. procera* added to the soil and cowpea populations

Sources of variation	DF	LER	IA	PEI	Z	A_b	A_c	CR	AYL
Blocks	3	2.42^{ns}	1.06^{ns}	3.75*	5.20**	0.20^{ns}	0.20^{ns}	0.06^{ns}	2.42^{ns}
Biomass amounts (A)	3	22.74**	7.30**	37.26**	64.29**	5.85**	5.85**	0.16^{ns}	22.76**
Cowpea populations (D)	3	60.29**	20.45**	9.75**	154.33**	2.63^{ns}	2.63^{ns}	0.60^{ns}	60.36**
A × D	9	0.60^{ns}	0.30^{ns}	0.96^{ns}	2.62*	0.73^{ns}	0.73^{ns}	0.87^{ns}	0.60^{ns}
Regression (Response surface)	X	29.30**	20.26**	29.43**	30.60	12.38**	12.17**	7.28**	33.82**
Error	45	0.003494	112.354	0.00047	0.040658	0.001532	0.001535	0.000131	0.014430
CV (%)		7.82	11.91	6.39	5.61	61.84	-61.84	2.12	7.81

*, **, ns - Significant at p ≤ 0.05 and at p ≤ 0.01, and non-significant at p > 0.05 by F test; CV – Coefficient of variation; DF - Degree of freedom (X varies from 3 to 5, indicating a model with 4, 5, and 6 terms in combination, see Figures)



*, ** - Significant at p ≤ 0.05 and p ≤ 0.01 by the F-test

Figure 2. Land equivalent ratio – LER (A), intercropping advantage – IA (B), productive efficiency index – PEI (C), and score of the canonical variable – Z (D) of the beet intercropped with cowpea in the combinations of biomass of *M. aegyptia* and *C. procera* and cowpea populations

between cultures (Cecílio Filho et al., 2015), being able to convert these advantages in profits for the producer.

When the RET value is greater than 1, the intercrop favors the growth, development, and crop yield that compose the system, thus expressing an advantage to the association system. The higher the value above 1, the more advantageous the system is. For IA and Z, the higher and more positive these values are, the more agronomically advantageous the association systems are (Andrade Filho et al., 2020; Lino et al., 2023). In addition to indicating agronomic advantage, this IA value can also indicate the economic feasibleness of association systems (Dhima et al., 2007). The results of these indices reveal that all the evaluated associated systems were advantageous. Additionally, the closer this value is to 1 for PEI, the more agronomically advantageous the evaluated associated system is (Bezerra Neto et al., 2012). Given this, it can be concluded that all the evaluated associated systems were advantageous.

