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Sustainability and agro-monetary return in beet–immature cowpea intercropping as a function of green manuring and population density

Sustentabilidade e retorno agro-monetário no consórcio de beterraba e feijão-caupi imaturo em função da adubação verde e densidades populacionais

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Highlights

Green manure increases efficiency in beet–cowpea strip-intercropping.
Adequate crop density and green manure produces high returns in intercropping.
Hairy woodrose and roostertree addition to soil is a viable technique for growers.

Abstract

One of the questions that have been asked about the intercropping of beet with immature cowpea is how to properly use green manuring and population density of the component crops and their interaction for system sustainability. The objective of this study was to evaluate the agro-monetary benefits and sustainability of intercropping beet and immature cowpea under the influence of green manure with *Merremia aegyptia* and *Calotropis procera* and the cowpea population density in a semi-arid environment during two years of cultivation. The experimental design was randomized blocks, with treatments arranged in a 4×4 factorial scheme with 4 replications. The first factor of this scheme consisted of equitable amounts of *M. aegyptia* and *C. procera* biomass at doses of 20, 36, 52 and 68 t ha^{-1} on a dry basis, and the second factor was cowpea population density, with 80, 120, 160 and 200 thousand plants ha^{-1}. The cowpea and beet cultivars planted were ‘BRS Tumucumaque’ and ‘Early Wonder’, respectively.

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The greatest agro-economic advantages of beet × immature cowpea intercropping were achieved with a productivity index system of 35.37 t ha^{-1}, land equivalent coefficient of 0.35 and monetary equivalence ratio of 1.79, respectively, in the combinations with equitable biomass amounts of the green manure of 62.19, 62.07 and 61.63 t ha^{-1} and a cowpea population density of 142 thousand plants ha^{-1}.
Key words: *Beta vulgaris. Calotropis procera.* Economic feasibility. *Merremia aegyptia. Vigna unguiculata.*

Resumo

Uma das questões levantadas sobre o consórcio de beterraba com feijão-caupi imaturo é como utilizar adequadamente a adubação verde e a densidade populacional das culturas componentes e sua interação na sustentabilidade do sistema. O objetivo deste estudo foi avaliar os benefícios agro-econômicos e a sustentabilidade nos consórcios de beterraba e feijão-caupi imaturo sob a influência da adubação verde com *Merremia aegyptia* e *Calotropis procera* e densidades populacionais de feijão-caupi em um ambiente semiárido durante dois anos de cultivo. O delineamento experimental utilizado foi em blocos casualizados, com tratamentos dispostos em esquema fatorial 4×4, com 4 repetições. O primeiro fator deste esquema consistiu em quantidades equitativas de biomassa de *M. aegyptia* e *C. procera* nas doses de 20, 36, 52 e 68 t ha^{-1} em base seca, e o segundo fator de densidades populacionais de feijão-caupi de 80, 120, 180 e 200 mil plantas ha^{-1}. As cultivares de feijão-caupi e beterraba plantadas foram ‘BRS Tumucumaque’ e ‘Early Wonder’, respectivamente. As maiores vantagens agro-econômicas do consórcio de beterraba x feijão-caupi imaturo foram alcançadas com um índice de produtividade do sistema (SPI) de 35,37 t ha^{-1}, coeficiente equivalente de terra (LEC) de 0,35 e razão de equivalência monetária (MER) de 1,79, respectivamente, nas combinações de quantidades equitativas de biomassa das adubações verdes de 62,19; 62,07 e 61,63 t ha^{-1}, utilizando-se a densidade populacional de feijão-caupi de 142 mil plantas ha^{-1}.
Palavras-chave: *Beta vulgaris. Calotropis procera. Merremia aegyptia.* Viabilidade econômica. *Vigna unguiculata.*

Introduction

The association between cowpea and tuberous vegetables has been gaining social importance in the Brazilian Northeast, mainly in agroecological terms, presenting several advantages in productivity, nutritional, economic and environmental aspects. Considering this association, greater production per area is sought by combining plants that will use space, nutrients and sunlight, in addition to the benefits that one plant brings to the other in controlling competing plants, pests and diseases (Pereira et al., 2016; Favacho et al., 2017). However, the biggest challenge of this production system is the way in which crops are associated, mainly with regard to the choice of crops, fertilization and population density of the crops making up the system and meeting the interests of producers.

Crop association is an agricultural practice that consists of growing two or more agricultural species in the same production area. Each of these species occupies a distinct root and vegetative stratification in a way that minimizes competition. This practice seeks to optimize space, labor and available resources and establish intercrops that promote beneficial relationships between species, improving the quality of life of farmers and consumers of foods derived from this practice (Arias et al., 2022).

The types of fertilizers that have gained prominence in the fertilization of vegetable cultivation systems in the semi-arid region of Northeastern Brazil are those from spontaneous species from the Caatinga biome. These include green manure, such as jitirana (hairy woodrose, *Merremia aegyptia* L. Urb.) and flor-de-seda (roostertree, *Calotropis procera* (Ait.) R.Br.) (V. A. S. Lino et al., 2021). Jitirana, also called jetirana or corda-de-viola, 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). The flor-de-seda, called algodão de seda or janaúba, is a shrubby species (Rangel & Nascimento, 2011), with an average phytomass production of around 3000 kg ha^{-1} per cutting on a dry basis (at 120 days), reaching 9 t ha^{-1} per year, with a nitrogen content of around 18.4 g kg^{-1} in dry matter and a C/N ratio of 25/1.

According to Bezerra et al. (2005), another production factor that affects vegetable intercropping systems is the population density of the component crops, as it induces a series of changes in plant growth and development. More research is necessary to determine the yield and productive efficiency of the system. An increase in population density can influence the quality of tuberous roots, such as beet, increasing the number of extra roots and reducing the average size of the roots due to greater competition for water and nutrients. The increase in population density also interferes with the aerial part of the plants, increasing branch production and decreasing their diameters (L. J. Oliveira et al., 2017).

Silva et al. (2020) intercropped cowpea and carrot and evaluated the production and agroeconomic benefits of their association as a function of *Merremia aegyptia* L.green manure biomass in different spatial arrangements and cropping seasons in a semi-arid environment; they observed maximum productivity of carrot and cowpea crops with the incorporation of 32.69 and 50.17 t ha^{-1} hairy woodrose biomass, respectively, into the soil and maximum agroeconomic efficiency of the intercropping system when they added 34.66 t ha^{-1} of the green manure biomass to the soil. Bezerra et al. (2019) evaluated carrot and cowpea intercropping fertilized with *Calotropis procera* (Ait) R. Br. and recorded the highest economic efficiency with a net income of BRL 17,856.43 ha^{-1} when 40.60 t ha^{-1} of green manure biomass was added to the soil.

To provide greater subsidies for the development of technologies to grow beet intercropped with green cowpea, this work aimed to evaluate the agro-monetary performance and sustainability of beet and cowpea intercropping when subjected to different amounts of green manure biomass from hairy woodrose and roostertree on a dry basis and different cowpea population densities during two consecutive growing seasons in a semi-arid environment.

Material and Methods

Two experiments were conducted, the first from September to December 2022 and the second from September to November 2023, at the 'Rafael Fernandes' Experimental Farm of the Universidade Federal Rural do Semi-Árido (UFERSA). This farm is located in the district of Lagoinha, 20 km from the city of Mossoró, RN, at the geographic coordinates 5° 03′ 37″ S, 37° 23′ 50″ W with an altitude of 80 m.

According to Köppen's classification, the region's climate is BShw – dry and very hot, with two distinct seasons: a dry season typically from June to January and a rainy season from February to May (Beck et al., 2018). During the period in which the experiments were carried out in 2022 and 2023, this region had an average maximum temperature of 35.1 and 36.3°C, relative humidity of 72.2 and 70.9%, and rainfall of 107.4 and 94 mm, respectively. The average monthly values of maximum and minimum temperatures and average relative humidity in each year of cultivation with beet × cowpea intercropping are shown in Figure 1.

