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Agrobio-economic return in radish-coriander intercropping under green manuring and population densities

Retorno agrobioeconômico do consórcio rabanete-coentro sob adubação verde e densidades populacionais

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Highlights

Manuring with green manure increases efficiency in radish–coriander intercropping.
Crop density and green manure produce high returns in radish–coriander intercropping.
Hairy woodrose and roostertree adding into soil is a viable technique for producers.

Abstract

Radish and coriander are vegetables that complement each other when intercropped under organic fertilizer and the ideal density of the component crops. In view of this, this study aimed to evaluate the treatments, similar amounts of green manure and population densities of coriander in the biological parameters of the radish–coriander intercrop and determine the interaction between these treatments that provides the greatest economic return in a semi-arid environment. The experimental design used was randomized blocks, with treatments arranged in a 4 × 4 factorial scheme with four replications. The first factor consisted of *Merremia aegyptia* and *Calotropis procera* biomass amounts in the proportion of 50% for each green manure at doses of 20, 35, 50 and 65 t ha^{-1} on a dry basis. The second factor comprised four coriander population densities of 400, 600, 800 and 1000 thousand plants ha^{-1}. The

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radish and coriander cultivars planted were 'Crimson Gigante' and 'Verdão', respectively. Significant agro-biological returns from this radish-coriander intercrop were obtained at a land equivalent ratio of 2.00, intercropping advantage of 11.39, canonical variable Z score of 2.45, radish aggressivity over coriander of 1.04, and actual yield loss of 2.15 with the incorporation of 65 t ha^{-1} of hairy woodrose and roostertree into the soil using a coriander population density of 1 million plants ha^{-1}. The greatest economic return from radish–coriander intercropping (107,278.10 BRL ha^{-1}) was achieved with the application of 25.88 t ha^{-1} of green manure biomass to the soil and a coriander population density of 1 million plants ha^{-1}.
Key words: *Merremia aegyptia. Calotropis procera.* Tuberous and leafy vegetables. Agro-bioeconomic feasibility.

Resumo

Rabanete e o coentro são hortaliças que se complementam quando consorciadas com adubação orgânica e na densidade ideal das culturas componentes. Diante disso, este estudo teve como objetivo avaliar os tratamentos, quantidades semelhantes de adubos verdes e densidades populacionais de coentro nos parâmetros biológicos do consórcio rabanete-coentro e determinar a interação entre esses tratamentos que proporciona maior retorno econômico, em ambiente semiárido. O delineamento experimental utilizado foi blocos casualizados, com os tratamentos dispostos em esquema fatorial 4 × 4 com quatro repetições. O primeiro fator consistiu das quantidades de biomassa de *Merremia aegyptia* e *Calotropis procera* na proporção de 50% para cada adubo verde nas doses de 20, 35, 50 e 65 t ha^{-1} em base seca. O segundo fator compreendeu quatro densidades populacionais de coentro de 400, 600, 800 e 1000 mil plantas ha^{-1}. As cultivares de rabanete e coentro plantadas foram 'Crimson Gigante' e 'Verdão', respectivamente. Retornos agrobiológicos expressivos deste consórcio de rabanete-coentro foram obtidos com uma razão equivalente de terra (RET) de 2,00, vantagem de consórcio (VC) de 11,39, escore da variável canônica Z de 2,45, índice de superação do rabanete sobre o coentro (A_r) de 1,04 e, perda de rendimento real (PRR) de 2,15 com a incorporação ao solo de 65 t ha^{-1} de jitirana e flor-de-seda na densidade populacional de coentro de 1 milhão de plantas por hectare. Maior retorno econômico do consórcio rabanete-coentro de 107.278,10 R$ ha^{-1} foi alcançado com a aplicação ao solo de 25,88 t ha^{-1} de biomassa dos adubos verdes e densidade populacional de coentro de 1 milhão de plantas por hectare.
Palavras-chave: *Merremia aegyptia. Calotropis procera.* Hortaliças tuberosa e folhosa. Viabilidade agrobioeconômica.

Introduction

Intercropping of tuberous and leafy vegetables is growing in social importance in the Brazilian Northeast, mainly in agroecological terms, presenting several advantages in the productive, nutritional, economic and environmental aspects. With this practice, greater production per area is sought by combining plants that use space, nutrients and sunlight, in addition to the benefits that one plant brings to the other in controlling competing plants, pests and diseases (Andrade et al., 2020; Sá et al., 2021; Guerra et al., 2021). However, the biggest challenge in this vegetable production system lies in the way in which crops must be associated, especially with regard to managing the system and meeting the interests of producers.

Another requirement for the success of this cultivation practice in the region has been the correct use of the types and quantities of green fertilizers from the Caatinga biome and the planting densities of the component crops (Andrade et al., 2020). Among the types of fertilizers that stand out are green manure, hairy woodrose and roostertree, which are spontaneous species from the Caatinga biome (Lino et al., 2021a; Sá et al., 2021). Hairy woodrose is a herbaceous species with an average production of green and dry matter of around 36,000 and 4000 kg ha^{-1}, respectively, with a high nitrogen content, around 26.2 g kg^{-1} of dry matter, and a C/N ratio of 18/1 (Linhares et al., 2012). Roostertree is a shrubby species (Rangel & Nascimento, 2011) with an average phytomass production of around 3000 kg ha^{-1} per cut (120 days), reaching 9 t ha^{-1} per year on a dry basis (Empresa de Pesquisa Agropecuária do Rio Grande do Norte [EMPARN], 2004), a nitrogen content of around 18.4 g kg^{-1} in dry matter, and a C/N ratio of 25/1 (Nunes et al., 2018).

Some research attempts carried out with green manure from the Caatinga biome with combinations of tuberoses and hardwoods have demonstrated satisfactory productive and competitive efficiency and economic returns in some production systems, including intercropping of beetroot and lettuce (Guerra et al., 2022), arugula and beetroot (Lino et al., 2021b), lettuce and radish (Lino et al., 2023), and arugula and radish (Sá et al., 2021).

However, among the main challenges for obtaining an intercropping system with tuberose, radish and coriander with high yield and economic viability, with great social and economic importance for the semi-arid region, is the appropriate choice of types of fertilizers from the biome and obtaining the correct quantities to be used.

Therefore, the present study aimed to evaluate treatments with similar amounts of green manure (*M. aegyptia* and *C. procera*) and coriander population densities within the biological parameters of radish-coriander intercropping and determine the interaction between these treatments to provide a greater economic return in a semi-arid environment.

Materials and Methods

Field research was conducted from October to December 2021 and from September to November 2022 in the Lagoinha region, RN, (latitude 5° 03 ‘37 “S; longitude 37° 23 ‘50” W) at an approximate altitude of 80 m.

According to the Köppen classification, the region’s climate is ‘BShw’, that is, dry and very hot, with two distinct seasons: a dry one, which generally occurs from June to January, and a rainy one, from February to May (Beck et al., 2018). The average meteorological data recorded during the crop development and growth period are presented in Table 1 (Laboratório de Instrumentação Meteorologia e Climatologia [LABIMC], 2022).

Table 1
Average meteorological data during the development and growth period of radish intercropped with coriander in the 2021 and 2022 cropping seasons

Cropping seasons	Temperature (ºC)			Relative humidity (%)	Solar radiation (MJ m^{-2})	Wind speed (m s^{-1})
	Minimum	Mean	Maximum			
2021	23.32	29.90	36.48	67.60	274.80	2.80
2022	22.53	29.38	36.23	62.87	256.41	1.71

Source: Labimc (2022).