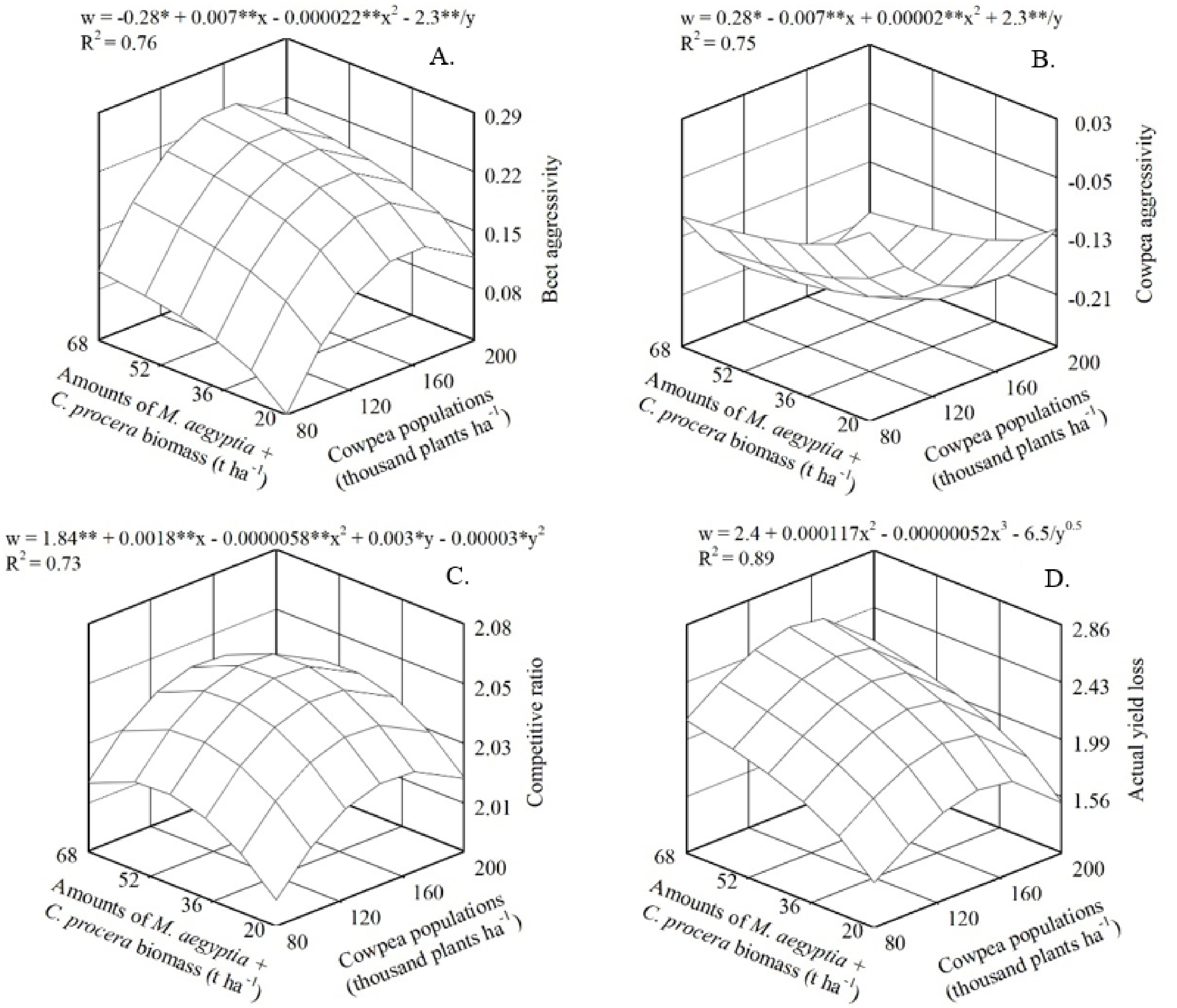
The advantages obtained from the evaluated associated systems confirmed that organic manuring based on *M. aegyptia* and *C. procera*, at an adequate secondary crop (cowpea) plant population, improved the soil chemical properties and contributed to higher productivities from the associated systems. According to Higashikawa et al. (2022), organic compounds can replace mineral fertilizers in onion cultivation.

Lanna et al. (2018) report that organic manuring brings some benefits to the soil, such as increased penetration and water retention; improved structure, aeration, and porosity; increased microbial life; and increased availability and absorption of nutrients to meet crop demand. The results obtained at the maximum agronomic efficiency of these indices enable beet and cowpea growers to determine the ideal amount of green manure to be incorporated, in combination with the most suitable planting density of the secondary crop, based on the agronomic indicator that best fits their conditions in terms of intercropping system yield.

Regarding crop competition indices, the aggressivity of beet over cowpea (Ac) increased with higher cowpea population densities and greater amounts of green manure applied to the soil, reaching a maximum value of 0.24 at the combination of 158,000 cowpea plants per hectare and 68 t ha^{-1} of green manure (Figure 3A).