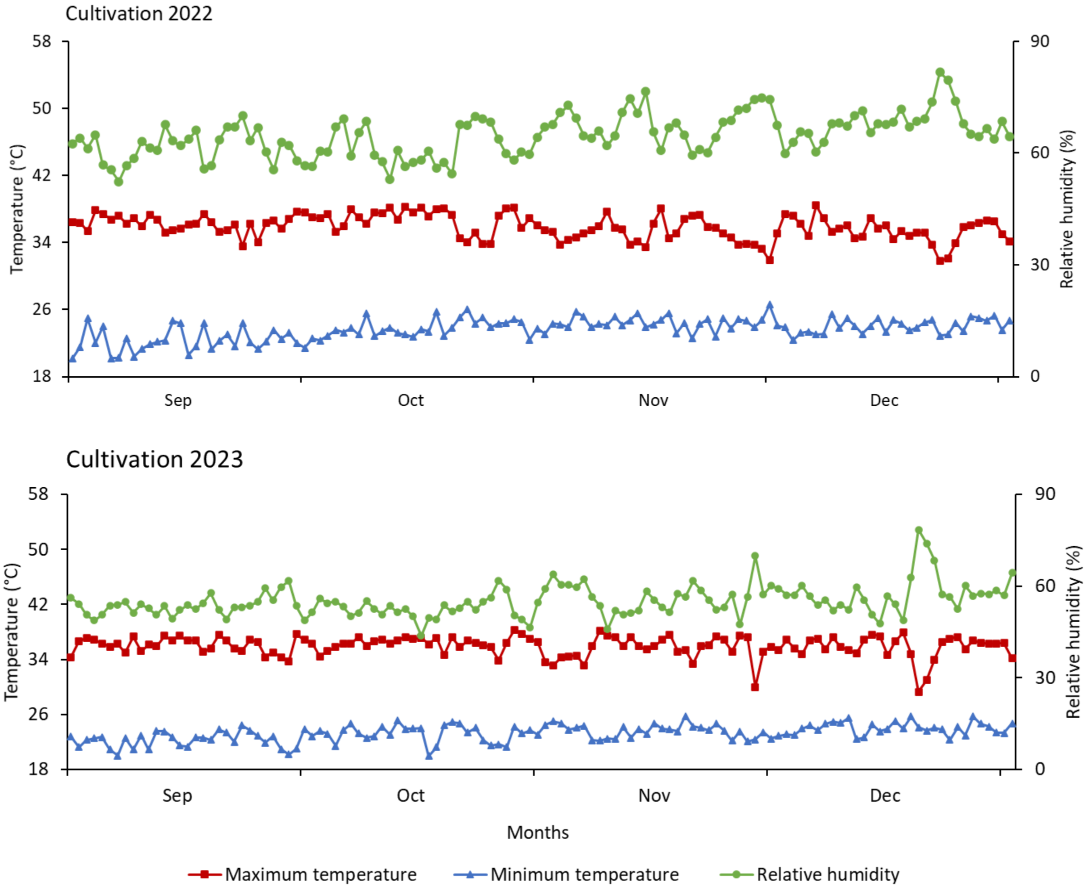


Figure 1. Average monthly climatic data on maximum and minimum temperatures and relative humidity in each year of cultivation of beet × cowpea intercropping.

The soils in the experimental areas were classified as typical dystrophic Red Argisols with a sandy loam texture (Santos et al., 2018). In each experimental area, simple soil samples were collected from the surface layer (0–20 cm) and homogenized to obtain a composite sample representative of the area. Subsequently, these samples were sent to the Water, Soil and Plant Tissue Analysis Laboratory of the Federal Institute of Education, Science and Technology of Ceará – Limoeiro do Norte Campus to determine their chemical attributes. The results in 2022 were as follows: pH (water) = 7.4; electrical conductivity (EC) = 0.34 dS m^{-1}; organic matter (OM) = 7.84 g kg^{-1}; phosphorus (P) = 6.0 mg dm^{-3}; potassium (K) = 1.35 $mmol_c$ dm_{-3}; calcium (Ca) = 3.28 $mmol_c$ dm_{-3}; magnesium (Mg) = 5.9 $mmol_c$ dm_{-3}; sodium (Na)= 1.74 $mmol_c$ dm_{-3}; copper (Cu) = 0.20 mg dm^{-3}; iron (Fe) = 5.2 mg dm^{-3}; manganese (Mn) = 10.8 mg dm^{-3}; zinc (Zn) = 1.10 mg dm^{-3} and boron (B) = 0.34 mg dm^{-3}. In 2023, they were as follows: pH (water) = 5.8; EC = 0.41 dS m^{-1}; OM = 13.25 g kg^{-1}; P = 7.0 mg dm^{-3}; K = 1.77 $mmol_c$ dm_{-3}; Ca = 8.4 $mmol_c$ dm_{-3}; Mg = 2.7 $mmol_c$ dm_{-3}; Na = 1.49 $mmol_c$ dm_{-3}; Cu = 0.22 mg dm^{-3}; Fe = 18.7 mg dm^{-3}; Mn = 4.9 mg dm^{-3}; Zn = 0.60 mg dm^{-3} and B = 0.44 mg dm^{-3}.

The experimental design used was randomized complete blocks, with treatments arranged in a factorial scheme (4×4) with 4 replications. The first factor was constituted by equitable amounts of *M. aegyptia* and *C. procera* biomass (20, 36, 52 and 68 t ha^{-1} on a dry basis), and the second factor consisted of the cowpea population density (80, 120, 160 and 200 thousand plants ha^{-1}). In each block, 2 plots were planted with monocropped beet and cowpea and fertilized with 49.87 and 50.48 t ha^{-1} of green manure biomass of hairy woodrose and roostertree, which was optimized by previous research in the region, to determine the agro-monetary indices (V. A. S. Lino et al., 2021; Desravines et al., 2022).

Beet–cowpea intercropping was established in alternating strips in the proportion of 50% of the area cultivated with beet and 50% of the area cultivated with cowpea. In each experimental plot, the alternating strips were composed of four rows of each crop flanked by two rows of cowpea on one side and two rows of beetroot on the other side, which were used as borders. The total area of each plot was 3.60 m² (3.00 m × 1.20 m), and the harvest area was 2.00 m² (2.00 m × 1.00 m) (Figure 2).