The soils in the experimental areas were classified as dystrophic red-yellow, with a sandy loam texture (Santos et al., 2018). Samples of these soils were analyzed, showing the following chemical attributes (Table 2).

Table 2
Chemical analyses of the soils in the areas where the experiments were implemented before incorporation of green manure in cropping seasons 2021 and 2022

Soils	C	O.M.	pH	EC	P	K	Ca	Mg	Na	Cu	Fe	Mn	Zn	B
	---- g kg^{-1}---		(H_2O)	dS m^{-1}	mg dm^{-3}		---------------------- $mmol_c$ dm^{-3} --------------------							
1	7.92	12.97	6.60	0.56	32.00	2.59	23.70	6.50	2.30	0.30	4.80	6.10	2.70	0.50
2	7.20	12.41	7.10	0.19	7.00	1.16	20.10	6.10	0.43	0.20	6.80	12.70	1.70	0.48

C: carbon; OM: organic matter; pH (H_2O): 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 experimental design used was randomized complete blocks in a 4 × 4 factorial scheme with four replications. The first factor consisted of hairy woodrose (*M. aegyptia*) and roostertree (*C. procera*) biomass amounts in a proportion of 50% for each green manure at doses of 20, 35, 50 and 65 t ha^{-1} on a dry basis. The second factor was the coriander population density: 400, 600, 800 and 1000 thousand plants ha^{-1}. In each block, plots of radish and coriander were monocropped, fertilized with equitable amounts of 39.43 and 49.56 t ha^{-1} of the green manure biomass, and optimized by research carried out in the region to determine agrobiological indices for competition and economic indicators of the intercropping systems. The radish and coriander plant spacings used in intercropping and monocropping are presented in Table 3. The recommended monocropping planting densities for the coriander and radish regions were 1000 and 500 thousand plants ha^{-1}, respectively.

Table 3
Description of population densities and spacings of radish and coriander used in the experiments in intercropping and monocropping

Population density of intercropped crops (thousand plants ha^{-1})		Spacings (m)	
Radish	Coriander	Radish (1 plant per hole)	Coriander (2 plants per hole)
500	400	0.20 × 0.05	0.20 × 0.120 (2 pl)
500	600	0.20 × 0.05	0.20 × 0.083 (2 pl)
500	800	0.20 × 0.05	0.20 × 0.062 (2 pl)
500	1000	0.20 × 0.05	0.20 × 0.050 (2 pl)
Recommended population density for monocrops (thousand plants ha^{-1})			(1 plant per hole)
Radish	500	0.20 × 0.10	
Coriander	1000		0.20 × 0.05 (1 pl)

Intercropping was established in alternating strips of the crops in a proportion of 50% of the area for radish and 50% of the area for coriander. The spatial arrangement of the planting strips in the experimental plots was four rows of radish alternating with four rows of coriander flanked by two rows of one of the crops on each side, which were used as borders (Figure 1). The total area of each plot was 2.88 m^2 (2.40 × 1.20 m), with a harvest area of 1.60 m^2 (1.60 × 1.00 m). This harvest area was made up of the two central strips, with the first and last plants in each row of the strip used as headboard borders.

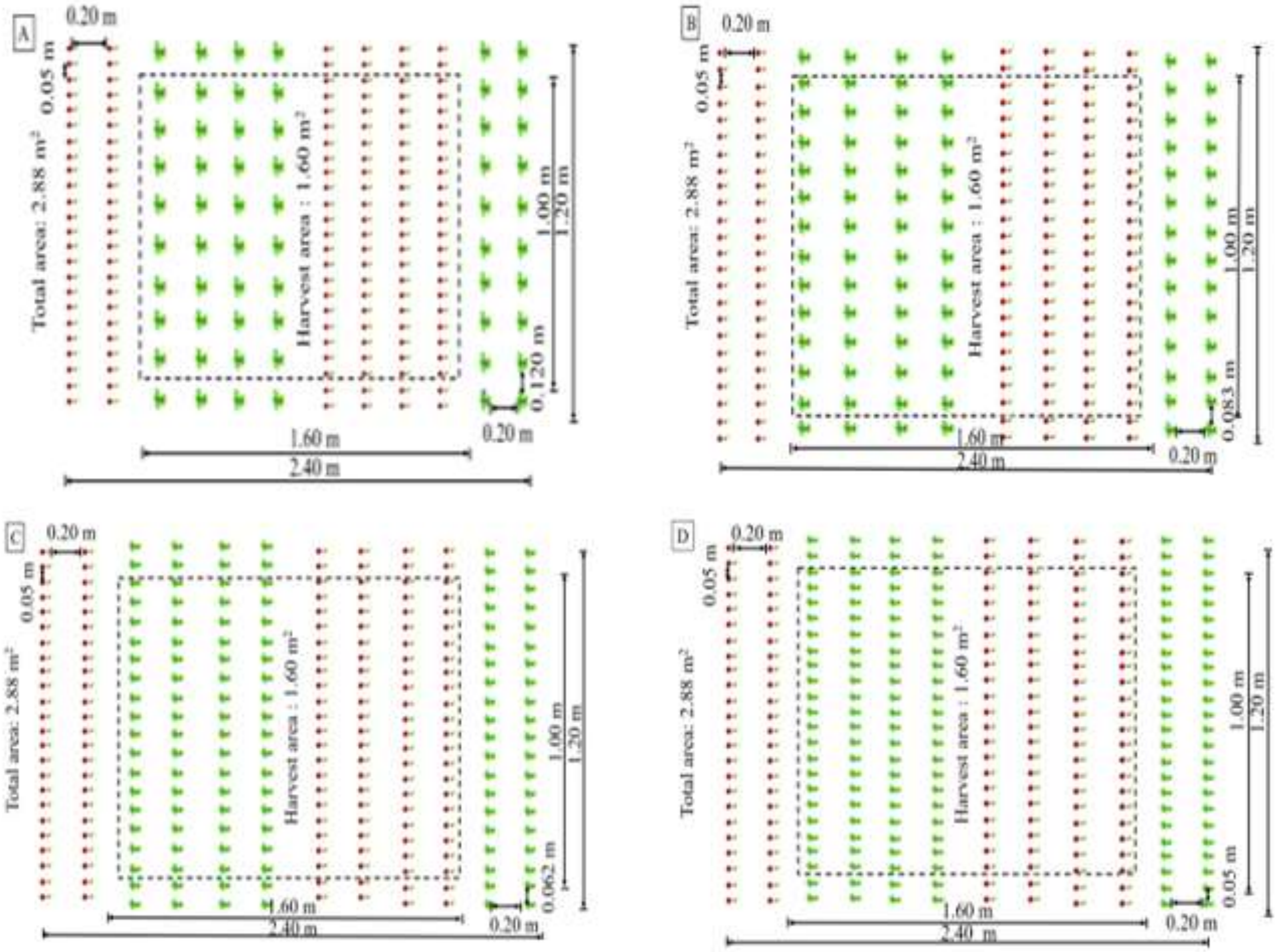

Figure 1. Representation of the radish-coriander experimental plots at a population density of 500 thousand radish plants ha^{-1} intercropped with coriander at a population density of 400 (A), 600 (B), 800 (C) and 1000 (D) thousand plants ha^{-1}.

