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Maximizing agro-bioeconomic benefits in intercropped systems of radish and lettuce in the semi-arid environment[1]

Maximização de benefícios agro-bioeconômicos em sistemas consorciados de rabanete e alface em ambiente semiárido

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HIGHLIGHTS:

Merremia aegyptia *and* Calotropis procera *biomass amounts provide agro-bioeconomic returns in radish-lettuce intercropping.*
Increasing population densities of lettuce provide agro-bioeconomic returns in radish-lettuce intercropping.
Using M. aegyptia *and* C. procera *as green manures proves a viable technology for radish-lettuce producers in semi-arid.*

ABSTRACT: Radish and lettuce are two crop vegetables that can be intercropped because they are companion cultures that complement each other. Thus, this study aimed to evaluate agro-bioeconomic returns arising from radish-lettuce intercropping in different equitable amounts of hairy woodrose (*Merremia aegyptia*) and roostertree (*Calotropis procera*) biomass at different population densities of lettuce, in the semi-arid environment. The experimental design was in randomized blocks, with treatments arranged in a 4 × 4 factorial scheme with four replicates. The first factor consisted of equitable amounts of *M. aegyptia* and *C. procera* biomass at doses of 20, 35, 50, and 65 Mg ha^{-1} on a dry basis. The second factor comprised four lettuce population densities of 150, 200, 250, and 300 thousand plants ha^{-1}. The lettuce and radish cultivars planted were 'Tainá' and 'Crimson Gigante', respectively. Expressive agro-bioeconomic returns from this radish-lettuce intercropping were obtained in the land equivalent ratio (LER) of 2.25, a score of the canonical variable Z of 3.00, net income (NI) of 52,270.48 R$ ha^{-1}, respectively, in the biomass amount of 65 Mg ha^{-1} of the green manures and lettuce population density of 300 thousand plants ha^{-1}. Also, there was a productive efficiency index (PEI) of 0.96 and a competitive ratio (CR) of 2.61 in the biomass amount of green manure of 65 Mg ha^{-1} and lettuce density of 150 thousand plants ha^{-1}. Using *M. aegyptia* and *C. procera* biomass from the Caatinga biome proved to be a viable technology for producers who practice the cultivation of radish and lettuce in intercropping in the semi-arid environment.

Key words: *Raphanus sativus*, *Lactuca sativa*, *Merremia aegyptia*, *Calotropis procera*, economic feasibility

RESUMO: O rabanete e a alface são duas hortaliças que podem ser consorciadas, porque são culturas companheiras que se complementam. Assim, este estudo teve como objetivo avaliar retornos agro-bioeconômicos advindos do consórcio rabanete-alface em diversas quantidades equitativas de biomassa de jitirana (*Merremia aegyptia*) e flor-de-seda (*Calotropis procera*) em diferentes densidades populacionais de alface, em ambiente semiárido. O delineamento experimental utilizado foi em blocos ao acaso, com os tratamentos dispostos em esquema fatorial 4 × 4, com quatro repetições. O primeiro fator consistiu em quantidades equitativas de biomassa de *M. aegyptia* e *C. procera* nas doses de 20, 35, 50 e 65 Mg ha^{-1} em base seca. O segundo fator compreendeu quatro densidades populacionais de alface de 150, 200, 250 e 300 mil plantas ha^{-1}. As cultivares de alface e rabanete plantadas foram 'Tainá' e 'Crimson Gigante', respectivamente. Retornos agro-bioeconômicos expressivos deste consórcio de rabanete-alface foram obtidos na razão equivalente de terra (RET) de 2,25, escore da variável canônica Z de 3,00 e na renda liquida (RL) de 52.270,48 R$ ha^{-1}, respectivamente, na quantidade de biomassa de 65 Mg ha^{-1} dos adubos verdes e densidade populacional de alface de 300 mil plantas ha^{-1}. Além disso, registrou-se também um índice de eficiência produtiva (IEP) de 0,96 e uma razão competitiva (RC) de 2,61 na quantidade de biomassa dos adubos de 65 Mg ha^{-1} e densidade de alface de 150 mil plantas ha^{-1}. A utilização de biomassa de *M. aegyptia* e *C. procera* do bioma Caatinga, mostrou-se uma tecnologia viável para produtores que praticam o cultivo de rabanete e alface em consórcio em ambiente semiárido.

Palavras-chave: *Raphanus sativus*, *Lactuca sativa*, *Merremia aegyptia*, *Calotropis procera*, viabilidade econômica

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Introduction

One of the cultivation practices used in vegetable production systems is the intercropping of crops, which consists of cultivating two or more crops close, intending to produce a greater yield per area, making use of environmental resources that would otherwise not be possible to be used by a single culture. Radish and lettuce are vegetables that meet this requirement for the efficiency of the intercropped system, as they are companion crops and complement each other (Damasceno et al., 2016).

Another requirement for the success of this cultivation practice has been how to properly manage production factors, types and amounts of fertilizers, and planting density of the component crops (Andrade Filho et al., 2020). Among the types of fertilizers that stand out are green manures, such as hairy woodrose and roostertree, which are spontaneous species from the Caatinga biome (Lino et al., 2021; Sá et al., 2021). The hairy woodrose is an herbaceous species with an average production of green and dry phytomass around 36,000 and 4,000 kg ha^{-1}, respectively, with high nitrogen content, around 26.2 g kg^{-1} in dry matter, and a C/N ratio of 18/1 (Linhares et al., 2012). The roostertree is a shrub species (Rangel & Nascimento, 2011) with an average production of phytomass on a dry basis, around 3,000 kg ha^{-1} by cut (120 days), reaching 9 Mg ha^{-1} per year (EMPARN, 2004), with nitrogen content around 18.4 g kg^{-1} in dry matter, and a C/N ratio of 25/1 (Nunes et al., 2018).

One of the great challenges has been using these species as green manure and the plant population in intercropped vegetable systems in determining the amount and plant density that optimizes the yield and agro-bioeconomic indicators of the system to achieve maximum agronomic, biological, and economic efficiency in their crops.

The present study aimed to evaluate agro-bioeconomic returns arising from radish-lettuce intercropping in different equitable amounts of hairy woodrose (*Merremia aegyptia*) and roostertree (*Calotropis procera*) biomass at different population densities of lettuce in the semi-arid environment.