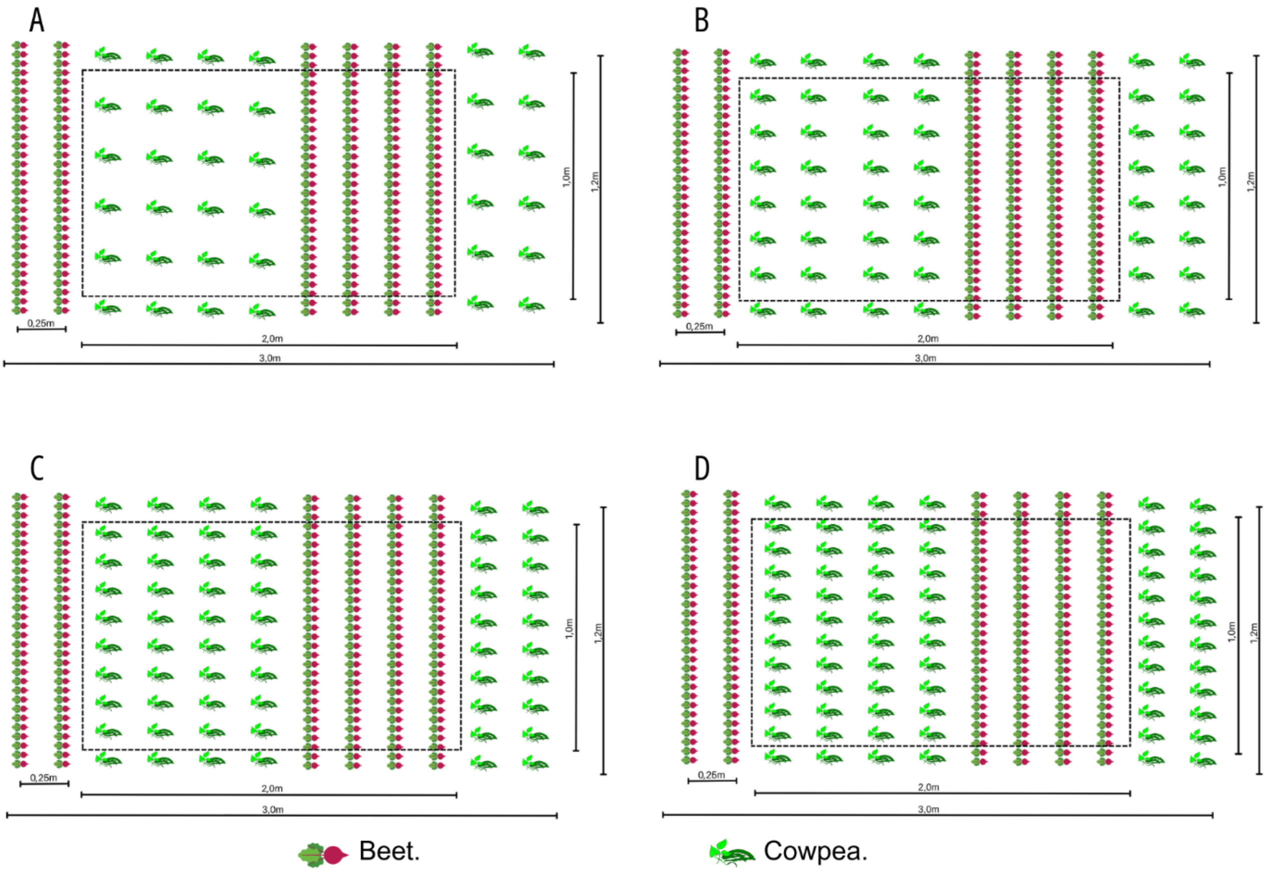


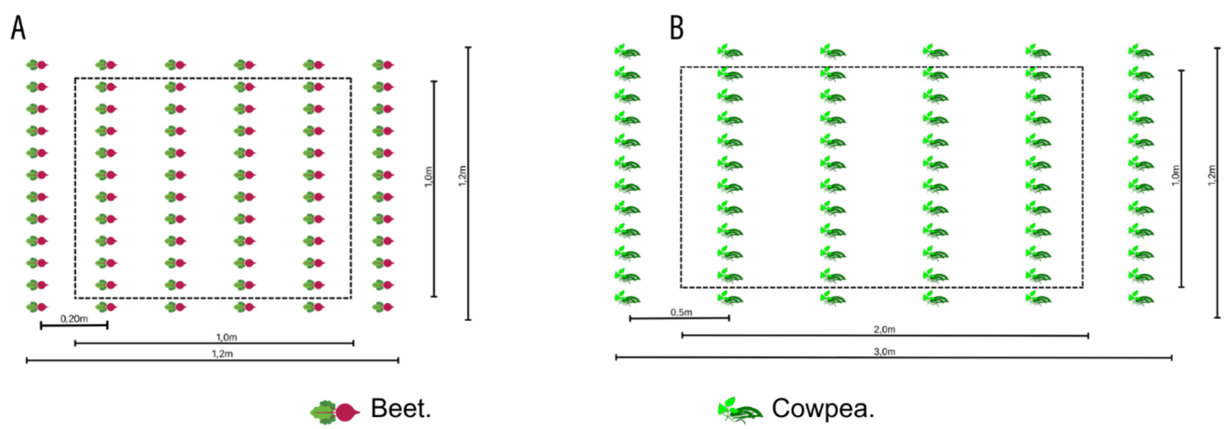
Figure 2. Graphical representation of the intercropping system plots:
(A) Beetroot intercropped with cowpea at a density of 80 thousand cowpea plants ha^{-1}; (B) 120 thousand cowpea plants ha^{-1}; (C) 160 thousand cowpea plants ha^{-1}; and (D) 200 thousand cowpea plants ha^{-1}.

This harvest area of the intercropped plots was made up of the 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 beet spacing in the intercropped treatments was 0.25 m × 0.04 m, providing a population of 500 thousand plants ha^{-1}. Each harvest area of the intercropping plot contained 100 beet plants (Figure 2). Cowpea spacing in the evaluated treatments was 0.25 m × 0.200 m, 0.25 m × 0.150 m, 0.25 m × 0.120 m and 0.25 m × 0.100 m, providing plant populations of 80, 120, 160 and 200 thousand plants ha^{-1}, respectively (Table 1). The number of cowpea plants in the harvest area was 16, 24, 32 and 40 at the evaluated spacings (Figure 2).

Table 1
Description of beet and cowpea population densities used in the intercropping and monocropping systems and their spacing

Population densities of intercropped crops (thousand plants ha^{-1})		Spacings (m)	
Beet	Cowpea	Beet	Cowpea
500	80	0.25 × 0.04	0.25 × 0.200
500	120	0.25 × 0.04	0.25 × 0.150
500	160	0.25 × 0.04	0.25 × 0.120
500	200	0.25 × 0.04	0.25 × 0.100
Population densities of the crops in monocropping (thousand plants ha^{-1})			
Beet	500	0.20 × 0.10	0.50 × 0.10
Cowpea	200		

Monocropped beet was established in a total area of 1.44 m² (1.20 m × 1.20 m), containing 6 rows, with a harvest area of 0.80 m² (0.80 m × 1.00 m) comprised of 4 rows, and a plant spacing of 0.20 m × 0.10 m. Monocropped cowpea was implemented in a total area of 3.60 m^2 (3.00 m × 1.20 m), containing 6 rows, with a harvest area of 2.00 m^2 (2.00 m × 1.00 m) comprised of 4 rows, and a spacing of 0.50 m × 0.10 m (Figure 3). Crop harvesting in both the intercropping and monocropping systems was carried out in the four central crop rows, excluding the lateral rows and the first and last plants in each crop row, which were considered borders.



Before installing the experiments, the soils in the experimental areas were mechanically cleaned using a tractor with a coupled plow, followed by harrowing and mechanized formation of planting beds. Pre-planting solarization was carried out in these beds with transparent plastic type Vulca Brilho Bril Flex (30 microns), which remained for 30 days to combat phytopathogenic microorganisms present in the soil that could affect crop productivity (Pereira et al., 2016).

After the solarization period, the materials used as green fertilizers were incorporated using hoes in two stages. In the first stage, 50% of the total quantity tested in each experimental plot was incorporated. The crops were planted 20 days after the first incorporation; this took place on October 11, 2022, for the first cultivation and September 27, 2023, for the second cultivation. The second incorporation was carried out with the remaining 50% of the green fertilizer doses 20 days after the crops were sown, specifically on October 31, 2022, for the first cultivation and on October 17, 2023, for the second cultivation, through the grooves opened in the space between the planting lines.

The materials used as green fertilizers were hairy woodrose (*Merremia aegyptia*) and roostertree (*Calotropis procera*) collected from native vegetation in several locations in the rural area of the municipality of Mossoró, RN, before flowering began. After collection the green manure was crushed in a conventional forager to obtain fragments of 2-3 cm. They were then dehydrated at room temperature until they reached 10% humidity and subsequently subjected to laboratory analysis. The chemical attributes of green manure in 2022 were as follows: 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 for hairy woodrose and 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 for roostertree. In 2023, the chemical attributes were as follows: 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 for hairy woodrose and 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 for roostertree.