Monocropping plots of the vegetables were planted in six rows of plants of each crop occupying a total area of 1.44 m^2 and harvest area of 0.80 m^2 (0.80 × 1.00 m), in the spacing of 0.20 m × 0.10 m for the radish crop and 0.20 m × 0.05 m for the coriander crop. The harvest area was made up of four rows of central plants, excluding the first and last plants of each row, used as borders (Figure 2).

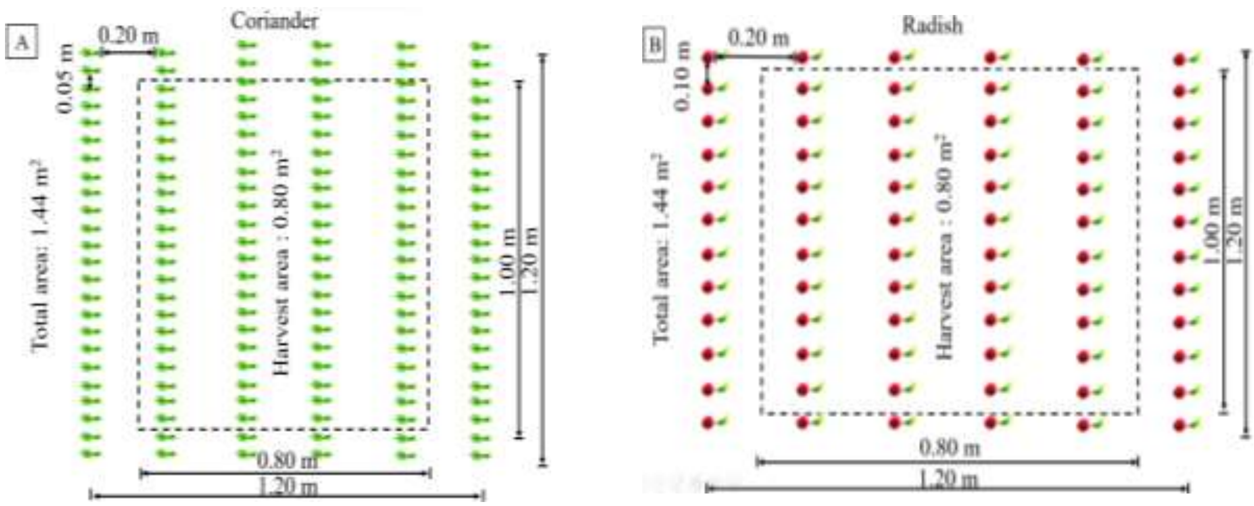

Figure 2. Representation of coriander and radish monocropping plots at a population density of 1000 (A) and 500 (B) thousand plants ha^{-1}

Before installing the experiments, the soils in the experimental areas were mechanically cleaned with the aid of a tractor with a coupled plow, and the beds were raised with a rotary digger. Subsequently, pre-planting solarization was carried out with transparent plastic, such as Vulca Brilho Bril Flex (30 microns), which remained for 30 days to combat phytopathogenic microorganisms present in the soil that could affect crop productivity (M. G. Silva et al., 2006).

After the solarization period, the materials used as green fertilizers were incorporated on October 13, 2021, and October 5, 2022, with the use of hoes. From the incorporation to harvesting of crops, daily irrigations were carried out using micro sprinklers divided into two shifts (morning and afternoon). The amount of water supplied was determined by the values of the radish cultivation coefficients (initial Kc = 0.45; average Kc = 0.95; and final Kc = 0.65), with irrigation depths, when necessary, of approximately 8 mm day^{-1}.

The spontaneous species from the Caatinga biome, hairy woodrose and roostertree, collected in diverse areas of the municipality of Mossoró, RN were used as green fertilizers in the fertilization of radish and coriander. These plants were collected at the beginning of flowering, and after collection, the plants were ground into particles measuring two to three centimeters using a forager, dehydrated at room temperature until reaching 10% humidity, and subsequently subjected to laboratory analysis. The chemical components obtained in 2021 and 2022 are presented in Table 4.

Table 4

Chemical analysis of macro and micronutrients in the dry biomass of hairy woodrose and roostertree incorporated into the soil in the radish and coriander intercropping system in two cropping seasons

Green manure	N	P	K	Mg	Ca	C:N
	---------------------------g kg^{-1}---------------------------					
2021			**Cropping season 2021**			
M. aegyptia	20.56	2.83	37.08	7.07	19.35	25:1
C. procera	15.14	2.96	24.84	9.20	17.00	27:1
2022			**Cropping season 2022**			
M. aegyptia	18.55	1.89	38.68	7.03	9.30	25:1
C. procera	14.09	1.54	22.72	13.50	16.30	27:1

The radish cultivar planted was ‘Crimson Gigante’ and the coriander cultivar was ‘Verdão’. Both crops were sown on November 3, 2021, in the first year and on October 27, 2022, in the second yea, in holes approximately 3 cm deep with 3–4 seeds per hole and covered with an organic substrate. At 7 days after sowing (DAS) radish, thinning was carried out, leaving one plant per hole. Coriander was thinned at 15 DAS, leaving 1 plant per hole in monocropping plots and 2 plants per hole in intercropping plots to achieve the population densities studied.

Weed control was carried out manually, whenever necessary. No chemical pest or disease control methods were used. In the first cropping season, coriander was harvested at 30 DAS, and radish was harvested at 34 DAS. In the second season, coriander was harvested at 33 days, while radish was harvested at 30 DAS.

The characteristics evaluated in the cultivation systems were commercial productivity of radish roots, quantified by the fresh mass of plant roots in the harvest area with a minimum size of 20 mm, free of cracks or deformations, and not isoporized (Souza et al., 2020) and expressed in t ha^{-1}. The yield of green coriander leaves was quantified by the fresh mass of the shoot plants in the harvest area and expressed in t ha^{-1}.

The agro-bioeconomic efficiency of intercropped radish and coriander systems was determined through agrobiological and competition indices and economic indicators. The agrobiological indices evaluated were as follows:

a) The land equivalent ratio (LER) was calculated using the expression used by Bezerra et al. (2019): $RET = \frac{Y_{rc}}{Y_r} + \frac{Y_{cr}}{Y_c}$,

where Y_{rc} is the productivity of commercial radish roots intercropped with coriander; Y_r is the productivity of commercial radish roots in monoculture; Y_{cr} is the yield of green leaves of coriander intercropped with radish; Y_c is the green leaf yield of coriander in monocropping. This agrobiological index is defined as the relative area of land under a single cropping condition required to provide the productivity achieved in intercropping. When the LER value is greater than 1, the intercropping favors the development, growth and productivity of the component crops. In contrast, when the LER is less than 1, intercropping between the component crops is negatively affected, harming the development, growth and productivity of the crops.

b) The intercropping advantage (IA) was determined by the expression used by Gebru (2015):

$IA = IA_r + IA_c$, where IA_r represents the advantage of intercropping radish and coriander and IA_c represents the advantage of intercropping coriander and radish. $IA_r = AYL_r \times P_r$ and $IA_c = AYL_C \times P_c$, where AYL_r and AYL_c are defined in the description of real yield loss (AYL), P_r is the price of radish in BRL kg^{-1} and P_c is the price of coriander in BRL kg^{-1}. The average prices used in the expressions were those paid to the producer during the research development period, which were 5.00 and 5.38 BRL kg^{-1} for coriander and radish, respectively. The higher the IA value, the more agronomically advantageous and profitable the intercropping system.