The positive values of beet aggressivity over cowpea in the intercropping systems indicate that the tuberous crop was dominant and became more competitive as the cowpea population density and the amount of green manure increased to their maximum. Similar behavior of the associated system was registered by Sá et al. (2021), when associated radish with arugula at different doses of green manures at diverse leafy crop plant populations, where they registered positive values of the radish aggressivity over the leafy crop, indicating that this tuberous crop was the dominant crop in the system. This behavior can be associated with factors related to the species' morphology, physiology, and nutritional needs. Passos et al. (2019) report that crop competitiveness is proportional to the increase in the plant population in the planted area. Thus, with the increase in the cowpea population and the increase in the green manure amounts, it was verified that the competitive capacity of beetroot increased, and the cowpea crop decreased.

Moreover, the cowpea aggressivity over beet (A_c) increased with decreasing amounts of green manure applied and decreasing cowpea populations, meeting a maximum value of -0.04 in the combination of 20 t ha^{-1} of green manure added to the soil and 80,000 cowpea plants per hectare (Figure 3B). The negative values of the cowpea aggressivity over beet reveal that this legume is the dominated crop as the green manure amounts and the cowpea population increased. These results also reveal that cowpea has a lower capacity for interspecific competition than beet, regardless of the plant number in the area. Plant population and the relative proportion of component cultures are essential to determine the efficiency of associated systems. The difference in plant architecture, especially of root vegetable crops, determines how they access and utilize soil nutrients (Zhang et al., 2015).



*, ** - Significant at p ≤ 0.05 and p ≤ 0.01 by the F-test

Figure 3. Beet aggressivity over cowpea – A_b (A), cowpea aggressivity over beet – A_c (B), competitive ratio – CR (C), and actual yield loss – AYL (D) of the beet intercropped with cowpea in different combinations of equal biomass amounts of *M. aegyptia* and *C. procera* and cowpea populations

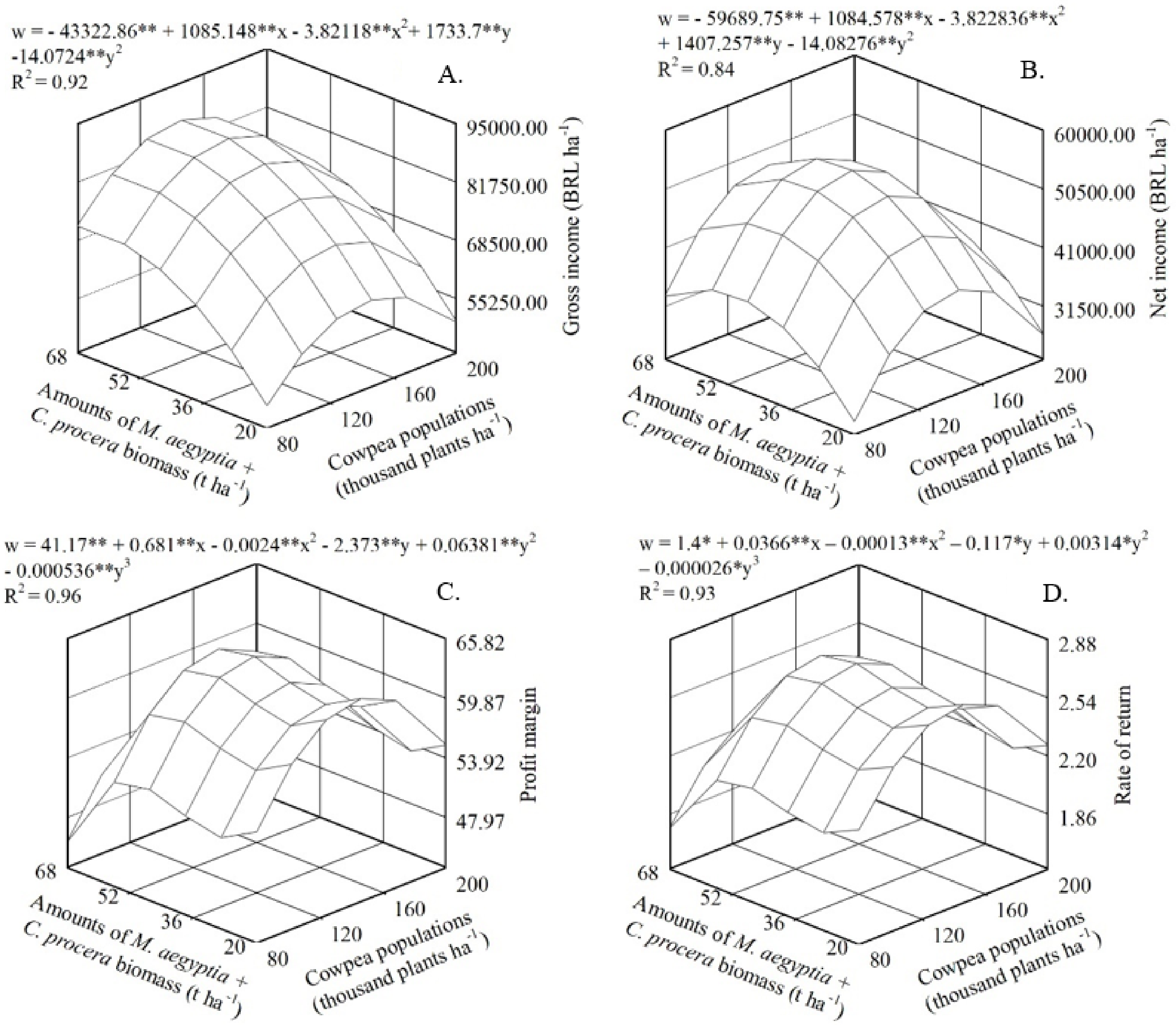
The competitive ratio (CR) and actual yield loss (AYL) of the tested associated systems increased with increasing of green manures amounts added and with increasing cowpea populations, getting to maximum values of 2.05 and 2.49 in the green manures amounts applied and cowpea densities of 50.22, and 68 t ha^{-1}, and 154 and 150 thousand plants per hectare, respectively (Figures 3C and D).