Material and Methods

Field experiments were conducted from October 2020 to January 2021 and from July to November 2021 at the Experimental Farm 'Rafael Fernandes', belonging to the Universidade Federal Rural do Semi-Árido (UFERSA), located in the district of Alagoinha, approximately 20 km from Mossoró, RN, Brazil, at 5º 03' 37" S, 37º 23' 50" W, and altitude of 80 m.

The climate of the region, according to the Köppen classification, is BShw, that is, dry and very hot with two seasons: a dry season starting in June and ending in January, and a rainy season starting in February and ending in May (Alvares et al., 2014). During the experimental periods of 2020/2021 and 2021, the average temperatures were 29.32 and 29.40 °C, the average minimum temperatures were 24.77 and 23.95 °C, the average maximum temperatures were 35.95 and 36.80 °C, the average relative air humidity was 61.08 and 58.50%, average wind speeds were 6.37 and 6.45 m s^{-1}, average solar radiations were 19.29 and 21.13 MJ m^{-2}, and rainfalls were 0 and 0 mm, respectively.

The soils of the experimental areas were classified as Ultisol (USDA, 2014). Before the installation of each experiment, soil samples were taken from the 0-20 cm layer and homogenized to obtain a composite sample representative of the entire area, whose results in 2020/2021 cultivation were: pH (water) = 6.3; electric conductivity (EC) = 0.44 dS m^{-1}; organic matter (OM) = 11.90 g kg^{-1}; N = 0.60 g kg^{-1}; P = 24.00 mg dm^{-3}; K = 52.28 mg dm^{-3}; Ca = 22.50 cmol$_c$ dm^{-3}; Mg = 4.80 cmol$_c$ dm^{-3}; Na = 1.73 mg dm^{-3}; Cu = 0.50 mg dm^{-3}; Fe = 5.70 mg dm^{-3}; Mn = 11.20 mg dm^{-3}; Zn = 3.80 mg dm^{-3}. In 2021 cultivation the results were: pH (water) = 6.60; EC = 0.56 dS m^{-1}; OM = 12.97 g kg^{-1}; N = 0.65 g kg^{-1}; P = 32.00 mg dm^{-3}; K = 61.27 mg dm^{-3}; Ca = 23.70 cmol$_c$ dm^{-3}; Mg = 6.50 cmol$_c$ dm^{-3}; Na = 2.30 mg dm^{-3}; Cu = 0.30 mg dm^{-3}; Fe = 4.80 mg dm^{-3}; Mn = 6.10 mg dm^{-3}; Zn = 2.70 mg dm^{-3}.

The experimental design used was complete randomized blocks, with treatments arranged in a 4 × 4 factorial scheme with four replicates. The first factor to be tested consisted of equitable biomass amounts of green manures of *M. aegyptia* and *C. procera* (20, 35, 50, and 65 Mg ha^{-1} on a dry basis, doses selected based on research carried out in the region by Silva et al., 2020) and the second of the following lettuce population densities (150, 200, 250, and 300 thousand plants ha^{-1}, corresponding to 60, 80, 100 and 120% of the recommended density for the lettuce monocropping (RDM). The recommended population densities for radish and lettuce monocropping in the region are 500 and 250 thousand plants ha^{-1}, respectively (Nunes et al., 2018; Silva et al., 2018). Radish and lettuce in monocropping were planted with equitable biomass amounts of *M. aegyptia* and *C. procera* optimized by the research (40 Mg ha^{-1} for radish and 48 Mg ha^{-1} for lettuce) to obtain the agronomic and competition indexes and economic indicators in the intercropped systems.

The intercropping cultivation was established in alternating strips of the crops, in 50% of the area for lettuce and 50% for radish. Each plot consisted of four rows of lettuce interspersed with four rows of radish, flanked by two rows of each crop used as borders. The total area of each intercropping plot was 2.88 m^2 (2.40 x 1.20 m), with a harvest area of 1.60 m^2 (1.60 x 1.00 m). The harvest area consisted of the two central strips of plants, excluding the two outer rows on each side and the last two plants of each row, used as borders. The spacing of the radish in the intercropping treatments was 0.20 x 0.05 m providing a population of 500 thousand plants ha^{-1}. The spacings of the lettuce in the treatments assessed were 0.20 x 0.15 m, 0.20 x 0.12 m, 0.20 x 0.10 m, and 0.20 x 0.08 m providing a population of lettuce plants per hectare, respectively, of 150, 200, 250 and 300 thousand plants ha^{-1}.

The monocropping of each vegetable consisted of six rows per plot with a total area of 1.44 m^2 (1.20 x 1.20 m) and a harvest area of 0.64 m^2 (0.80 x 0.80 m) for the lettuce crop at a spacing of 0.20 x 0.20 m and a harvest area of 0.80 m^2 (0.80 x 1.00 m) for radish crop at a spacing of 0.20 x 0.10 m. These harvest areas were constituted by the four central rows of cultivation, excluding the lateral rows and the first and last plants of each row, considered as borders.

The methodology used to install the experiments in the experimental areas followed the methodology proposed by Nunes et al. (2018).

The materials used as green manures in the experiments were hairy woodrose (*M. aegyptia*) and roostertree (*C. procera*), collected from native vegetation in several rural areas near the municipality of Mossoró, RN, Brazil. After collection, these materials were crushed in a conventional forage machine, obtaining fragments of around 2.0 to 3.0 cm, and dehydrated under sunlight until reaching a moisture content of around 10%. Samples of these materials were subjected to chemical analysis in the laboratory to obtain the chemical compositions, following the methodology proposed by EMBRAPA (2009). In 2020 the composition for *M. aegyptia* was: N = 16 .60 g kg^{-1}; P = 2.79 g kg^{-1}; K = 37.80 g kg^{-1}; Mg = 7.07 g kg^{-1} and Ca = 19.35 g kg^{-1}, and for *C. procera* were: N = 21.90 g kg^{-1}; P = 1.92 g kg^{-1}; K = 20.90 g kg^{-1}; Mg = 9.20 g kg^{-1} and Ca = 17.00 g kg^{-1} for roostertree. In 2021: N = 15.30 g kg^{-1}; P = 4.00 g kg^{-1}; K = 25.70 g kg^{-1}; Mg = 7.03 g kg^{-1} and Ca = 9.30 g kg^{-1}, for *M. aegyptia* and N = 18.40 g kg^{-1}; P = 3.10 g kg^{-1}; K = 24.50 g kg^{-1}; Mg = 13.50 g kg^{-1} and Ca = 16.30 g kg^{-1} *C. procera*.