c) The productive efficiency index (PEI) was calculated for each treatment using the Data Envelopment Analysis (DEA) model, with constant returns to scale and as there was no evidence of significant scale differences. The DEA model was generated using the following mathematical formulation: $Max\, z_o = \sum_{j=1}^{r} \mu_j X_{jo}$ subject to restrictions: $\sum_{i=1}^{s} v_i w_{io} = 1$ on which $\sum_{j=1}^{r} \mu_j X_{jk} - \sum_{i=1}^{s} v_i w_{ik} \leq 0$ k = 1,..., n; μ_j, $v_i \geq 0$, j, i. Max z_o is the maximum measure of the efficiency z of treatment o; x_{jo} is the value of the output (product) j for the plot under analysis O; w_{io} is the value of input (resource) i for the plot under analysis O; x_{jk} is the value of the output j (j = 1,..., r), for treatment k and w_{ik}, the value of input i (i = 1,..., s), for treatment k (k = 1,..., n); and vi and μj are the weights assigned to inputs and outputs, respectively (Cooper et al., 2004; Bezerra et al., 2012). To measure the efficiency of each experimental plot (treatment), unitary inputs were assumed for all units.

For the case under study, the evaluation units were in the plots, with a total of 64 (16 treatments from the 4 × 4 factorial, with 4 replications). The yields of green coriander leaves and the commercial productivity of radish roots were used as outputs. To evaluate the performance of each plot, each one used a single resource with a unitary level since the outputs incorporated the possible inputs. Thus, the closer the PEI value is to 1, the more agronomically advantageous the intercropping system.

d) The score of the canonical variable (Z) was evaluated through bivariate analysis of variance of the yields of coriander green leaves and commercial productivity of radish roots. The higher and more positive the Z value, the more agronomically efficient the intercropping system.

The competition indices evaluated in the intercropping systems were: aggressivity of the crops (A_r and A_c), competitive ratio (CR) and actual yield loss (AYL).

e) The aggressivity of the crops (A) is an index that indicates how much of the relative increase in production of component crop r (in this case, radish) is greater than the production of the other component c (coriander) in an intercropping system. This index was determined by the following expressions used by Cecílio et al. (2015): $A_r = \left(\frac{Y_{rc}}{Y_r Z_{rc}}\right) - \left(\frac{Y_{cr}}{Y_c Z_{cr}}\right)$ and $A_c = \left(\frac{Y_{cr}}{Y_c Z_{cr}}\right) - \left(\frac{Y_{rc}}{Y_r\, Z_{rc}}\right)$, where A_r and A_c are the aggressivity of radish and coriander in intercropping; Y_{rc} is the commercial productivity of radish roots intercropped with coriander; Y_r is the commercial productivity of monocropped radish; Z_{rc} the proportion of the radish planting area intercropped with coriander; Y_{cr} is the green leaf yield of coriander intercropped with radish; Y_c is the yield of monocropped green coriander leaves; Z_{cr} is the proportion of the coriander planting area intercropped with radish. If A is positive, the component culture with a positive sign is dominant, and the one with a negative sign is the dominated culture. If the A value is zero, the crops are equally competitive.

f) The competitive ratio (CR) of the intercropping system was also obtained using the expression used by Cecílio et al. (2015): $\mathrm{CR} = \mathrm{CR_r} + \mathrm{CR_c}$. The $\mathrm{CR_r} = \left[\left(\frac{\mathrm{RET_r}}{\mathrm{RET_c}} \times \frac{Z_{cr}}{Z_{rc}}\right)\right]$ and the $\mathrm{CR_c} = \left[\left(\frac{\mathrm{RET_c}}{\mathrm{RET_r}} \times \frac{Z_{rc}}{Z_{cr}}\right)\right]$, where CR_r is the competitive ratio of radish intercropped with coriander and CR_c is the competitive ratio of coriander intercropped with radish. The terms LER_r, LER_c, Z_{cr} and Z_{rc} were previously defined. The competitive ratio provides the exact degree of competition by indicating the number of times the dominant species is more competitive than the dominated species (Eskandari & Ghanbari, 2010; Egbe et al., 2010). The culture with the highest CR makes better use of environmental resources.

g) The actual yield loss (AYL) of the intercropping system was determined by the expression used by J. N. da Silva et al. (2021): $\mathrm{AYL} = \mathrm{AYL_r} + \mathrm{AYL_c}$, where a $\mathrm{AYL_r} = \left[\left\{\left(\frac{Y_{rc}}{Z_{rc}}\right) \div \left(\frac{Y_r}{Z_r}\right)\right\} - 1\right]$ and $\mathrm{PAYL_c} = \left[\left\{\left(\frac{Y_{cr}}{Z_{cr}}\right) \div \left(\frac{Y_c}{Z_c}\right)\right\} - 1\right]$, where AYL_r is the actual yield loss of radish; AYL_c is the actual yield loss of coriander; Y_{rc} is the commercial productivity of radish roots intercropped with coriander; Z_{rc} is the proportion of radish planting intercropped with coriander; Y_r is the commercial productivity of monocropped radish roots; Z_r is the proportion of monocropped radish; Y_{cr} is the yield of green coriander leaves intercropped with radish; Z_{cr} is the planting proportion of coriander intercropped with radish; Y_c is the yield of monocropped green coriander leaves and Z_c is the planting proportion of monocropped coriander. AYL > 0 indicates an advantage of intercropping compared to monocropping, while AYL < 0 indicates the disadvantage of the intercropping system.

The economic efficiency indicators evaluated in the intercropping systems were gross income (GI), net income (NI), rate of return (RR) and profit margin (PM).

Gross income (GI) was calculated based on the production value of the combined crops involved in the intercropping system without considering the total costs (TC) of production of the products involved in inputs and services (Feiden, 2001). Gross income (GI) was determined by the product of crop productivity per hectare by the price paid to the producer at market level in the region in December 2021. The average prices paid were 5.00 BRL kg^{-1} for coriander and 5.38 BRL kg^{-1} for radish. Following Cecílio et al. (2010), the total production costs of an intercropping system were obtained from the total expenses (total costs) per hectare with the component crops that made up the system at an experimental level, which covered the services provided by the capital stable (depreciation, fixed labor and costs associated with working capital), input prices and the value of alternative costs (also called opportunity costs). Net income (NI) was calculated by subtracting, the system's total production costs (TC) per hectare from the gross income (GI). The rate of return (RR) was obtained by the relationship between gross income (RB) and total costs (TC), that is, corresponding to how many reals were obtained for each real invested in the application of the radish and coriander intercropping treatment. The profit margin (PM) was obtained by the relationship between net income (NI) and gross income (GI), expressed as a percentage.

Univariate variance analysis was performed on all indices and indicators evaluated using SISVAR software (Ferreira, 2011). Due to the homogeneity of variances between cropping seasons, an average was calculated for each treatment. Subsequently, regression analysis was performed on each index or indicator and then a response surface was adjusted as a function of the equitable amounts of hairy woodrose and roostertree biomass incorporated into the soil and the population densities of coriander plants, using Table Curve 3D software (Systat Software Inc. [SYSTAT], 2021).