The beet cultivar was ‘Early Wonder’ and the cowpea cultivar sown was ‘BRS Tumucumaque’. Both were sown in holes approximately 3 cm deep, with 3 to 4 seeds per hole, and covered with a commercial substrate for germination. Thinning in cowpea and beet crops was carried out 7 and 14 days after sowing, respectively. Only one plant per hole was left after thinning for both crops, both in the intercropping and monocropping systems. Throughout the entire period during which the experiments were conducted, manual weeding and hilling of beetroot was carried out when necessary. Any pests and diseases that appeared in the crops were controlled using the bio-insecticide Azamax - UPL.

Irrigation was carried out daily using the microsprinkler irrigation system, divided into two shifts (morning and afternoon). The amount of water supplied was determined based on the beet cultivation coefficient (main crop) obtained in the region (average Kc of 0.83) (D. H. Oliveira et al., 2011), providing a water depth of approximately 8 mm per day.

Beet was harvested at 65 days after planting (DAP) in the first cultivation and 69 DAP in the second cultivation. Cowpea harvests were carried out at 57 and 60 DAP in the first cultivation and at 48, 51 and 56 DAP in the second cultivation. The products from these harvests, both beet and cowpea, were sent to the laboratory for evaluation.

In the beet crop, the following characteristics were evaluated: plant height (cm), number of leaves per plant, fresh mass of the shoots and dry mass of roots (t ha^{-1}) and commercial and total root productivity (t ha^{-1}). The commercial productivity of roots was classified according to diameter, as large (> 7 cm), extra AA (≥ 6 and < 7 cm), extra A (≥ 5 and < 6 cm) and extra (> 4 and < 5 cm). In cowpea, the following characteristics were evaluated: plant height (cm), number of green pods per plant, length of green pods (cm), weight of 100 green grains (g), productivity of green pods and productivity of green grains (t ha^{-1}).

In the beet and cowpea intercropping system, the following agro-monetary indices were evaluated:

a) The system productivity index (SPI) was calculated using the following equation (Amanullah et al., 2020): $SPI = [(Y_b/Y_c) \times Y_{cb}] + Y_{bc}$, where Y_b represents the commercial productivity of monocropped beet roots (main crop); Yc represents the productivity of green grains of monocropped cowpea (secondary crop); Y_{cb} is the productivity of green cowpea grains in a system intercropped with beetroot; and Y_{bc} is the commercial productivity of beet roots intercropped with cowpea. The advantage of this SPI is that it standardizes the productivity of the secondary crop (cowpea) in relation to that of the main crop (beet). The higher the value of this index, the more efficient the intercropping system.

b) The land equivalent coefficient (LEC) was determined using the formula given by Diniz et al. (2017): $LEC = LER_b \times LER_c$, where LER_b and LER_c represent the partial land equivalence ratios of intercropped beet and cowpea, respectively. In the intercropping system, the minimum LEC value was 0.25, thus demonstrating that the intercropping system had a production advantage when it exceeded a value of 0.25.

c) The monetary equivalence ratio (MER) was determined using the formula given by Afe and Atanda (2015): $MER = (GI_{bc} + GI_{cb}) / G_{lb}$, where GI_{bc} is the gross income of beet intercropped with cowpea; GI_{cb} is the gross income of cowpea intercropped with beet; GIb is the highest gross income of monocropped beet compared to that of cowpea. Gross income (GI) was determined by multiplying the value of production obtained ha^{-1} by the price paid to the producer in the region's market in December 2022 and 2023. The prices paid to producers in the western region of the state of Rio Grande do Norte for cowpea green grains in 2022 and 2023 were BRL 12.00 and 14.00 per kilogram, respectively, and for beet roots, the prices were BRL 3.00 and BRL 3.25 per kilogram. This index measures the economic superiority of intercropping over monocropping of the most economical crop. The higher the value of this index, the more viable the cultivation system.

Univariate analysis of variance for a randomized block design in a factorial scheme was used to evaluate the homogeneity of variances between cultivations in each characteristic or index analyzed. Given the homogeneity of variances (observed by fulfilling the assumption that the ratio of the mean squares of the errors of the two cultivations should not be greater than 7), an average of the values obtained in each treatment in the two cultivations was calculated. Then, regression analysis was carried out for each characteristic or index using a response surface adjustment procedure as a function of the equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil and the cowpea population density in TableCurve 3D software v 4.0 (SYSTAT Software, 2021). A Student's t-test was used to determine whether there were significant differences between the intercropping and monocropping systems.

Results and Discussion

Cowpea crop performance

The results of the variance and regression analyses for the agronomic characteristics evaluated in cowpea are presented in Table 2. No significant interaction in plant height (PH), green pod length (GPL), number of green pods per plant (NGPP), weight of 100 green grains (W100GG), productivity of green pods (PGP) and productivity of green grains (PGG)was observed between amounts of the green manure and cowpea population densities. On the other hand, it was possible to observe significant differences between the studied production systems in the number of green pods per plant (NGPP), productivity of green pods (PGP), and productivity of green grains (PGG), with monocropping standing out from the intercropping system (Table 2).

Table 2
F values for plant height (PH), green pod length (GPL), number of green pods per plant (NGPP), weight of 100 green grains (W100GG), productivity of green pods (PGP) and productivity of green grains (PGG) of cowpea with different equitable amounts of *M. aegyptia* and *C. procera* biomass and cowpea population densities

Sources of variation	DF	PH	GPL	NGPP	W100GG	PGP	PGG
Blocks	3	5.53**	1.66^{ns}	0.17^{ns}	1.81^{ns}	0.44^{ns}	1.24^{ns}
Amounts of M. aegyptia and C. procera biomass (A)	3	6.75**	6.17**	4.76**	2.76*	11.39**	7.68**
Population densities of cowpea (D)	3	3.13*	7.87**	3.08*	0.64 ns	4.15**	2.73*
A × D	9	0.45^{ns}	0.85^{ns}	0.12^{ns}	1.02^{ns}	0.33^{ns}	0.21^{ns}
Monocropping (M) × Intercropping (C)	1	0.25^{ns}	2.59^{ns}	20.43**	0.11^{ns}	129.62**	121.14**
Regression (Response surface)		15.51**	8.74**	8.86**	6.40**	23.78**	14.14**
Error		1.13788	0.14422	0.07288	0.24593	0.05355	0.01100
Cropping systems		**PH (cm)**	**GPL (cm)**	**NGPP**	**W100GG (g)**	**PGP (t ha^{-1})**	**PGG (t ha^{-1})**
Monocropping		66.95 a	22.07 a	6.71 a	44.58 a	7.29 a	3.38 a†
Intercropping		66.22 a	21.42 a	4.98 b	44.27 a	3.77 b	1.68 b
CV (%)		4.24	3.68	14.59	4.08	15.08	16.77

*, **, ns - Significant at $p \leq 0.05$ and at $p \leq 0.01$, and non-significant at $p > 0.05$ by F test; CV – Coefficient of variation. †Means followed by different lowercase letters in the column differ statistically from each other by the F test at the 5% probability level.