After solarization, the amounts of green manure biomass were incorporated into the soil 15 days before sowing the crops. In the first cropping season, incorporation was conducted on December 9, 2020, and in the second, on September 13, 2021, with the aid of hoes. Irrigations were performed daily by the micro-sprinkler system, divided into two applications (morning and afternoon), providing a water depth of approximately 8 mm per day. This irrigation depth was determined from the average Kc of the radish crop. The initial Kc used was 0.45, the average Kc was 0.95, and the final Kc was 0.65 (Nunes et al., 2018).

The lettuce and radish cultivars planted were 'Tainá' and 'Crimson Gigante', respectively. After 21 days after sowing (DAS), the plants were transplanted to the beds in holes of approximately 5 cm, on December 29, 2020, in the first cropping season, and on September 28, 2021, in the second season. At eight days after transplanting (DAT) of lettuce, a hilling of the seedlings was performed to prevent damping-off, followed by the application of the foliar biostimulant Agromos® in order to strengthen and activate the plants' natural resistance.

The seeds of the radish cultivar were sown on December 29, 2020, in the first cropping season, and on September 28, 2021, in the second season. After seven days of sowing, thinning was performed, leaving only one plant per hole, and at 15 DAS, a hilling.

During the conduction of the field experiments, whenever necessary, manual weeding was carried out to control weeds. No chemical control method was used. Lettuce was harvested 28 days after transplanting in the first and second cropping seasons. The radish was harvested 30 days after sowing.

The characteristics evaluated in the intercropped systems were: commercial productivity of radish roots, quantified by the fresh mass of roots of plants in the harvest area with a minimum size of 20 mm, free of cracks or deformations, and not styrofoam (Souza et al., 2020), expressed in Mg ha^{-1} and the yield of lettuce leaves, quantified by the fresh mass of the shoots of the plants in the harvest area and expressed in Mg ha^{-1}.

The agro-bioeconomic efficiencies of the radish and lettuce intercropped systems were determined using agronomic and competition indexes and economic indicators:

a) The land equivalent ratio (LER) was calculated using the expression used by Bezerra Neto et al. (2019).

$$\mathrm{LER} = \frac{Y_{rl}}{Y_r} + \frac{Y_{lr}}{Y_l} \tag{1}$$

where:

LER - land equivalent ratio;

Y_{rl} - yield of commercial radish roots intercropped with lettuce;

Y_{lr} - productivity of lettuce leaves intercropped with radish;

Y_r - productivity of commercial radish roots in single cropping; and,

Y_l - productivity of lettuce leaves in single cropping.

This agronomic index is defined as the relative land area under single cropping conditions required to provide the yields achieved in intercropping. When the LER value is greater than 1, intercropping favors the development, growth, and yield of the component crops. On the other hand, when LER is less than 1, the intercropping between the component cultures are negatively affected, harming the development, growth, and yield of the cultures.

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

$$\mathrm{IA} = \mathrm{IA}_r + \mathrm{IA}_l \tag{2}$$

$$\mathrm{IA}_r = \mathrm{AYL}_r \times P_r \tag{3}$$

$$\mathrm{IA}_l = \mathrm{AYL}_l \times P_l \tag{4}$$

where:

IA - intercropping advantage;

IA_r - intercropping advantage of radish with lettuce;

IA_l - intercropping advantage of lettuce with radish;

AYL_r and AYL_l - defined in the description of the actual yield loss (AYL);

P_r - price of radish in R$ kg^{-1}; and,

P_l - price of lettuce in R$ kg^{-1}.

The average prices paid to the producer in January and December 2021 were R$ 2.70 and R$ 4.83 kg^{-1} for lettuce and radish, respectively. The higher the AI value, the more agronomically advantageous and profitable the intercropped system.

c) The productive efficiency index (PEI) was calculated for each treatment using the DEA (Data Envelopment Analysis) model with constant returns to scale, as there was no evidence of significant differences in scale. The DEA model has the following mathematical formulation:

$$\text{MAX } z = \sum_{j=1}^{r} \mu_j x_{jo} \tag{5}$$

subject to restrictions:

$$\sum_{i=1}^{S} \upsilon_i w_{io} = 1 \tag{6}$$

$$\sum_{j=1}^{r} \mu_j x_{jk} - \sum_{i=1}^{S} \upsilon_i w_{ik} \le 0 \tag{7}$$

$k = 1, \ldots, n; \mu_j, \upsilon_i \ge 0; i = 1, \ldots, s; j = 1, \ldots, r.$

where:

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

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

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 plot (treatment), unitary inputs were assumed for all units.

The treatments (intercrops) were used as evaluation units, sixteen in total. As outputs, lettuce leaf yield and commercial radish yield were used. To assess the performance or yield of each plot, it was considered that each one uses a single resource at a unitary level since the outputs incorporated the possible inputs. Thus, the closer the PEI value is to 1, the more agronomically advantageous is the tested intercropped system.

d) The efficiency of the intercropped system was also evaluated by the agronomic index, canonical variable score (Z), obtained by the bivariate analysis of variance (Andrade Filho et al., 2020) of lettuce leaves and radish commercial roots productivities. The higher and more positive the value of Z, the more agronomically efficient the intercropped system is evaluated.