Results and Discussion

Agrobiological advantages

The results of the univariate and regression analyses of the agrobiological and competition indices of radish and coriander intercropping under different equitable amounts of *M. aegyptia* and *C. procera* and the diverse population densities of coriander are presented in Table 5, as well as the average values of radish commercial productivity and yield of coriander green leaves that produced these indices. Significant interactions among factors and treatments were observed for equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil and coriander population densities in the agrobiological indices LER, IA and PEI and in the competition index and AYL. There was no significant interaction among the factors or treatments in the agrobiological index score of Z or in the competition indices A_r, A_c or CR of the intercropping systems (Table 5).

Table 5

F values for land equivalent ratio (LER), intercropping advantage (IA), actual yield loss (AYL), productive efficiency index (PEI), score of canonical variable (Z), aggressivity of radish over coriander (A_r), aggressivity of coriander over radish (A_c), competitive ratio (CR) and the regressions of these indices in the radish-coriander intercropping system under equitable amounts of *Merremia aegyptia* and *Calotropis procera* biomass and coriander plant densities, and the mean yields of coriander green leaves and commercial productivities of radish roots over two cropping seasons

Sources of variation	Agrobiological indices					Competition indices			
	DF	LER	IA	PEI	Z	A_r	A_C	CR	AYL
Blocks	3	3.97*	1.47^{ns}	2.45^{ns}	2.60^{ns}	6.07**	6.07**	6.53**	5.21**
Amounts of *M. aegyptia* and *C. procera* biomass (A)	3	4.80**	2.98*	88.55**	2.46^{ns}	2.48^{ns}	2.48^{ns}	6.30**	4.89**
Coriander population densities (D)	3	9.17**	27.15**	80.20**	49.47**	3.89*	3.89*	3.64*	37.23**
A × D	9	2.88**	2.13*	24.51**	1.86^{ns}	0.63^{ns}	0.63^{ns}	0.77^{ns}	2.11*
Regression		7.52**	28.67**	6.75**	55.35**	16.69**	16.69**	7.23**	22.75**
Error	45	0.01047	1.16670	0.00120	0.02171	0.08297	0.08297	0.02335	0.06867
CV (%)		5.43	11.12	5.60	6.70	35.12	−35.12	6.58	14.81

Coriander population densities (1000 plants ha^{-1})	Mean yields of coriander green leaves and commercial productivities of radish roots (t ha^{-1})							
	20		35		50		65	
	Coriander	Radish	Coriander	Radish	Coriander	Radish	Coriander	Radish
400	0.379	11.614	0.316	12.955	0.487	13.669	0.524	14.116
600	0.517	11.950	0.538	14.598	0.749	15.195	0.776	15.355
800	0.535	11.559	0.905	12.772	0.870	12.182	1.051	15.268
1000	0.746	10.825	0.983	12.431	1.111	13.452	1.435	15.848

** = P < 0.01; * = P < 0.05; ns = P > 0.05; CV – Coefficient of variation.

The LER, IA and Z values increased with the increase in the amount of green manure and coriander population density, reaching maximum values of 2.00, 11.39 and 2.45, respectively, with the combination of 65 t ha^{-1} of green fertilizer incorporated into the soil and at a population density of 1000 thousand coriander plants ha^{-1} (Figure 3A, B and D). For the productive efficiency index (PEI), the behavior was the opposite, as it grew until a quantity of green manure of 38.75 t ha^{-1}, with a decrease in the coriander population density, thus providing a maximum value of 0.78 with a combination of 38.75 t ha^{-1} of the green manure added to the soil at a density of 400 thousand coriander plants ha^{-1} (Figure 3C).

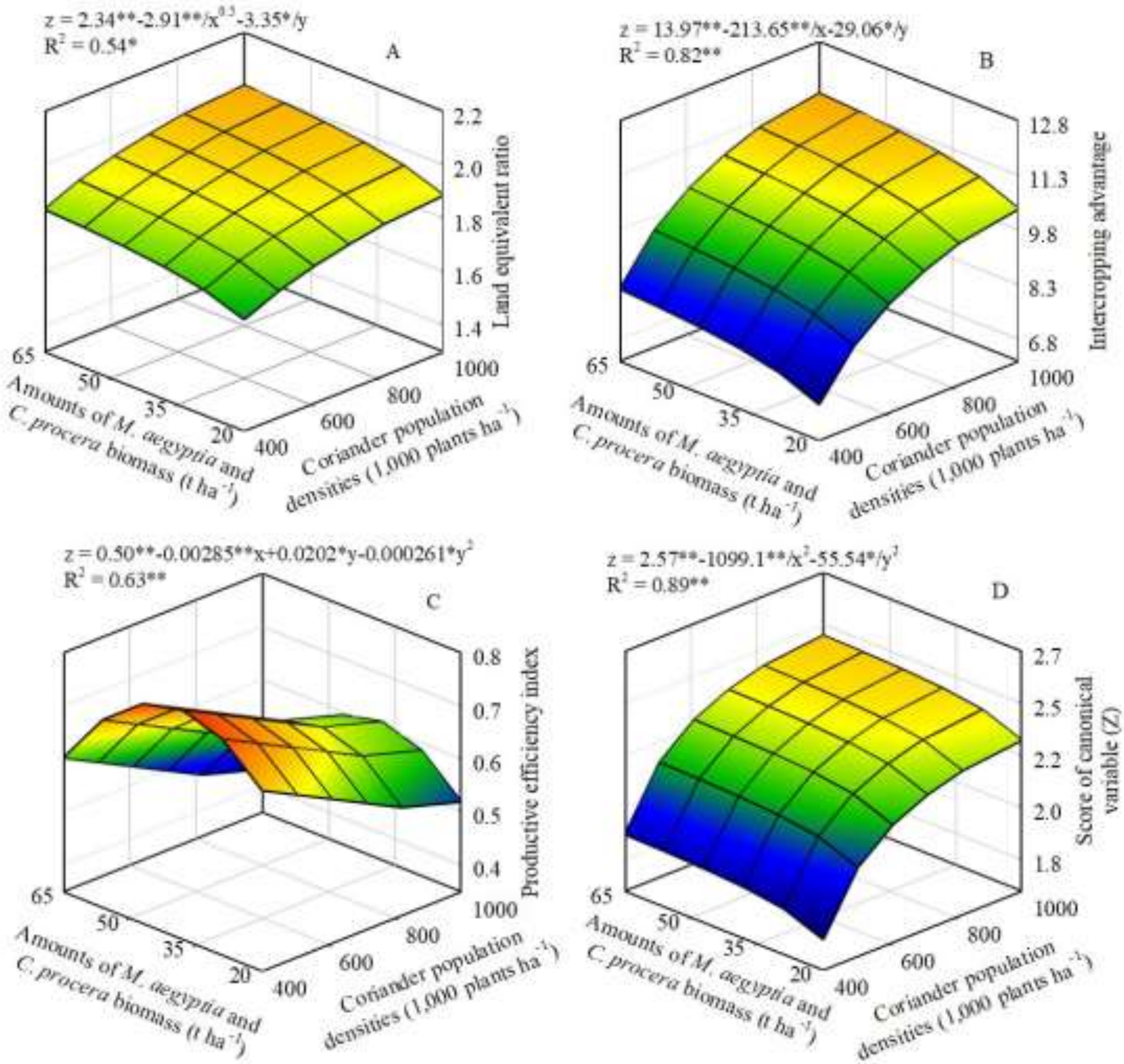

Figure 3. Land equivalent ratio – LER (A), intercropping advantage – IA (B), productive efficiency index – PEI (C) and score of the canonical variable – Z (D) of radish intercropped with coriander with different combinations of equitable amounts of *Merremia aegyptia* and *Calotropis procera* biomass and coriander population densities.
*, ** - Significant at P ≤ 0.05 and P ≤ 0.01 by the F-test.