However, a response surface was fitted across all these cowpea traits as a function of treatment factors, biomass amounts of *M. aegyptia* and *C. procera,* and population densities of cowpea plants intercropped with beet (Figure 4). The highest PH, PGP and PGG values of 69.48 cm, 4.53 and 2.06 t ha^{-1} were achieved in the combinations of equitable amounts of the green manure biomass of 68 t ha^{-1} and cowpea population densities of 145, 150 and 150 thousand plants ha^{-1}, respectively (Figures 4A, 4E and 4F). For GPL, NGPP and W100GG, the maximum values obtained were 22.44 cm, 5.9 and 45.65 g in the combinations of equitable amounts of the green manure biomass of 50.28, 56.41 and 57.24 t ha^{-1} at cowpea population densities of 80, 80 and 138 thousand plants ha^{-1}, respectively (Figures 4C, 4B and 4D).

It can be seen from the results obtained in PH, PGP and PGG that these characteristics were most affected by the treatment factor, amounts of biomass of *M. aegyptia* and *C. procera,* as their maximum points were reached at the maximum dose of the green manure tested. Shimada et al. (2000) state that when cowpea is subjected to increased planting density, there is a compensatory effect on grain yield due to the increase in plant population per area and the increase in seed mass. Therefore, these maximum production values obtained per unit area determine the ideal population of the crop.

In turn, the results obtained with GPL, NGPP and W100GG were achieved at doses lower than the maximum incorporated, with GPL and NGPP at lower cowpea population density and W100GG at density between the intermediate and to higher added to the soil. This is probably due to the genetic nature of the characteristics evaluated, not allowing significant influence of quantitative treatment factors on their expression. These different results show that the cowpea cultivar "BRS Tumucumaque" is a plant that presents reasonable adaptability in different situations of population density and fertilizer doses tested in edaphoclimatic conditions of the semi-arid region of Northeastern Brazil. However, it is known that when spacing decreases within rows, population density increases, and within certain limits, production may remain stable or with low variation due to the level of competition not being strong enough to alter its behavior (Chaves et al., 2020).

The characteristics evaluated in cowpea had higher averages in monocropping compared to the intercropping system. These results are due to the type of competition between the two systems. In monocropping, the type of competition recorded is intraspecific, while in the intercropping system, two types of competition occur: intraspecific and interspecific. In intercropping systems with companion crops, the degree of complementarity between the component crops is always maximized, thus minimizing the types of competition between them and promoting advantages to the intercropping system (Barot et al., 2017).

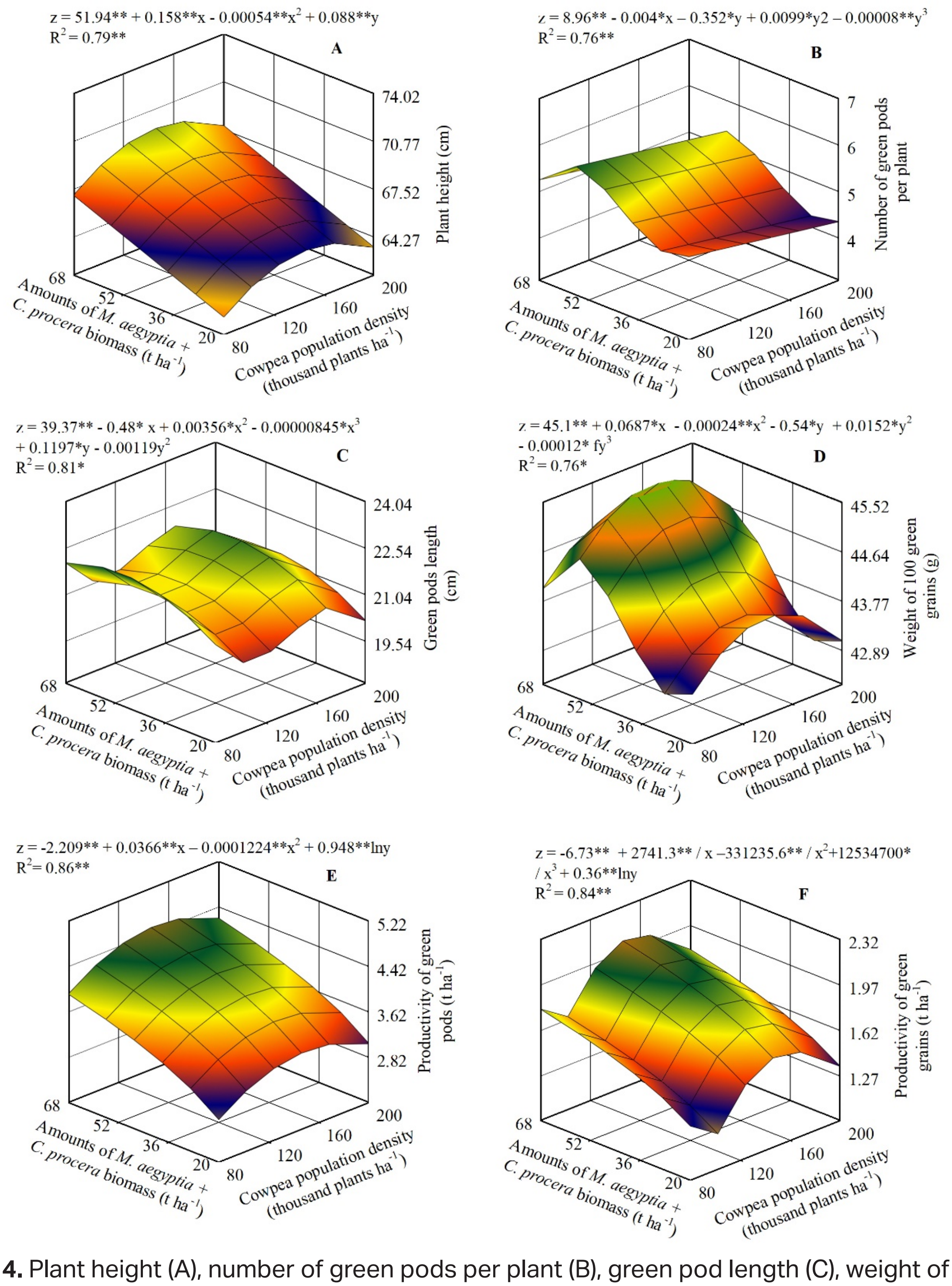


Figure 4. Plant height (A), number of green pods per plant (B), green pod length (C), weight of 100 green grains (D), and productivity of green pods (E) and productivity of green grains (F) of cowpea intercropped with beet with different equitable amounts of *M. aegyptia* and *C. procera* biomass and cowpea population densities.

Beet crop performance

Agronomic characteristics

There was no significant interaction between the equitable amounts of hairy woodrose and roostertree biomass incorporated into the soil and cowpea population densities for any of the agronomic characteristics studied in the beet crop (Table 3). However, evaluating the cropping systems studied, it was possible to observe significant differences between them in plant height (PH), number of leaves per plant (NLP), fresh mass of shoots (FMS) and dry mass of roots (DMR) of beet intercropped with cowpea. For PH, the intercropping system stood out from the monocropping system, while for NLP, FMS and DMR, monocropping stood out from intercropping (Table 3).

Table 3

F values for plant height (PH), number of leaves per plant (NLP), fresh mass of shoots (FMS) and dry mass of roots (DMR) of beet intercropped with cowpea with different equitable amounts of *M. aegyptia* and *C. procera* biomass and cowpea population densities

Sources of variation	DF	PH	NLP	FMS	DMR
Blocks	3	1.01^{ns}	3.42*	2.49^{ns}	9.64**
Amounts of M. aegyptia and C. procera biomass (A)	3	7.22**	6.38**	7.56**	3.94*
Population densities of cowpea (D)	3	4.71**	0.40 ns	2.68*	3.31*
A × D	9	1.17^{ns}	0.03^{ns}	0.54^{ns}	0.48^{ns}
Monocropping (M) × Intercropping (C)	1	7.25**	14.94**	22.58**	184.22**
Regression (Response surface)		9.97**	69.12**	14.79**	26.09**
Error		1.2079	0.0057	0.0154	0.0064
Cropping systems		**PH (cm)**	**NLP**	**FMS (t ha^{-1})**	**DMR (t ha^{-1})**
Monocropping		40.92 b	8.70 a	2.82 a	3.74 a†
Intercropping		43.83 a	7.57 b	1.97 b	1.71 b
CV (%)		4.79	7.40	17.27	15.93

*, **, ns - Significant at $p \leq 0.05$ and at $p \leq 0.01$, and non-significant at $p > 0.05$ by F test; CV – Coefficient of variation. †Means followed by different lowercase letters in the column differ statistically from each other by the F test at the 5% probability level.

