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Yield performance and agro-economic efficiency of radish-arugula intercropping under green manuring and planting density

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ABSTRACT

The cultivation of radish with arugula in strip-intercropped systems is growing in semi-arid environments. The great challenge has been to assess whether there is agro-economic efficiency in the intercrops when fertilized with plant biomass of spontaneous species from the Caatinga biome. Thus, the objective of this study was to evaluate the productive and economic viability of radish and arugula strip-intercrops fertilized with *Merremia aegyptia* and *Calotropis procera* biomass equitable amounts from the Caatinga biome at different population densities of arugula at two cropping years. The experimental design used was randomized blocks, with the treatments arranged in a 4x4 factorial scheme, with four replicates. The first factor was constituted by four biomass equitable amounts of *M. aegyptia* and *C. procera* (20, 35, 50 and 65 t ha^{-1} on a dry basis), and the second factor by the population densities of arugula plants [40, 60, 80 and 100% of the recommended density for single crop (RDSC)] intercropped with 100% of the radish RDSC. The highest agro-economic advantages of radish and arugula intercropping were obtained for a land equivalent coefficient (LEC) and monetary equivalent ratio (MER) of 0.55 and 1.35, respectively, for *M. aegyptia* and *C. procera* biomass amounts of 54.75 and 54.55 t ha^{-1} added to the soil. The arugula population density of 100% of the RDSC provided the greatest agro-economic efficiency of the intercropped system of radish with arugula with LEC and MER of 0.58 and 1.33, respectively. 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 arugula in intercropped systems in a semi-arid environment. The concern of the farmer regarding the preservation of natural resources, as well as with the search for a better quality of life, circumvents the possible limitations that the environment may offer in a given intercropping crop. The option by intercropping system can provide to producers viable alternatives to optimize the planted area, in addition to greater productivity and economic stability of activities on the rural property.

Keywords: *Eruca sativa*, *Raphanus sativus*, *Merremia aegyptia*, *Calotropis procera*, productive and economic optimization.

RESUMO

Desempenho produtivo e eficiência agroeconômica do consórcio rabanete-rúcula sob adubação verde e densidade de plantio

O cultivo de rabanete com rúcula em sistemas consorciados em faixas está crescendo em ambientes semiáridos. O grande desafio tem sido avaliar se há eficiência agroeconômica no consórcio quando fertilizado com biomassa vegetal de espécies espontâneas do bioma Caatinga. Assim, o objetivo deste estudo foi avaliar a viabilidade produtiva e econômica do consórcio de rabanete e rúcula fertilizado com quantidades eqüitativas de biomassa de *Merremia aegyptia* e *Calotropis procera* do bioma Caatinga em diferentes densidades populacionais de rúcula em dois anos de cultivo. O delineamento experimental utilizado foi em blocos ao acaso, com os tratamentos arranjados em esquema fatorial 4x4, com quatro repetições. O primeiro fator foi constituído por quatro quantidades eqüitativas de biomassa de *M. aegyptia* e *C. procera* (20, 35, 50 e 65 t ha^{-1} em base seca), e o segundo fator pelas densidades populacionais de plantas de rúcula [40, 60, 80 e 100% da densidade recomendada em cultivo solteiro (DRCS)] em consórcio com 100% da densidade de rabanete recomendada em cultivo solteiro. As maiores vantagens agroeconômicas do consórcio de rabanete e rúcula foram obtidas com um coeficiente equivalente de terra (LEC) e razão monetária equivalente (MER) de 0,55 e 1,35, respectivamente, nas quantidades de biomassa de *M. aegyptia* e *C. procera* de 54,75 e 54,55 t ha^{-1} adicionada ao solo. A densidade populacional de rúcula de 100% da DRCS proporcionou a maior eficiência agroeconômica do sistema consorciado de rabanete com rúcula com LEC e MER de 0,58 e 1,33, respectivamente. 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 rúcula em sistemas consorciados em ambiente semiárido. A preocupação do agricultor com a preservação dos recursos naturais, bem como com a busca por uma melhor qualidade de vida, contorna as possíveis limitações que o meio ambiente pode oferecer em uma determinada cultura consorciada. A opção pelo sistema consorciado pode proporcionar aos produtores alternativas viáveis para otimizar a área plantada, além de maior produtividade e estabilidade econômica das atividades na propriedade rural.

Palavras-chave: *Eruca sativa*, *Raphanus sativus*, *Merremia aegyptia*, *Calotropis procera*, otimização econômica e produtiva.

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Radish and arugula represent a group of horticultural crops of economic, social and nutritional importance in the production systems of semi-arid regions. Radish has medicinal properties including a diuretic action, blood glucose control, blood pressure maintenance and strengthening of bones, teeth and muscles, while arugula has an antioxidant action, strengthens the immune system, improves brain function, prevents osteoporosis and improves digestion, among other benefits (Leite, 2019a, b).

In some places of these semi-arid regions, the cultivation of these vegetables has grown mainly in intercropping systems, as it is a common practice among small producers in these regions (Grangeiro *et al.*, 2007). The choice of radish in this system is preferred because it is a tuberous plant, where the product of exploitation is below ground and that of the leafy vegetable, arugula, above the ground, so that the high competition for environmental resources during development and growth does not occur at the same space and at the same time, leading these vegetables to behave as companion crops. It is also known that this practice is an existing reality in the sustainable agricultural systems, where there is complementarity between cultures by environmental resources, such as water, light and nutrients, for the growth and development of cultures.