The agrobiological efficiency of radish–coriander intercropping can be observed explicitly through the values obtained with LER, IA and Z, with values higher than those of monocropping with radish or coriander crops, indicating complementarity and ideal competitiveness between the component crops and consequently demonstrating better use of environmental resources. When the values of LER, IA and Z are greater than unity, this is indicative of superiority of the associated system with regard to the use of environmental resources compared to monocropping (Oseni & Aliyu, 2010). This means that there was gradual growth in the use of resources with the increase in the quantities of green fertilizers and the population densities of coriander, expressed by the values obtained. The increase in coriander density positively influenced the interspecific competition of radish and coriander crops, resulting in more advantageous intercropping than monoculture.

However, this better use of environmental resources was due to the adequate management of treatment-factors, amounts of green fertilizers and population densities of coriander plants, which when well managed provided chemical, physical and biological improvements to the soil, thus achieving maximum agrobiological efficiency of the intercropping system. Intercropping of tuberose (radish) and leafy coriander makes it possible to optimize the use of environmental resources, such as nutrients, water and solar radiation, since the plant species have different growth cycles. In this way, companion plants do not compete for nutrients, space or light and do not have toxic (allelopathic) effects on each other (Lima et al., 2024).

Lino et al. (2023) intercropped the same tuberose (radish) with a leafy vegetable (lettuce) using the same quantities of green fertilizers, *M. aegyptia* and *C. procera*, tested in this work and diverse lettuce population densities and found agronomic advantages by using intercropping with biological indexes of LER (2.25) and Z (3.00) practically similar to that of this research and IA (8.03) lower than that obtained (IA=11.39). These small differences in intercropping efficiency are due to the type of leafy vegetable intercropped and the population densities tested. However, it is important to obtain agronomic advantages in the intercropping of tuberose with the leafy vegetable.

In turn, studying the intercropping advantage of tuberose (beetroot) with the leafy vegetable arugula using the same doses of green fertilizers, *M. aegyptia* and *C. procera*, tested in this work and in diverse arugula population densities in the same semi-arid region, Lino et al. (2021b) found agronomic advantages of intercropping that were inferior to this work, with com maximum biological indices LER, IA and Z of 1.87, 7.44 and 2.52, respectively. These differences in the efficiency of intercropping are due to the type of tuberose and leafy vegetable tested, as they are more aggressive in competing for environmental resources than the combination tested in this research.

The aggressivity of the radish over coriander (A_r) increased with the increase in the amount of green fertilizers applied and with the population densities of coriander, reaching a maximum value of 1.03 in the combination of 1000 thousand coriander plants ha^{-1} and 65 t ha^{-1} of green manure incorporated into the soil (Figure 4A). For the aggressivity of coriander over radish (A_c), the behavior was the opposite, as it increased with the decrease in the amounts of green fertilizers applied and with the population densities of coriander, reaching a maximum value of −0.50 in the combination of 20 t ha⁻¹ of green manure incorporated into the soil and 400 thousand coriander plants ha⁻¹ (Figure 4B).

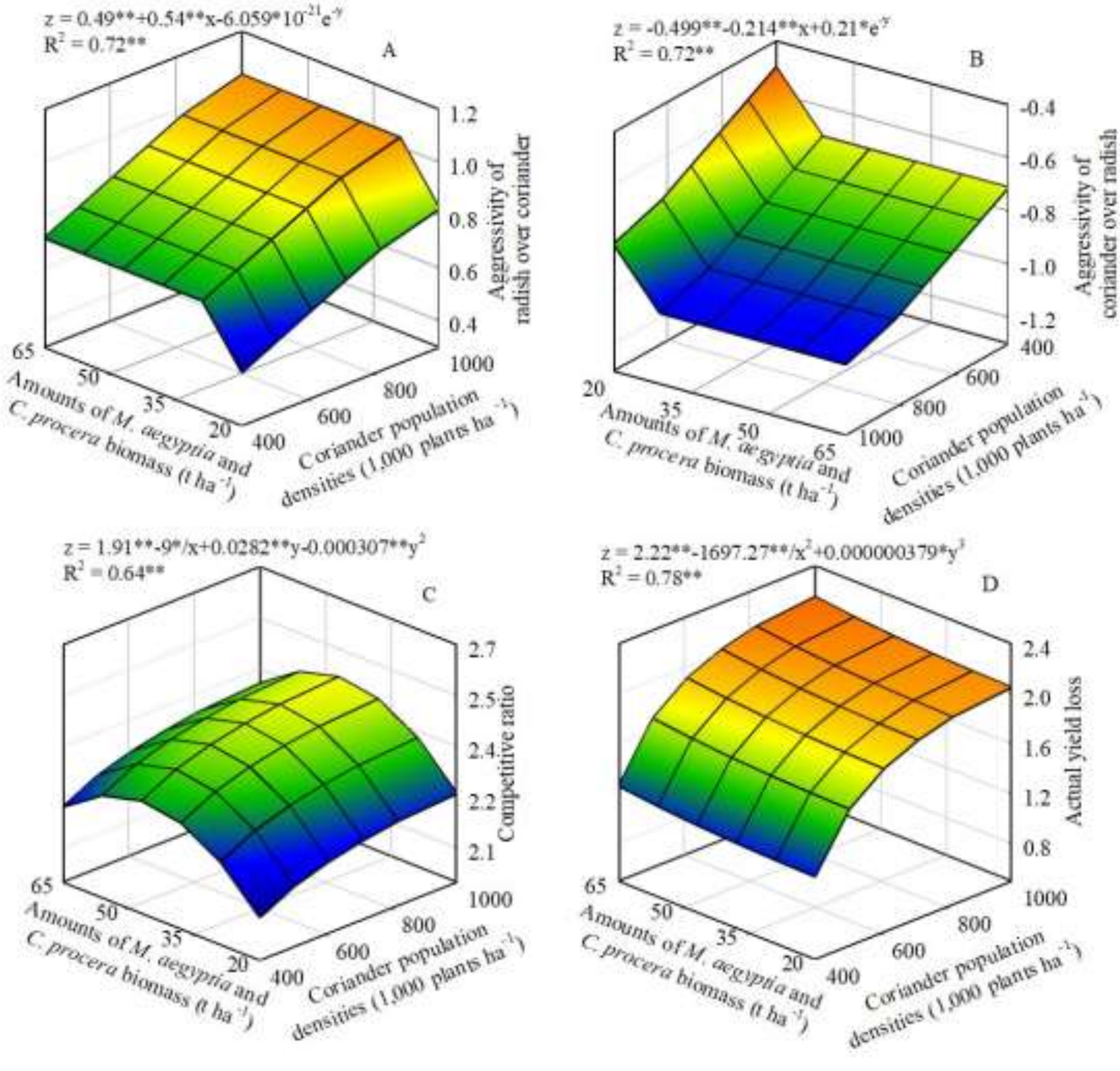

Figure 4. Radish aggressivity over coriander – A_r (A), coriander aggressivity over radish – A_c (B), competitive ratio – CR (C) and actual yield loss – AYL (D) of radish intercropped with coriander with different combinations of equitable amounts of *Merremia aegyptia* and *Calotropis procera* biomass and coriander population densities.
*, ** - Significant at P ≤ 0.05 and P ≤ 0.01 by the F-test.