A response surface adjustment was performed on each agronomic trait evaluated in beet. For PH, FMS and DMR (Figures 5A, 5C and 5D), the combination of cowpea densities with the tested doses showed maximization and optimization of the degree of complementarity between crops, with maximum values of 46.35 cm, 2.45 and 1.97 t ha^{-1} at cowpea planting densities of 140, 152 and 124 thousand plants ha^{-1}, respectively, and 68 t ha^{-1} of green manure biomass. For NLP, the maximum value was 8.0 leaves per plant in the combination with a cowpea planting density of 200 thousand plants ha^{-1} and 57.66 t ha^{-1} of green manure biomass (Figure 5D).

In general, PH, FMS and DMR were more affected by the amount of green manure incorporated into the soil than by the cowpea density. NLP was more affected by the cowpea density than by the dry mass of hairy woodrose and roostertree added to the soil.

High population densities of cowpea (above 140 thousand plants per hectare) caused beet plants to have shorter plant heights, lower fresh shoot mass, and lower dry mass of roots. Probably, the shading caused by cowpea plants and the inter-species competition for natural resources hindered the development of beet plants. In this case, cowpea plants intercepted part of the solar radiation, as they were taller than the beet plants. With less available light, there was a reduction in photosynthesis and the production of photoassimilates, consequently leading to reduced development of beet plants (Peixoto et al., 2020).

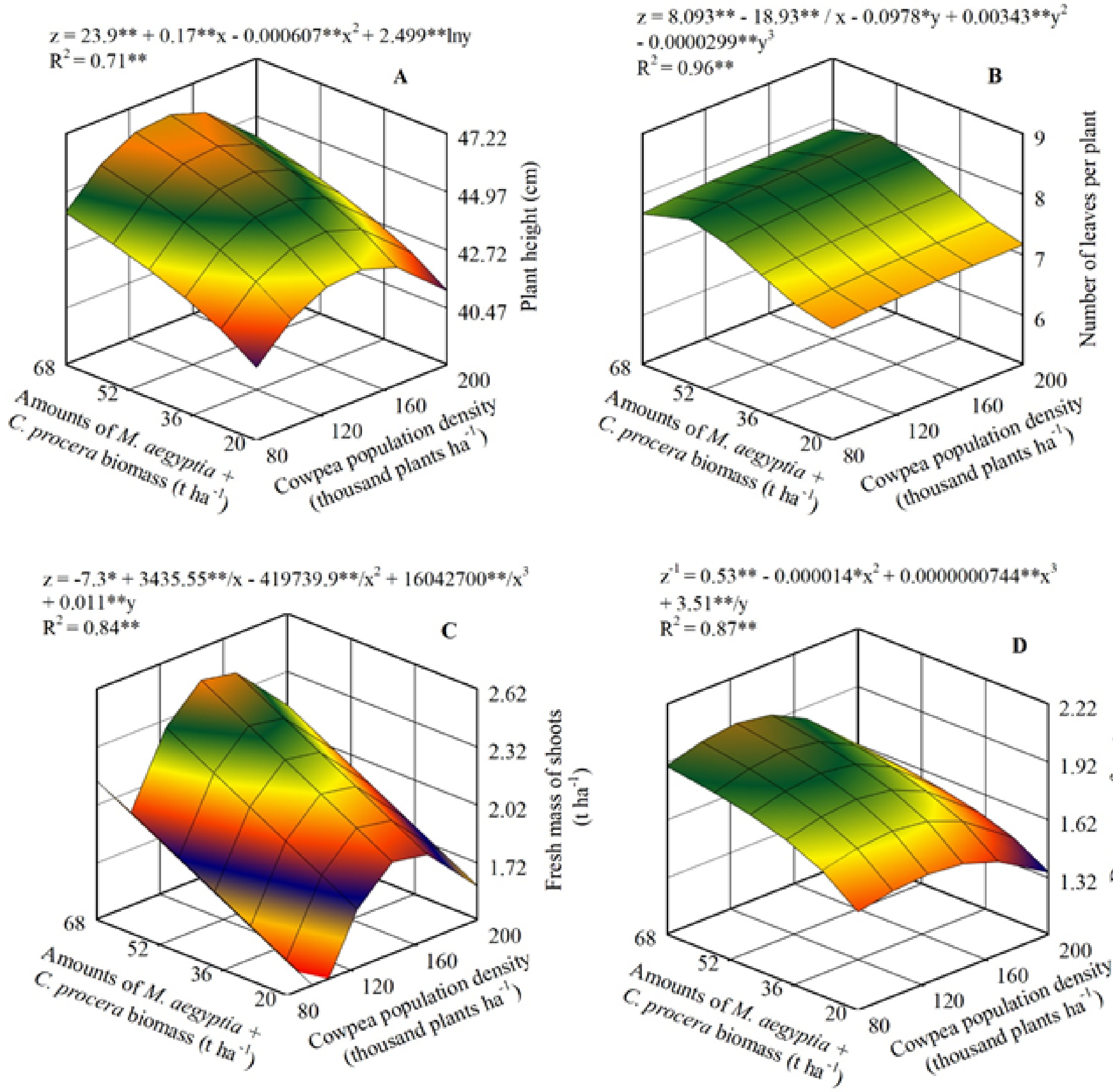


Figure 5. Plant height (A), number of leaves per plant (B), fresh mass of shoots (C) and dry mass of roots (D) of beet intercropped with cowpea with different equitable amounts of M. aegyptia and C. procera biomass and cowpea population densities.

Productivity characteristics

There was no significant interaction between treatment factors, equitable amounts of hairy woodrose and roostertree biomass incorporated into the soil, and cowpea population densities on classified root productivity in large, extra AA, extra A and extra beet (Table 4). However, a significant interaction was recorded between these treatment factors for commercial and total root productivities. Significant differences in the productivity characteristics of beet, except in the productivity of extra A roots, were observed between the cropping systems. For the productivities of large, extra AA, commercial and total roots, the monocropping system stood out from the intercropping system, while in terms of extra root productivity, the intercropping system surpassed the monocropping system (Table 4).

Table 4
F values for root productivities (large, extra AA, extra A, extra, commercial (PC), and total (PT) roots) of beet intercropped with cowpea with different equitable amounts of *M. aegyptia* and *C. procera* biomass and cowpea population densities

Sources of variation	DF	Large	Extra AA	Extra A	Extra	PC	PT
Blocks	3	2.92*	6.98**	3.24*	0.02^{ns}	5.14**	10.81**
Amounts of M. aegyptia and C. procera biomass (A)	3	28.30**	31.53**	8.74**	9.90**	145.24**	63.55*
Population densities of cowpea (D)	3	8.77**	8.86**	7.22**	8.46**	62.05**	20.93**
A × D	9	0.96^{ns}	1.70^{ns}	0.30^{ns}	0.37^{ns}	2.89*	3.45**
Monocropping (M) × Intercropping (C)	1	578.24**	30.77**	1.05^{ns}	13.64**	851.98**	772.04**
Regression (Response surface)		36.90**	12.14**	25.67**	11.34**	33.17**	19.56**
Error		0.2544	0.3076	0.0385	0.05969	0.89921	0.16076
Cropping systems		**Large**	**Extra AA**	**Extra A**	**Extra**	**PC**	**PT**
		----------------	----------------	t ha^{-1}	----------------	----------------	
Monocropping		17.44 a	5.90 a	2.74 a	2.34 b	28.41 a	32.28 a†
Intercropping		4.79 b	4.01 b	3.01 a	3.16 a	14.97 b	16.90 b
CV (%)		18.44	16.02	17.38	13.93	5.66	6.03

*, **, 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. †Means followed by different lowercase letters in the column differ statistically from each other by the F test at the 5% probability level.