The competition indexes evaluated in the intercropped systems were the crop aggressivity (A_r and A_l), the competitive ratio (CR), and the actual yield loss of the system (AYL).

e) The aggressivity (A) is an index that indicates how much of the relative increase in production of the r component crop (radish in this case) is greater than that of the l component (lettuce) in an intercropping system. This index was determined by the following expressions used by Cecílio Filho et al. (2015).

$$A_r = \left(\frac{Y_{rl}}{Y_r Z_{rl}}\right) - \left(\frac{Y_{lr}}{Y_l Z_{lr}}\right) \tag{8}$$

$$A_l = \left(\frac{Y_{lr}}{Y_l Z_{lr}}\right) - \left(\frac{Y_{rl}}{Y_r Z_{rl}}\right) \tag{9}$$

where:

A_r and A_l - aggressivity of the radish and lettuce in intercropping;

Y_{rl} - commercial productivity of radish roots intercropped with lettuce;

Y_r - commercial productivity of radish in single cultivation;

Z_{rl} - proportion of radish planted area intercropped with lettuce;

Y_{lr} - productivity of lettuce leaves intercropped with radish;

Y_l - productivity of lettuce leaves in single cropping; and,

Z_{lr} - proportion of the area planted with lettuce intercropped with radish.

If A is positive, then the component culture with a positive sign is the dominant one, and the one with a negative sign is the dominated culture. If the value of A is zero, both cultures are equally competitive.

f) The competitive ratio (CR) of the intercropped system was also obtained by the formula used by Cecílio Filho et al. (2015), where:

$$CR = CR_r + CR_l \tag{10}$$

The

$$CR_r = \left[\left(\frac{LER_r}{LER_l} \times \frac{Z_{lr}}{Z_{rl}}\right)\right] \tag{11}$$

$$CR_l = \left[\left(\frac{LER_l}{LER_r} \times \frac{Z_{rl}}{Z_{lr}}\right)\right] \tag{12}$$

where:

CR_r - competitive ratio of the radish in intercropping with lettuce;

CR_l - competitive ratio of the lettuce in intercropping with radish;

LER_r - land equivalent ratio in radish; and,

LER_l - land equivalent ratio in lettuce.

The terms Z_{lr} and Z_{rl} are defined earlier.

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). The culture with the highest CR makes better use of environmental resources.

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

$$AYL = ALY_r + AYL_l \tag{13}$$

$$AYL_r = \left\{\left[\left(\frac{Y_{rl}}{Z_{rl}}\right) \div \left(\frac{Y_r}{Z_r}\right)\right] - 1\right\} \tag{14}$$

$$AYL_l = \left\{\left[\left(\frac{Y_{lr}}{Z_{lr}}\right) \div \left(\frac{Y_l}{Z_l}\right)\right] - 1\right\} \tag{15}$$

where:

AYL_r - actual yield loss of the radish;

AYL_l - lettuce's actual yield loss;

Y_{rl} - yield of commercial roots of radish intercropped with lettuce;

Z_{rl} - proportion of radish planting intercropped with lettuce;

Y_r - productivity of commercial radish roots in single crop;

Z_r - proportion of radish planting in single cropping;

Y_{lr} - leaf yield of lettuce intercropped with radish;

Z_{lr} - planting proportion of lettuce intercropped with radish;

Y_l - yield of lettuce leaves in single cropping; and,

Z_l - proportion of lettuce planting in single cropping.

If AYL > 0, it indicates an advantage of the intercropping concerning the monocropping; if AYL < 0, it indicates a disadvantage of the intercropping system.

The economic efficiency indicators evaluated in the intercropped systems were: gross income (GI), net income (NI), rate of return (RR), and profit margin (PM). GI was determined by the product of crop production per hectare and the price paid to the producer at the market level in the region in December 2021. The average prices paid were 2.70 R$ kg^{-1} for lettuce and 4.79 R$ kg^{-1} for radish. This indicator does not consider the total costs (TC) of production of the products involved (Feiden, 2001).

The total production costs of an intercropped system, according to Cecílio Filho et al. (2010), are obtained through the total expenditures (total costs) per hectare with the component crops that are part of the system at an experimental level, which covers the services provided by stable capital (depreciation, fixed labor, and costs associated with working capital), prices of inputs and value of alternative costs (also called opportunity costs).

NI was calculated by subtracting from the gross income (GI) the total production costs (TC) of the system per hectare. RR was obtained from the relation between gross income (GI) and total costs (TC), that is, RR = GI/TC, corresponding to the value of Reais (R$) obtained for each Real (R$) invested in the application of the treatment of the intercropping of radish and lettuce. PM was obtained from the ratio between net income (NI) and gross income (GI), expressed as a percentage.

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

Results and Discussion

A significant interaction between equitable biomass amounts of *M. aegyptia* and *C. procera* incorporated into the soil and population densities of lettuce was recorded for the intercropping advantage (IA) and the competitive ratio (CR) of the radish-lettuce intercropping (Table 1). No significant interaction was recorded between the factors for the land equivalent ratio (LER), productive efficiency index (PEI), canonical variable score (Z), radish aggressivity over lettuce (A_r), lettuce aggressivity over radish (A_l), and actual yield loss (AYL) of radish and lettuce intercropped systems (Table 1).