The competitive ratio (CR) of the intercropping system increased with the increase in the amount of green manure and with the coriander population density, up to the maximum value of 2.47 with 45.95 t ha^{-1} of green manure and at a density of 1000 thousand coriander plants ha^{-1} (Figure 4C). On the other hand, the actual yield loss increased with the increase in the amount of green fertilizer applied and with the coriander population density, reaching a maximum value of 2.15 in the combination of 1000 thousand coriander plants ha^{-1} and 65 t ha^{-1} of the green manure incorporated into the soil (Figure 4D).

The positive aggressivity values of radish over coriander in the intercrop indicate that this tuberose was the dominant crop in the system and more competitive than coriander (dominated crop), as the broadleaf planting density and the amount of green fertilizers increased. This index is a good indicator of the degree of complementarity between the component crops, as it dictates the intra- and interspecific competition between them in the intercropping system. These aggressivity results also indicate that coriander has a lower capacity for interspecific competition when compared to radish, regardless of the number of plants in the area. In general, plant density and the relative proportion of component crops are essential to determining the efficiency of intercropping systems. According to Willey and Osiru (1972), when the proportion of the component crops is approximately equal, the efficiency and yield of the system appear to be determined by the most aggressive crop in the system. The behavior of this tuberose can also be attributed to factors related to the morphology, physiology and nutritional needs of the crop.

The CR values in each treatment studied provide the exact degree of competition between the component crops in intercropping, indicating the number of times in which the dominant species is more competitive than the dominated species. In an intercropping system, the crop with the highest CR makes better use of environmental resources, which in this research was the radish crop. The increasing CR values recorded with the increase in the amount of green manure up to the maximum value and with the increase in the coriander population density indicate a reduction in the degree of competition between species and, thus, provide an increase in the efficiency of intercropping cultivation due to better use of environmental resources. This effect can be attributed to factors related to the morphology, physiology and nutritional requirements of plants. According to Zhang et al. (2015), differences in plant architecture, especially roots, determine how they access and use soil nutrients.

AYL values much higher than 1, resulting from the increase in the amounts of green manure and the coriander population density, highlight the positive effect of intra- and interspecific competition of radish and coriander crops, resulting from better use of resources and environmental factors, thus providing more advantageous intercrops than monocrops. It is important to highlight that the AYL value provides accurate information about the competition. The agrobiological effectiveness of radish–coriander intercropping explicitly highlights the values of these competition indices and shows the superiority of intercropping over monocropping, indicating ideal complementarity and competitiveness between crops, therefore demonstrating a better use of environmental resources.

The results from the competition indices indicate the best use of environmental resources due to the adequate management of production factors, amount of green fertilizer and coriander population density, which would provide chemical, physical and biological improvements to the soil, thus achieving the maximum agronomic efficiency of the intercropping system. Green manure, in addition to providing the nutrients necessary for crop development, increases the organic matter content, reduces erosion levels, increases the permeability and activity of the soil microbiota, increases nutrient availability, and reduces the amount of invasive plants (Graham & Haynes, 2006; Batista et al., 2016; Oliveira et al., 2017). However, competition between crops that form part of an intercropping system is regulated through morphophysiological and management differences with population density, amount of fertilizer and proportion of crops in the system. In other words, they are factors that limit the growth and development of cultures (Morgado & Willey, 2008). Thus, the increase in coriander population density and the greater total absorption of nutrients by the crops that make up the intercropping system are the main causes of agronomic advantages in that system.

According to Sá et al. (2021), intercropping radish with arugula using different doses of green fertilizer, hairy woodrose and roostertree, and diverse arugula population densities obtained positive values of radish aggressivity over the leafy crop, indicating that this tuberose was the dominant crop in the system. A similar result was obtained in this research on radish and coriander. However, they obtained a CR value of 2.75, which was slightly higher than that obtained in this work (2.47), in the smallest combination of an equitable amount of green manure biomass of 20 t ha^{-1} with a population density of 400 thousand plants ha^{-1} of arugula, a combination opposite to that obtained in this research. For AYL, the maximum value achieved was 1.31, which was lower than that achieved in this research (2.15), in the greatest combination of an equitable amount of green manure biomass of 65 t ha^{-1} with a population density of 1 million plants ha^{-1} of arugula. These differences in the results of radish–coriander and radish–arugula intercrops can be attributed to factors related to the morphology, physiology and nutritional needs of leafy crops.

Economic advantages

For the economic indicators, gross income (GI), net income (NI), rate of return (RR) and profit margin (PM), a significant interaction was observed between the treatment-factors for profit margin (Table 6).

Table 6
F values for gross income (GI), net income (NI), rate of return (RR) and profit margin (PM) of radish intercropped with coriander and for the regressions of these indicators in the radish–coriander intercropping system under equitable amounts of Merremia aegyptia and Calotropis procera biomass and coriander plant density over two cropping seasons

Sources of variation	DF	GI	NI	RR	PM
Blocks	3	2.41^{ns}	2.71^{ns}	1.84^{ns}	4.94**
Amounts of M. aegyptia and C. procera biomass (A)	3	5.29**	21.48**	169.61**	264.48**
Coriander population densities (D)	3	28.08**	29.19**	16.37**	30.60**
A × D	9	0.62^{ns}	1.14^{ns}	0.93 ^{ns}	2.87**
Regression		69.00**	51.07**	209.81**	129.22**
Error	45	76435	82276	0.15500	4.77008
CV (%)		7.79	11.08	10.13	3.04

** and ns - Significant at P ≤ 0.01 and non-significant at P > 0.05 by F-test; CV - Coefficient of variation.

However, response surfaces were adjusted for GI and NI as a function of the treatment-factors, showing maximum values of 130,397.88 and 107,277.39 BRL ha^{-1} in the combination of 1000 thousand coriander plants ha^{-1} and the amount of green fertilizer applied to the soil of 29.92 and 25.89 t ha^{-1}, respectively (Figure 5A and 5B). For the rate of return and profit margin, BRL 6.00 for each real invested and a 85.36% profit margin was obtained with an equitable amount of biomass of 20 t ha^{-1} of green fertilizer and with a coriander population density of 1000 thousand plants ha^{-1} (Figure 5C and 5D). These small differences in the behavior of the indicators in relation to the treatment-factors are probably due to the total production costs of each tested treatment.