A response surface was adjusted for all productivity traits of beetroot as a function of the treatment factors, equitable amounts of *M. aegyptia* and *C. procera* biomass, and cowpea population densities when intercropped with beet (Figure 6). For the productivities of large, extra AA, extra A, extra roots, commercial and total roots (Figures 6A, 6B, 6C, 6D, 6E, and 6F), maximum values of 7.19, 5.46, 3.74, 3.68, 18.96 and 19.94 t ha−1 were achieved in the combinations with cowpea densities of 142, 115, 136, 200, 142 and 137 thousand plants ha^{-1} with 68, 68, 68, 46.48, 60.79 and 68 t ha^{-1} green manure biomass, respectively.

Based on the obtained results, the productivities of large roots, extra AA and extra A and the total productivity of roots were more affected by the amount of green manure since their maximum points were reached at the maximum dose of green manure at intermediate cowpea densities. However, the productivity of extra roots was more affected by the cowpea density, as its maximum point was reached at the highest cowpea population density when fertilized at an intermediate dose of green manure. The commercial root productivity was affected by both the amounts of green manure and the cowpea densities since its maximum point was reached at an intermediate density and green manure dose.

This result of the commercial root productivity achieved with green fertilizer and an intermediate cowpea population density shows that the complementarity of the intercropping system was achieved through the characteristics of the crops, such as architecture, cycle and nutritional requirements. This behavior can be explained by the rapid mineralization and availability of nutrients released by green fertilizer. At a certain point in the plant cycle, the nutritional requirement reaches a maximum level, and in this study, this may have occurred at the time of nutrient release, thus creating a synchrony and, consequently, better use of this resource (Bezerra et al., 2014).

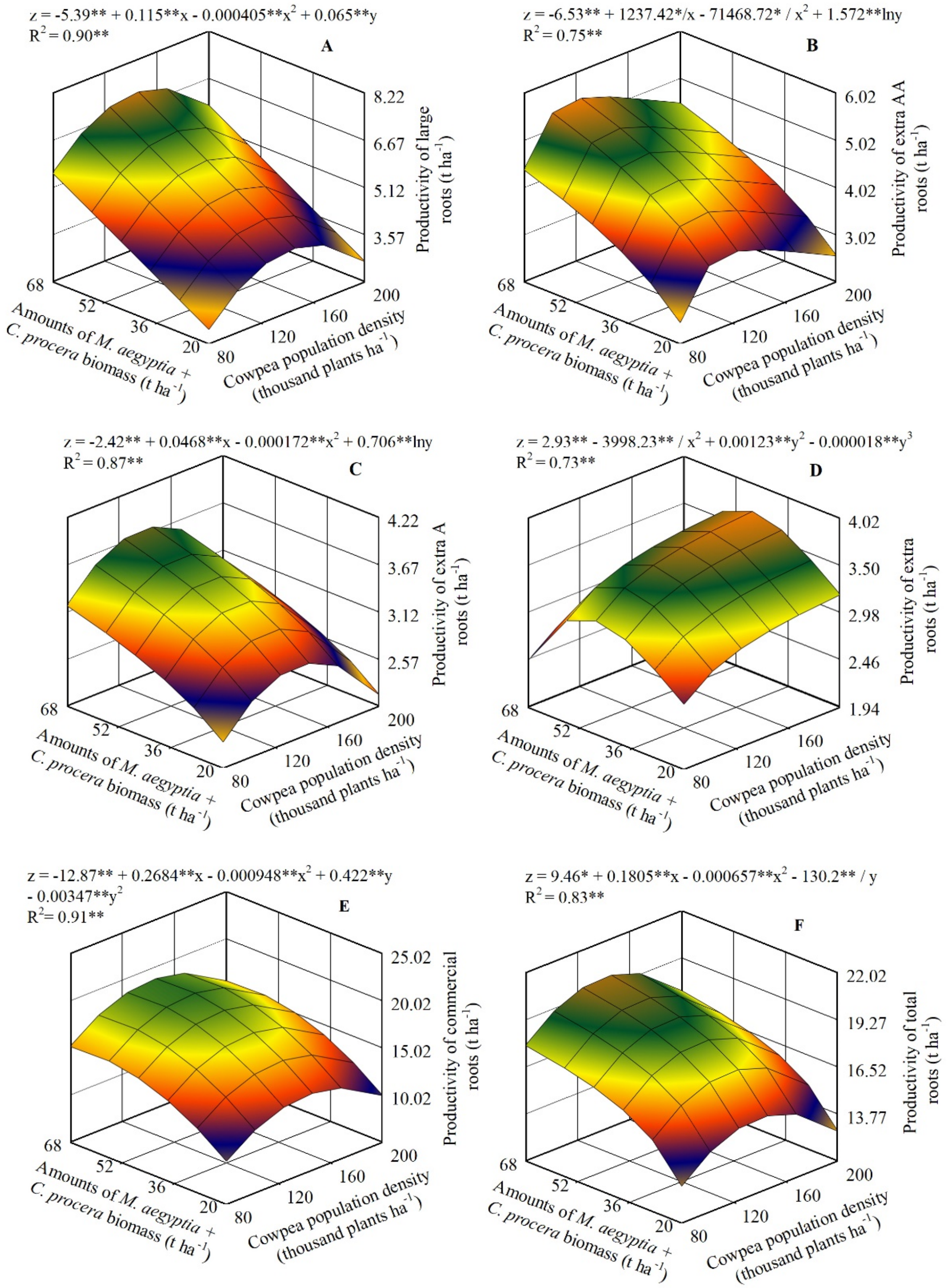


Figure 6. Productivities of large (A), extra AA roots (B), extra A (C), extra (D), commercial (E) and total roots (F) of beet intercropped with cowpea with different equitable amounts of *M. aegyptia* and *C. procera* biomass and cowpea population densities.

For the productivity of commercial roots (14.97 t ha^{-1}) in the intercropping system, 4.79 t ha^{-1} was attributed to large roots, 4.01 t ha^{-1} to extra AA roots, 3.01 t ha^{-1} to extra A roots and 3.16 t ha^{-1} to extra roots. The highest productivities were from large and extra AA roots. These results partially agree with those found by Guerra et al. (2021), who studied beet–lettuce intercropping in the same region as this research with different equitable amounts of Merremia aegyptia and Calotropis procera biomass (20, 35, 50 and 65 t ha^{-1} on a dry basis) at diverse lettuce population densities (150, 200, 250 and 300 thousand plants ha^{-1}). In the intercropping system, they found a commercial root productivity of 24.79 t ha^{-1}, in which 10.45 t ha^{-1} were attributed to large roots, 6.60 t ha^{-1} to the extra AA type, 3.57 t ha^{-1} to the extra A type and 4.17 t ha^{-1} to the extra type. These differences between the studies are due to the secondary crop used, which was lettuce in the referenced study, the small differences in competition between them, temperature and relative humidity of the experimental locations, and treatment factors tested. Both authors used the same beet cultivar 'Early Wonder' and found a predominance of large and extra AA roots.