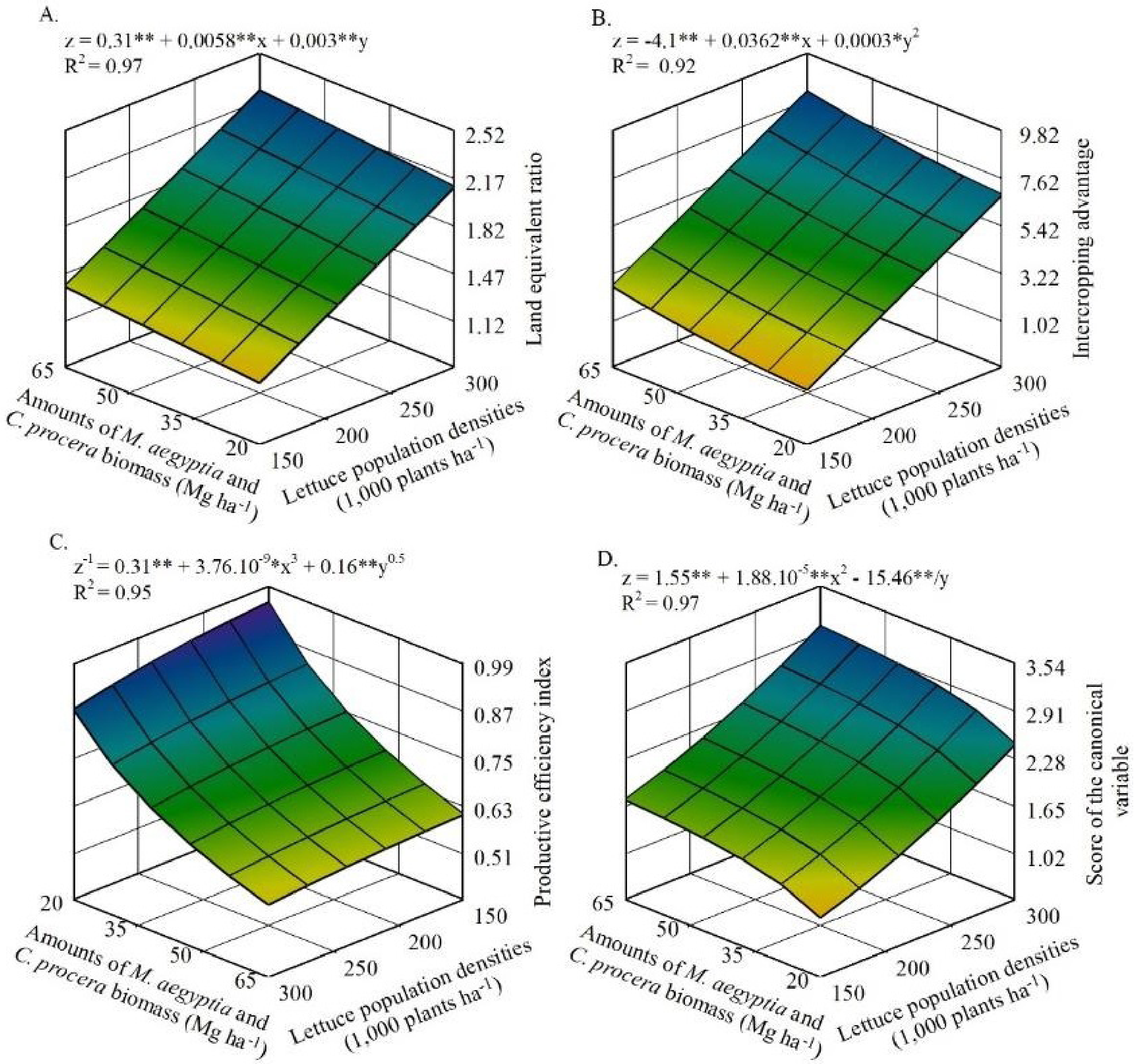
A response surface was adjusted for all these agronomic and competition indexes of the intercropped systems according to the equitable amounts of *M. aegyptia* and *C. procera* biomass and population densities of lettuce plants intercropped with radish. The LER, IA, and Z values increased with the increase in the amounts of the green manures and in the population densities of lettuce, where the maximum values of these agronomic indexes were 2.25, 8.03, and 3.00, respectively, in the combination of 65 Mg ha^{-1} of the green manures incorporated into the soil with the population density of 300 thousand lettuce plants per hectare (Figures 1A, B and D). For PEI, the behavior was inverted because it grew with the decrease in the amounts of the green manures and of the population densities of lettuce, thus providing a maximum value of 0.96 in the combination of 20 Mg ha^{-1} of the green manures placed in the soil with the density of 150 thousand lettuce plants per hectare (Figure 1C).

All the maximum values obtained with these agronomic indexes, LER (2.25), IA (8.03), PEI (0.96), and Z (3.00), show that the intercropped systems of radish and lettuce tested were advantageous (see the reference values in the description of these indexes), determined by the degree of complementarity in the use of environmental resources between the component cultures (Cecílio Filho et al., 2015),

Table 1. F-values for land equivalent ratio (LER), intercropping advantage (IA), productive efficiency index (PEI), score of the canonical variable (Z), aggressivity of radish over lettuce (A_r), aggressivity of lettuce over radish (A_l), competitive ratio (CR), and actual yield loss (AYL) of the radish-lettuce intercropping under different equitable biomass amounts of *M. aegyptia* and *C. procera* incorporated into the soil and diverse lettuce population densities

Sources of variation	DF	LER	IA	PEI	Z	A_r	A_l	CR	AYL
Blocks	3	0.03^{ns}	0.49^{ns}	0.05^{ns}	0.05^{ns}	0.42^{ns}	0.42^{ns}	0.10^{ns}	0.40^{ns}
Amounts of *M. aegyptia* and *C. procera* biomass (A)	3	4.30^{**}	18.24^{**}	15.04^{**}	45.98^{**}	51.25^{**}	51.25^{**}	43.78^{**}	2.78^{*}
Lettuce population densities (D)	3	126.91^{**}	266.52^{**}	1.53^{ns}	250.55^{**}	13.14^{**}	13.14^{**}	14.32^{**}	130.17^{**}
A x D	9	0.64^{ns}	4.70^{**}	0.53^{ns}	1.53^{ns}	1.13^{ns}	1.13^{ns}	2.92^{**}	1.20^{ns}
Regression (Response surface)	2	200.41^{**}	71.35^{**}	130.12^{**}	202.46^{**}	31.77^{**}	31.77^{**}	24.99^{**}	237.89^{**}
Error	45	0.01783	0.33401	0.00216	0.01968	0.03196	0.03196	0.01327	0.05401
CV (%)		7.66	12.34	6.39	6.60	26.90	-26.90	5.23	15.14

*, **, 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



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

Figure 1. Land equivalent ratio – LER (A), intercropping advantage – IA (B), productive efficiency index – PEI (C), and score of the canonical variable – Z (D) of the radish intercropped with lettuce in different combinations of equitable amounts of *M. aegyptia* and *C. procera* biomass and lettuce population densities

with the possibility that these advantages can be converted into profits for the producer.