The CR and AYL values, which were much higher than 1, resulted from the increased amounts of green manure and higher cowpea population densities. These conditions positively affected intra- and interspecific competition between beet and cowpea by promoting better utilization of environmental resources, thus making intercropping more advantageous than monocropping. The CR gives the exact degree of competition by indicating the number of times the dominant species is more competitive than the dominated species (Eskandari & Ghanbari, 2010). Therefore, it is important to highlight that CR and AYL values provide accurate information about

Table 4. F-values for gross income (GI), net income (NI), rate of return (RR), and profit margin (PM) of the beet-cowpea intercropped systems under biomass amounts of *M. aegyptia* and *C. procera* added to the soil and cowpea populations

Sources of variation	DF	GI	NI	RR	PM
Blocks	3	4.05*	4.05*	4.07*	4.81**
Biomass amounts (A)	3	43.86**	43.84**	42.24**	39.38**
Cowpea populations (D)	3	111.39**	32.39**	30.97**	33.43**
A × D	9	1.33^{ns}	1.34^{ns}	1.57^{ns}	0.81^{ns}
Regression (Response surface)	X	33.412**	15.40**	27.15**	53.88**
Error	45	1548341	1555117	0.008865	1.6410785
CV (%)		6.13	10.90	6.43	2.85

*, **, ns - Significant at p ≤ 0.05 and at p ≤ 0.01, and non-significant (p > 0.05) by F test; CV – Coefficient of variation; DF – Degree of freedom (X varies from 4 to 5, indicating a model with 5 and 6 terms in combination, see Figures)



*, ** - Significant at p ≤ 0.05 and p ≤ 0.01 by the F-test

Figure 4. Gross income – GI (A), net income – NI (B), rate of return – RR (C), and profit margin – PM (D) of the beet intercropped with cowpea in different combinations of equal biomass amounts of *M. aegyptia* and *C. procera* and cowpea populations

competition between companion crops in the associated systems, both intra- and interspecific (Dhima et al., 2007). Therefore, the values obtained in the competitive relationships show the ability to utilize resources more efficiently, such as light, nutrients, and water (Nunes et al., 2018). Through CR and AYL indices, it is possible to get the appropriate degree of competitiveness between species, indicating the number of times the dominant species is more efficient in utilizing these available environmental resources than the dominated crop.