Agro-monetary performance of beet × cowpea intercropping

The results of variance and regression analyses for the agro-monetary indexes evaluated for beet and cowpea intercropping are presented in Table 5. No significant interaction was recorded between the studied treatment factors, equitable amounts of M. aegyptia and C. procera biomass, and cowpea population densities in SPI, LEC and MER.

Table 5
F values for system productivity index (SPI), land equivalent coefficient (LEC) and monetary equivalence ratio (MER) of beet intercropped with cowpea with different equitable amounts of *M. aegyptia* and *C. procera* biomass and cowpea population densities

Sources of variation	DF	SPI	LEC	MER
Blocks	3	2.42^{ns}	2.20^{ns}	4.05*
Amounts of *M. aegyptia* and *C. procera* biomass (A)	3	60.22**	53.47**	111.38**
Population densities of cowpea (D)	3	22.72**	20.83**	43.80**
A × D	9	0.60^{ns}	0.74^{ns}	1.33^{ns}
Regression (Response surface)		29.30**	21.77**	33.42**
Error		2.5778	0.0011	0.0063
CV (%)		7.83	15.80	6.13

*, **, ns - Significant at $p \leq 0.05$ and at $p \leq 0.01$, and non-significant at $p > 0.05$ by F test; CV – Coefficient of variation.

However, a response surface for each agro-monetary indicator was fitted (Figure 7). The maximum values achieved for SPI, LEC and MER were 35.37 t ha^{-1}, 0.35 and 1.79, using a combination of equitable amounts of green manure biomass of 62.19, 62.07, and 61.63 t ha^{-1}, respectively, at a cowpea population density of 142 thousand plants ha^{-1} (Figures 7A, 7B and 7C).

Given these results, *M. aegyptia* and *C. procera* biomass was the factor that most affected these indices, when combined with a cowpea population density of 142 thousand plants ha^{-1}, an intermediate density. The high SPI and LEC values demonstrated the agronomic efficiency of the beet–cowpea intercropping system in this combination compared to monocropping. SPI is used to standardize the productivity of the primary crop (beet) compared to the secondary one (cowpea) (Jardim et al., 2021), while LEC with values higher than 0.25 in the intercropping system had a production advantage over monocropping (F. K. K. S. Lino et al., 2022).

Regarding the maximum value obtained for MER (1.79), the agronomic efficiency of beet–cowpea intercropping was translated into economic terms. According to Afe and Atanda (2015), when MER is greater than 1.0, the intercropping systems are considered more profitable compared to monocropping of the component crops. This superiority of the MER can also be attributed to the complementary nature of the crops involved in the system and to the similarity in cycle length between beet and cowpea crops (which varies widely between cultivars).

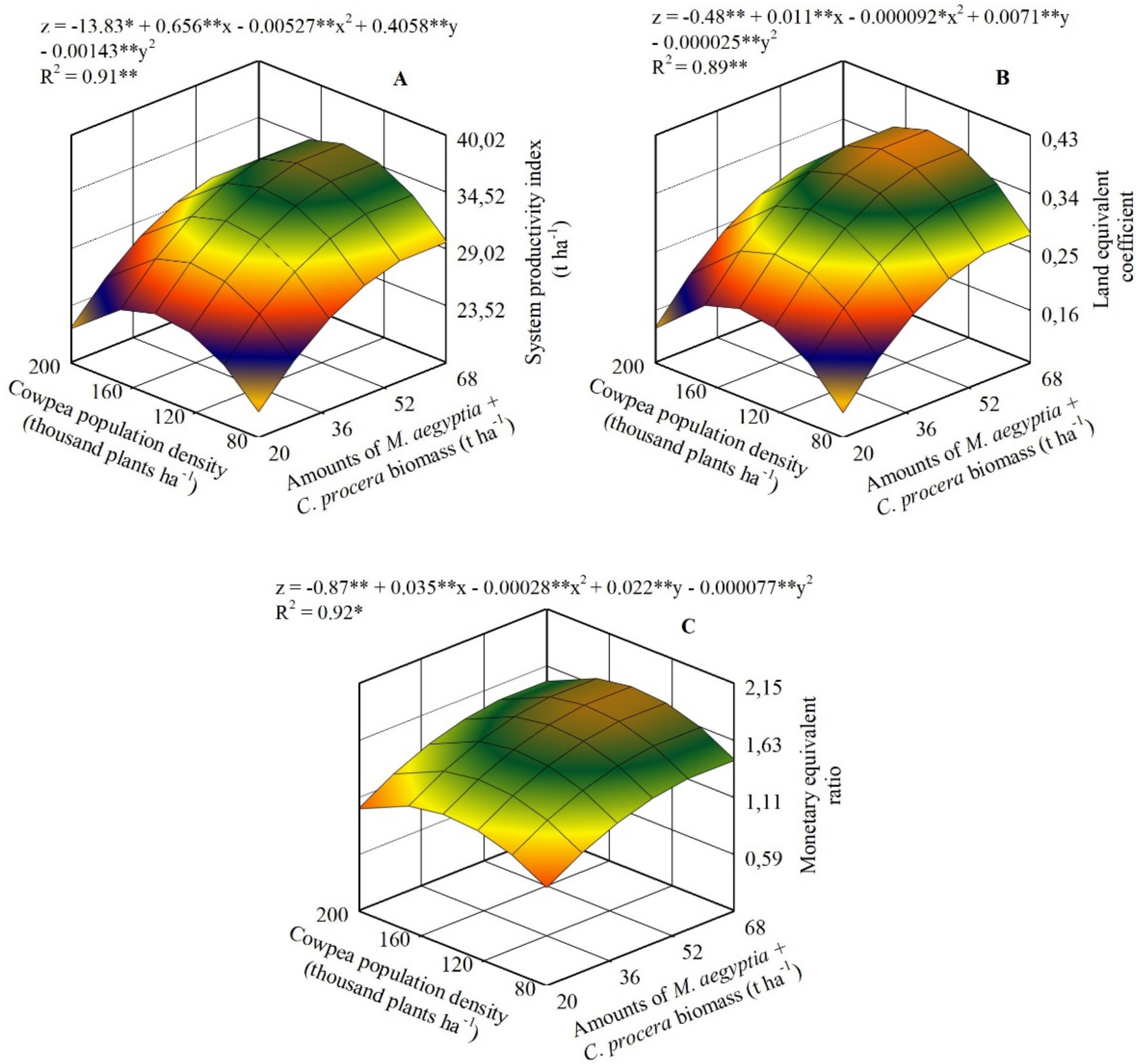


Figure 7. System productivity index (SPI) (A), land equivalent coefficient (LEC) (B) and monetary equivalence ratio (MER) (C) of beet intercropped with cowpea with different equitable amounts of *M. aegyptia* and *C. procera* biomass and cowpea population densities.

The achievement of good agro-monetary indicators can be explained both by the good nutritional input provided by green manure and by the ability of the intercropped crops to express their agronomic potential, even at high densities. Based on the obtained results, we verified that, even at a high density of the secondary crop (cowpea), interspecific competition was reduced because the component crops had the capacity to explore distinct ecological niches, thus strengthening the degree of complementarity between the component crops (Costa et al., 2017).

Conclusion

Beet–cowpea intercropping showed agronomic and economic viability and sustainability with a SPI of 35.37 t ha^{-1}, LEC of 0.35 and MER of 1.79 in the combinations with an equitable amount of green manure biomass of 62.19, 62.07 and 61.63 t ha^{-1} and a cowpea population density of 142 thousand plants ha^{-1}. The use of biomass mixtures of *M. aegyptia* and *C. procera* from the Caatinga ecosystem proved to be a viable strategy for producers who grow beet with cowpea in intercropping systems in a semiarid environment. The indexes used in the evaluation of cropping systems can help producers make appropriate decisions in terms of complementarity and sustainability in the implementation of their intercropping system.

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