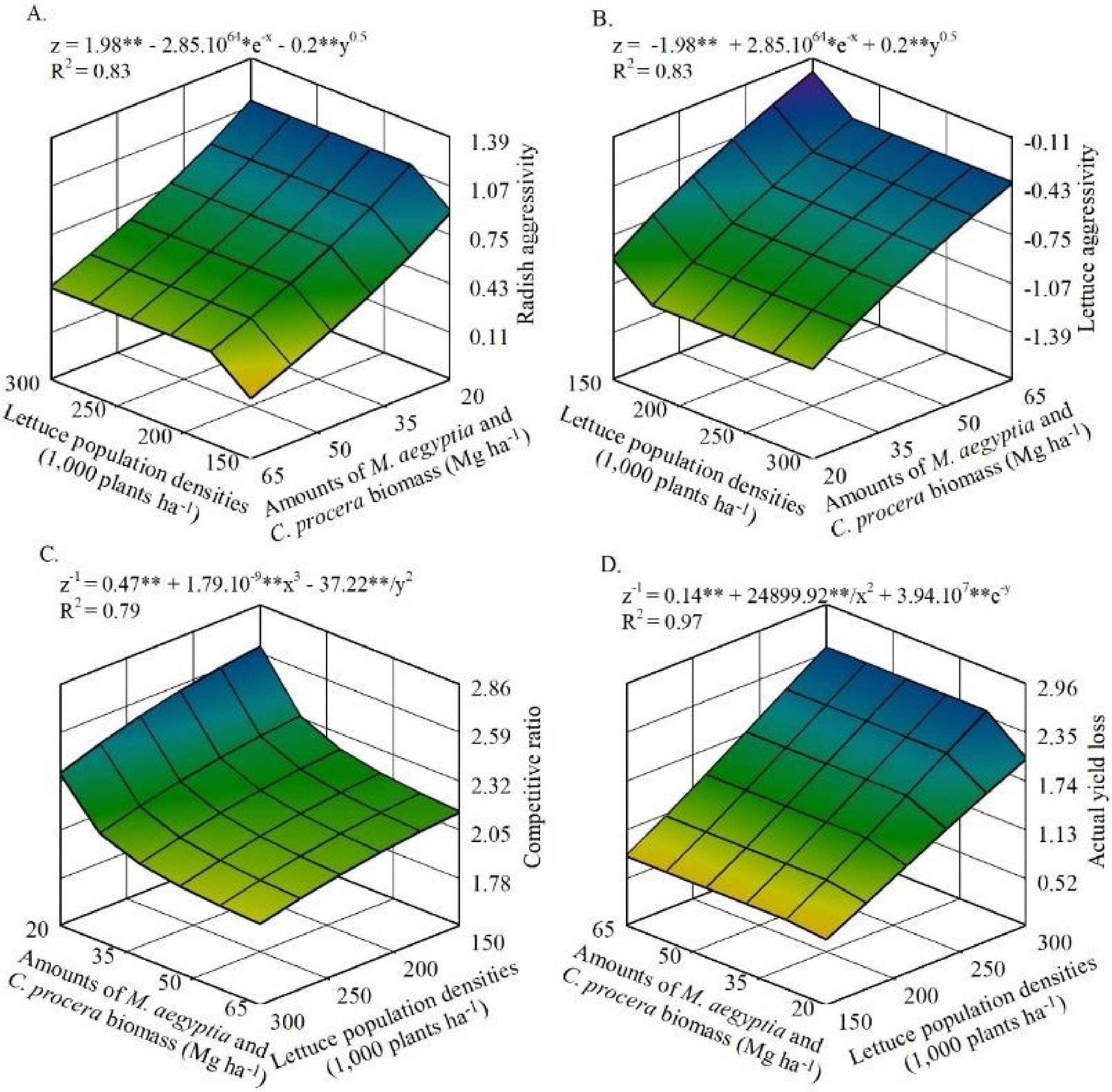
When the LER value is greater than 1, intercropping favors the development, growth, and yield of the component crops. On the other hand, the closer the PEI value is to 1, the more agronomically advantageous the intercropped system is tested, and the higher and positive the IA and Z values, the more agronomically advantageous the intercropped system is. The AI value indicates an agronomic advantage and can also be considered an indicator of the economic viability of the intercropped systems (Dhima et al., 2007). The results obtained with these indexes indicated that all the intercropped systems evaluated were advantageous.

Thus, according to the tested treatments, these agronomic indexes prove that organic fertilization made with the green manures *M. aegyptia* and *C. procera*, regardless of the population density of the component crops, improved soil chemical properties and contributed to obtaining higher yields of the intercropped systems. This can be confirmed by the chemical analysis of the soils shown above, revealing that the soil has low fertility and that adding organic fertilizers improved the yields of the intercropped systems, as revealed by the indexes and indicators evaluated. According to Kumar et al. (2014) and Kiran et al. (2016), organic fertilization improves radish growth and yield. On the other hand, it is also known that organic fertilization brings some benefits to the soil, such as increasing water penetration and retention; improved structure, aeration, and porosity; increase in microbial life; increased nutrient availability and absorption to meet crop demand (Lanna et al., 2018).

Given this, the results obtained from the maximum agronomic efficiency of these indexes allow the radish and lettuce producer to choose the ideal amount of green manures for incorporation in combination with the ideal planting density of the component crops based on the agronomic indicator that best suits them in terms of agronomic yield of the intercropped system.

The aggressivity of radish over lettuce (A_r) grew with the increase in lettuce population densities and decreased with the increase in amounts of applied green manures, reaching a maximum value of 1.09 in the combination of 252 thousand lettuce plants per hectare and 20 Mg ha^{-1} of green manures incorporated into the soil (Figure 2A). For the lettuce aggressivity over radish (A_l), the behavior was inverse because it grew with the increase in the amounts of applied green manures and decreased with the increase in population densities of lettuce, reaching a maximum value of -0.16 in the combination of 65 Mg ha^{-1} of green manures incorporated into the soil and 150 thousand lettuce plants per hectare (Figure 2B).

The positive values of the aggressivity of radish over lettuce in the intercropping indicate that this tuberose was the dominant crop in the system and more competitive as the lettuce planting density increased and the amount of green manure decreased. A similar result was obtained by Sá et al. (2021), when intercropping radish with arugula in different doses of organic fertilizers and diverse leafy crop populations, obtained positive values of the radish aggressiveness over the leafy crop, indicating that this tuberose was the dominant crop in the system. This behavior can be attributed to factors related to the morphology, physiology, and nutritional needs of the crop. According to Passos et al. (2019), crop competitiveness is proportional to the increase in plant population in the planted area. Thus, with the increase in the lettuce population and decrease in the amount of green manure, it was observed that the competitive capacity of the radish increased, and that of the lettuce crop decreased.