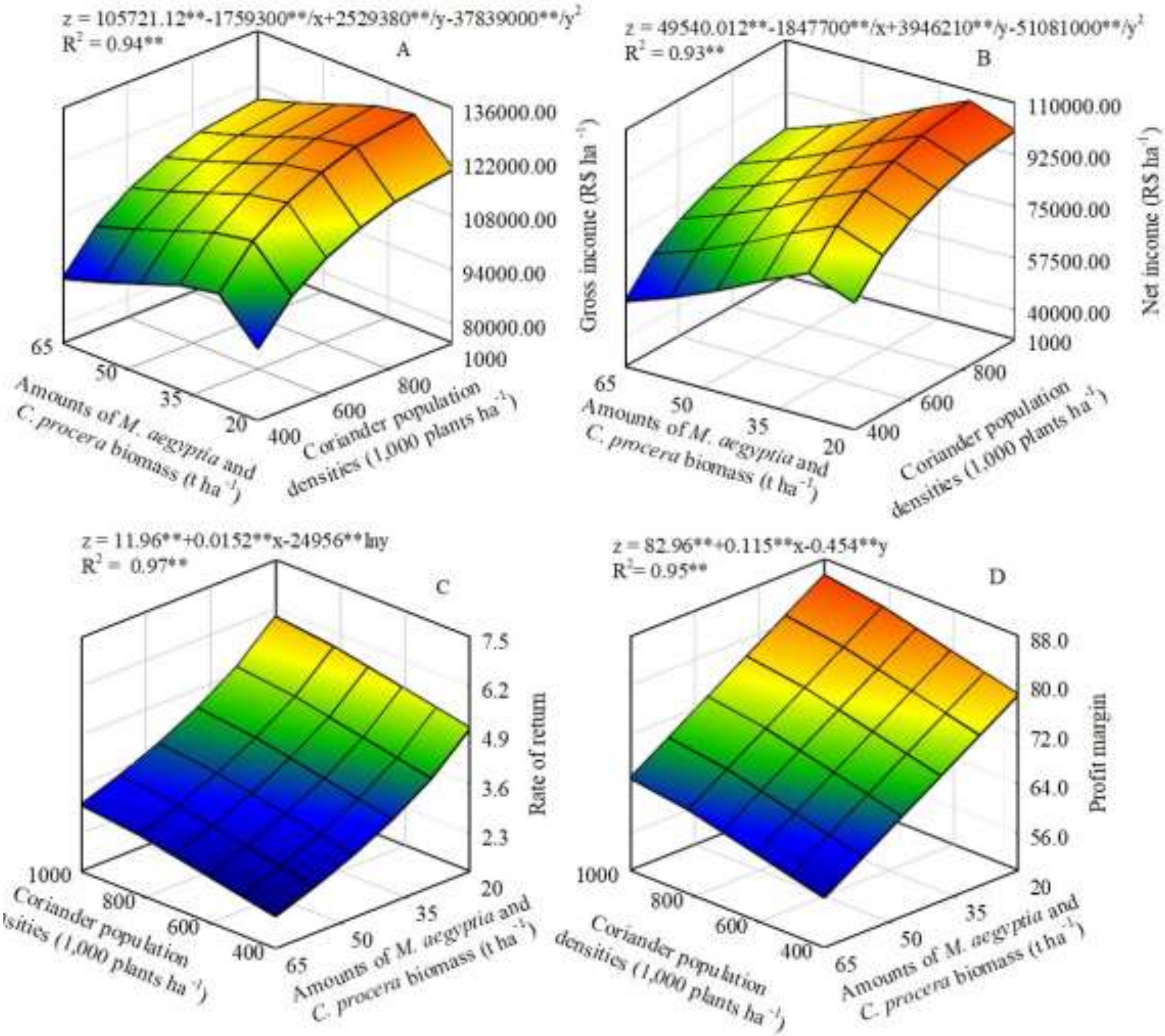

Figure 5. Gross income – GI (A), net income – NI (B), rate of return – RR (C), and profit margin – PM (D) of radish intercropped with coriander in different combinations of equitable amounts of *Merremia aegyptia* and *Calotropis procera* biomass and coriander population densities.
*, ** - Significant at P ≤ 0.05 and P ≤ 0.01 by the F-test.

Comparing the results of these economic indicators obtained with the intercropping of the tuberose radish and leafy coriander with other intercrops of radish and lettuce as well as beetroot and arugula evaluated in the same region and testing the same green fertilizers and different population densities of the leafy vegetable used in the research, an attractive economic advantage was observed for the radish and coriander intercrop, with indicators of GI = 130,397.88 BRL ha^{-1}; NI = 107,277.39 BRL ha^{-1}; RR = 6.00 reals for each real invested and PM = 85.38%. The indicators obtained by Lino et al. (2023) when intercropping radish and lettuce were as follows: GI = 95,456.62 BRL ha^{-1}; NI = 52,270.48 BRL ha^{-1}; RR = 2.43 reals for each real invested and PM = 60.27%. When intercropping beetroot and arugula, Lino et al. (2021b) obtained the following values: GI = 85,827.79 BRL ha^{-1}; NI = 65,425.01 BRL ha^{-1}; RR = 4.24 reals for each real invested and PM = 77.02%. The results observed in these economic indicators, mainly net income, express the agronomic-biological advantage of the intercropping of radish with coriander in monetary terms as a function of the increase in the equitable amounts of biomass of *M. aegyptia* and *C. procera* incorporated into the soil and the increase in coriander population density, expressed by greater agronomic/biological efficiency in relation to monocropping. The results indicate that it is advantageous to combine radish and coriander organically while adequately managing the population density of coriander culture. Net income is an indicator that has the advantage of comparing not only the agronomic/biological efficiency of cropping systems but also considers the fact that inputs, especially labor, are limited and need to be used in different quantities for different cultivation systems. This indicator expresses the value of biological efficiency in net terms and is free of production costs.

Economic analysis complements the assessment of the agronomic/biological efficiency of intercropping systems, as in addition to the physical production of crops, it considers the price of products according to their commercial classification, of quality and cropping season in the year. Gross income is an indicator that represents the value of the combined productivity of crops in each intercropping system, regardless of production costs. It depends exactly on the price at which the system's production is sold. The rate of return is another indicator that depends on production costs, as it is standardized in terms of these costs. The higher the values of these indicators, the greater the advantage of the intercropping system. In turn, the profit margin is another standardized net profit indicator, which expresses, in percentage terms, the agronomic/biological efficiency of the intercropping system. The higher the values of these indicators, the greater the advantage of the system. Thus, the results obtained in the agrobiological and competition indices agree with those obtained in the economic indicators evaluated in this study.

Finally, the results of the economic indicators achieved in this work are highly promising with regard to the economic advantage for intercropping radish and coriander due to the net income and rate of return, which in economic terms, expresses the agrobiological advantages achieved in intercropping under equitable amounts of biomass of *M. aegyptia* and *C. procera* and coriander density. These indicators show that it is advantageous to intercrop radish and coriander, fertilizing the system organically with green fertilizer, hairy woodrose and roostertree, and adequately managing the coriander population density.

Conclusions

The highest agrobiological returns from radish cultivation intercropped with coriander were obtained with a land equivalent ratio (LER) of 2.00, intercropping advantage (IA) of 11.30, score of the canonical variable Z of 2.45, aggressivity of radish over coriander (A_r) of 1.03, and actual yield loss (AYL) of 2.15 with the incorporation of 65 t ha^{-1} of hairy woodrose and roostertree into the soil using a coriander population density of 1 million plants ha^{-1}. However, the highest economic return from radish–coriander intercropping was 107,277.39 BRL ha^{-1}, which was achieved with the application of 25.89 t ha^{-1} of green manure biomass and a coriander population density of 1 million plants ha^{-1}. The use of hairy woodrose and roostertree from the Caatinga biome as green manure biomass proved to be a viable technology for producers who practice intercropping of radish and coriander in a semi-arid environment.

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