In the economic indicators, gross income (GI), net income (NI), rate of return (RR), and profit margin (PM) of the associated systems, there was no registered significant interaction between equal biomass amounts of *M. aegyptia* and *C. procera* added to the soil and cowpea populations (Table 4).

For economic indicators of the associated systems were adjusted as a function of the tested treatment-factors, equal biomass amounts of *M. aegyptia* and *C. procera* and cowpea plant populations associated with beet, where the maximum values of the GI, and NI of 87,115.24, and 52,392.71 BRL ha^{-1} were obtained in the combinations of equal biomass amounts of green manures added to the soil and cowpea population of 61.60 and 142 and of 49.96 t ha^{-1} of green manures and 142 thousand cowpea plants per hectare, respectively (Figures 4A and B).

For RR and PM, the maximum values, BRL 2.72 for each BRL invested and 63.36%, respectively, were obtained with the combinations of 49.63 t ha^{-1} of green manure and 142,000 cowpea plants per hectare (Figures 4C and 4D). Given this, it is observed that the values of GI, NI, RR, and PM increased with the increase in the green manure amounts and cowpea populations (Figure 4). This harmony in behavior is probably due to the total production costs of each treatment assessed.

Lino et al. (2021b), studying the intercrop of beetroot and arugula based on increasing equal biomass amounts of *M. aegyptia* and *C. procera* added to the soil and arugula populations, got maximum values for GI and NI of 85,827.79 and 65,425.01 BRL ha^{-1}, RR of BRL 4.24 for each BRL invested, and PM of 77.02%. The differences between this study and the work of Lino et al. (2021b) are mainly due to the type of secondary crop involved in the crop association (the leafy crop of arugula) and, consequently, also to the differences in the total production costs of the component crops that are part of the association systems.

The economic analysis of intercropping systems aims to complement the assessment of agronomic performance and competition indices, considering the physical production of the component crops and the market price of their products, which depends on commercial classification, quality, and growing season. It is a valuable tool for producers of tuberous vegetables (beetroot) with legumes (green cowpea) to consider when implementing and evaluating their intercropped systems. The economic indicators, net income, rate of return, and profit margin are of capital importance in the assessment of associated systems, since they depend on the total production costs, that is, they are standardized and estimated in terms of total costs. The higher their values, the greater the agro-bioeconomic benefits of the intercropping systems evaluated.

Conclusions

1. The cowpea and beet intercropping showed high agro-bioeconomic viability when adequately fertilized with biomass equitable amounts of *M. aegyptia* and *C. procera* of 65.00, 68.00, 49.96, and 49.46 t ha^{-1} (dry weight) at the cowpea density of 142,000 plants per hectare, respectively, yielding a land equivalent ratio of 1.27, a canonical variate score of 3.60, a net income of BRL 52,392.71 ha^{-1}, and a rate of return of BRL 2.72 per real invested.
2. The use of *M. aegyptia* and *C. procera* biomass from the Caatinga biome proved a viable technology for producers who practice intercropping of beet and cowpea in a semi-arid environment.
3. Beetroot was the dominant crop, presenting positive aggressivity values, regardless of the amounts of green manures assessed and cowpea densities used. In contrast, cowpea was the dominated crop, presenting negative aggressivity values, regardless of the levels of the tested treatments.
4. Opting for the intercropping system can provide family smallholders with viable alternatives to optimize the planted area, greater crop yield, and economic stability of activities.

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