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

Figure 2. Radish aggressivity over lettuce – A_r (A), lettuce aggressivity over radish – A_l (B), competitive ratio – CR (C), and actual yield loss – AYL (D) of the radish intercropped with lettuce in different combinations of equitable amounts of *M. aegyptia* and *C. procera* biomass and lettuce population densities

The negative values of the aggressivity of lettuce over radish indicate that this hardwood was the dominated crop as the amount of green manure increased and the density of lettuce decreased. These results also indicate that lettuce 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 in determining the efficiency of intercropped systems. According to Willey & Osiru (1972), when the proportion of component crops is approximately equal, the efficiency and yield seem to be determined by the most aggressive crop in the system.

The competitive ratio (CR) of the intercropped system increased with the decrease in the amounts of green manure applied and with the decrease in the population densities of lettuce, reaching a maximum value of 2.61 in the combination of 20 Mg ha^{-1} of green manures incorporated into the soil and 150 thousand lettuce plants per hectare (Figure 2C). These decreasing values of CR registered with the increase of the amounts of green manures and the increase of the population densities of lettuce indicate a reduction in the degree of competition between the species and, thus, they provide an increase in the efficiency of the intercropping, in the function of the better use of environmental resources. This effect can be attributed to the aggressiveness of the dominant species, the radish, and factors related to the morphology, physiology, and nutritional requirements of plants. According to Zhang et al. (2015), the difference in plant architecture, especially the roots, determines how they access and use soil nutrients.

Opposite behavior was recorded for the actual yield loss (AYL), where it increased with the increase in the amounts of green manures applied and with the increase in the population densities of lettuce, reaching a maximum value of 2.40 in the combination of 65 Mg ha^{-1} of the green manures incorporated into the soil and 300 thousand lettuce plants per hectare (Figure 2D). This result was superior to that of Sá et al. (2021) when intercropping radish with arugula under green manure and population densities, reaching an AYL value of 1.31. This AYL value, much higher than 1, resulting from the increase in the amounts of green manures and the population densities of lettuce, positively influenced the intra and interspecific competition of radish and lettuce crops, resulting from the better use of environmental resources, providing more advantageous intercrops than their monocrops. It is important to emphasize that the AYL value provides accurate information about the competition between the companion crops in the intercropping systems, both intra and interspecific (Dhima et al., 2007).

The values obtained in the competitive relationships show the ability to use resources more efficiently, such as light, nutrients, and water (Nunes et al., 2018). Through these indexes, it is possible to obtain the appropriate degree of competitiveness between species, indicating the number of times that the dominant species is more efficient in using these available environmental resources than the dominated culture.

One of the challenges of intercropping a tuberous vegetable with hardwood is to recognize whether there is an agronomic and biological advantage (due to competition) in this association. Sá et al. (2021), associating the tuberous radish with the leafy arugula in the semi-arid environment fertilized with *M. aegyptia* and *C. procera* biomass under various arugula population densities, obtained higher values of agronomic indexes LER (1.64), AI (5.16), PEI (0.86) and Z (1.54) in the population density of arugula plants of 100% of the recommended density for monocropping - RDM (1000 thousand plants per hectare) fertilized with 65 Mg ha^{-1} of biomass of the green manures incorporated into the soil.

For the radish aggressivity over arugula (A_r) and CR, the highest values obtained by the authors were 0.19 and 2.75 achieved in the combination of the amount of biomass of the green manures of 20 Mg ha^{-1} and population density of 40% of the arugula RDM (400 thousand plants ha^{-1}). For the arugula aggressivity over radish (A_a) and AYL, they obtained -0.03 and 1.31 in the combination of the biomass amount of the green manures of 65 Mg ha^{-1} and population density of 100% of the arugula RDM (1000 thousand plants ha^{-1}). These values achieved in this intercropped system corroborate with those obtained in this investigation, thus demonstrating that the association of green manures amounts with population densities of planting leafy crops is very useful in the efficient use of environmental resources, resulting in agronomic and biological advantages for intercropped systems of tuberose and leafy vegetables.

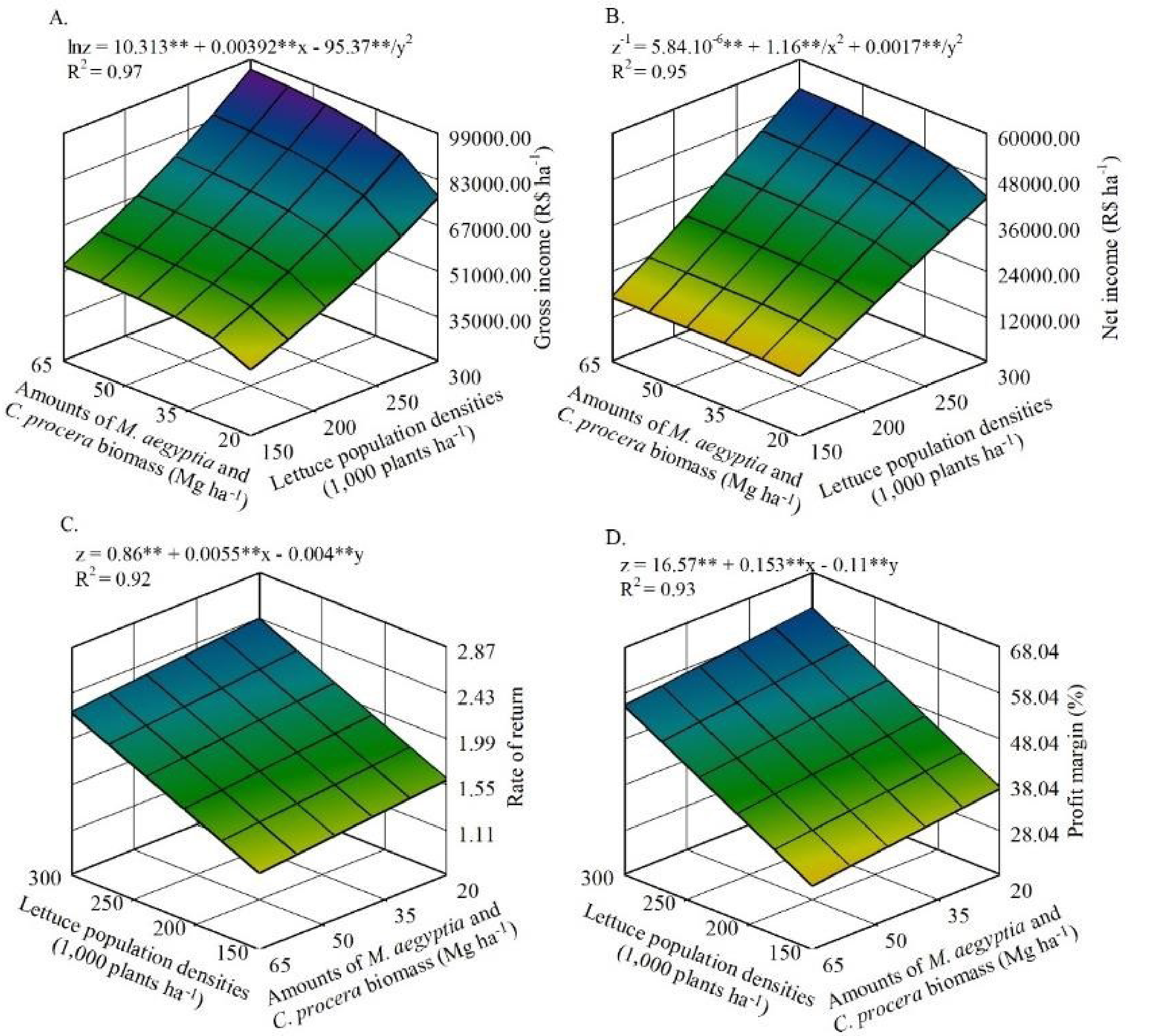
No significant interaction was observed between equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil and lettuce population densities in the gross income (GI), net income (NI), rate of return (RR), and profit margin (PM) of the intercropped systems (Table 2).

A response surface was adjusted for all these economic indicators of the intercropped systems according to the treatments, equitable amounts of *M. aegyptia* and *C. procera* biomass and population densities of lettuce plants intercropped with radish, where the maximum values of GI and NI of

Table 2. F-values for gross income (GI), net income (NI), rate of return (RR), and profit margin (PM) of the radish-lettuce intercropping under different equitable biomass amounts of *M. aegyptia* and *C. procera* incorporated into the soil and diverse lettuce population densities

Sources of variation	DF	GI	NI	RR	PM
Blocks	3	0.08^{ns}	0.08^{ns}	0.15^{ns}	0.10^{ns}
Amounts of *M. aegyptia* and *C. procera* biomass (A)	3	32.10**	5.43**	9.54**	8.90**
Lettuce population densities (D)	3	229.97**	168.72**	126.45**	125.88**
A x D	9	1.55^{ns}	1.58^{ns}	1.65^{ns}	1.22^{ns}
Regression (Response surface)	2	222.54**	124.21**	71.53**	89.40**
Error	45	20959734	20953794	0.01647	12.72929
CV (%)		6.74	15.95	6.67	7.70

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



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

Figure 3. Gross income – GI (A), net income – NI (B), rate of return – RR (C), and profit margin – PM (D) of the radish intercropped with lettuce in different combinations of equitable amounts of *M. aegyptia* and *C. procera* biomass and lettuce population densities

95,456.62 and 52,270.48 R$ ha^{-1} were obtained by combining an equitable amount of biomass of 65 Mg ha^{-1} of the green manures with a population density of lettuce of 300 thousand plants per hectare (Figures 3A and B).

For RR and PM, the maximum values of R$ 2.43 for each Real invested and 60.27% were obtained by combining equitable biomass of 20 Mg ha^{-1} of the green manures with a population density of lettuce of 300 thousand plants per hectare (Figures 3C and D). As can be seen, the GI and NI values increased with the increase in the amounts of green manures and the population densities of lettuce (Figures 3A and B). In contrast, the values of RR and PM increased with the increase in the lettuce population densities and with the decrease in the amounts of green manures applied to the soil (Figures 3C and D). This difference in behavior is probably due to the total production costs of each tested treatment.

Sá et al. (2021), evaluating the intercropping of radish with arugula according to increasing equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil and arugula population densities, obtained GI and NI values of 45,543.92 and 24,662.31 R$ ha^{-1}, RR of R$ 2.20 for each Real invested and PM of 56.37%. These differences between the two studies are mainly due to the type of intercropping of the tuberous vegetable, radish with the different leafy crops (arugula and lettuce), consequently also due to the differences in total production costs of the component crops that are part of the intercropped systems.

It is known that the economic analysis in intercropping systems has the objective of complementing the evaluation and analysis of agronomic and competition indexes, as it takes into account, in addition to the physical production of the component cultures of the intercropped systems, the price of products with based on their commercial classification, quality and growing season. It can be an important tool for tuberous and leafy vegetable producers to consider when implementing their intercropping systems.

Gross income is an indicator that can be used. It expresses the value of the joint production of crops in each associated system, disregarding the total production costs. It depends precisely on the price at which the production of the system is marketed. On the other hand, economic indicators, net income, rate of return, and profit margin, depend on total production costs, as they are standardized and estimated in terms of total costs. The higher its values, the greater the agro-bioeconomic benefits of the evaluated intercropped systems.

The results obtained in this study for the economic indicators indicate that the intercropping between the radish and lettuce vegetables, when fertilized with the spontaneous species of the Caatinga biome *M. aegyptia* and *C. procera*, is promising for the semi-arid region, as it converts bio-agronomic benefits into economic efficiency. Thus, this intercropping is seen as an efficient and more economical production system, as it increases production per unit of area and time and improves efficiency in using environmental resources.

Conclusions

1. Expressive agro-bioeconomic returns from this radish-lettuce intercropping are obtained in the land equivalent ratio (LER) of 2.25, intercropping advantage (IA) of 8.03, the score of the canonical variable Z of 3.00, actual yield loss (AYL) of 2.40, and in the net income (NI) of 52,270.48 R$ ha^{-1} with the biomass amount of 65 Mg ha^{-1} of the green manures and lettuce population density of 300 thousand plants ha^{-1}.

2. The use of *M. aegyptia* and *C. procera* biomass from the Caatinga biome proved to be a viable technology for producers who practice the cultivation of radish and lettuce in intercropping in the semi-arid environment.

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