However, among the main challenges for obtaining viable production systems with vegetables in intercropping, is the adequate choice of production factors to obtain high productivity and economic efficiency of the system (Guerra *et al.*, 2021). Among the factors that can be manipulated are fertilization and population density of crops.

In fertilization, spontaneous species from the Caatinga biome, such as *Merremia aegyptia* and *Calotropis procera*, have been used as green manure in these vegetable production systems. These species are adapted to the edaphoclimatic conditions of the region, in addition to presenting high biomass production, rapid growth, and a close C/N ratio (Batista *et al.*, 2013).

Silva *et al.* (2018a), evaluating different levels of *M. aegyptia* and *C. procera* biomass as green manures in intercropped systems of beet and lettuce obtained maximum productivity and agro-economic efficiency of the intercropping with the incorporation into the soil of approximately 35.30 t ha^{-1} of *M. aegyptia* and *C. procera* biomass.

Population density, when properly managed, intervenes in the spatial and temporal complementarity of the intercropping, providing an increase in productivity and the rationalization of the necessary cultural treatments. In addition, population density can promote a series of changes in plant growth and development, dictated by intra and interspecific competition for environmental resources; thus, affecting the production of crops and their components (Ribeiro *et al.*, 2018).

Andrade Filho *et al.* (2020), researching the effect of the population density of coriander and arugula intercropped with beet, observed greater productivity of the intercropping when 40% of the coriander and arugula densities were used.

In this context, the objective of this study was to evaluate the intercropping of radish and arugula influenced by green manuring and arugula population densities in two cropping years.

MATERIAL AND METHODS

The work was carried out from October to December 2018 and from June to August 2019 at the Rafael Fernandes Experimental Farm, located at the Universidade Federal Rural do Semi-Árido (UFERSA), 20 km from the municipality of Mossoró, Rio Grande do Norte, Brazil. The climate of this region, according to the Köppen classification, is BShw, dry and very hot, with two seasons: a dry season, normally occurring from June to January, and a rainy season from February to May. During the experimental periods, the recorded average values for minimum and maximum temperatures, relative humidity and precipitation for the cropping years 2018 and 2019 were respectively: 27.4 and 25.7°C; 28.5 and 27.0°C; 67.0 and 72.2% and 0 and 32.3 mm (INMET, 2019).

The soils of the experimental areas were classified as typical Argisol Red Yellow Dystrophic with a sandy-loam texture (Santos *et al.*, 2018). In each experimental area, simple soil samples of the 0-20 cm surface layer were collected, and then homogenized to obtain a composite sample representative of the area, whose results in cultivation in 2018 were: pH (water) = 8.10; EC = 0.24 dS m^{-1}; O.M. = 4.97 g kg^{-1}; N = 0.35 g kg^{-1}; P = 22.80 mg dm^{-3}; K = 64.70 mg dm^{-3}; Ca = 3.28 $cmol_c$ dm^{-3}; Mg = 0.78 $cmol_c$ dm^{-3}; Na = 32.70 mg dm^{-3}; Cu = 0.10 mg dm^{-3}; Fe = 1.91 mg dm^{-3}; Mn = 11.67 mg dm^{-3}; Zn = 2.63 mg dm^{-3}. In the 2019 cultivation the results were: pH (water) = 7.10; EC = 0.10 dS m^{-1}; O.M. = 5.27 g kg^{-1}; N = 0.28 g kg^{-1}; P = 22.00 mg dm^{-3}; K = 69.47 mg dm^{-3}; Ca = 2.70 $cmol_c$ dm^{-3}; Mg = 0.50 $cmol_c$ dm^{-3}; Na = 26.70 mg dm^{-3}; Cu = 0.24 mg dm^{-3}; Fe = 2.71 mg dm^{-3}; Mn = 12.17 mg dm^{-3}; Zn = 5.27 mg dm^{-3}.

The experimental design used was a randomized block, with treatments arranged in a 4x4 factorial scheme, with four replicates. The first factor was constituted by four equitable amounts of *M. aegyptia* and *C. procera* biomass (20, 35, 50 and 65 t ha^{-1} on a dry basis), and the second factor by four population densities of arugula plants [40, 60, 80 and 100% of the recommended density for single crop (RDSC)], intercropped with 100% of the radish recommended density in single crop, in a spacing of 0.20 x 0.05 m. The recommended population densities for single croppings of radish and arugula in the region are 500 and 1,000 thousand plants ha^{-1}, respectively. In each block, radish and arugula single plots were planted with biomass equitable amounts of *M. aegyptia* and *C. procera* optimized by the research to obtain the agronomic and economic indexes of the intercropped systems.

The intercropped cultivation was established in alternating crop strips in a proportion of 50% of the area for radish and 50% of the area for arugula. Each plot consisted of four rows of radish alternating with four rows of arugula, flanked by two rows of each crop on each side used as borders. The total area of the plot was 2.88 m² (2.40 x 1.20 m), with a harvest area of 1.60 m² (1.60 x 1.00 m), where this area consisted of two central strips of plants, excluding the two final plants of each row used as borders. In this cultivation system, the same radish population density of the single crop was used.

In single croppings, six rows per plot were planted with a total area of 1.44 m² (1.20 x 1.20 m) and a harvest area of 0.80 m² (0.80 x 1.00 m), with 0.20 m x 0.05 m spacing for arugula and 0.20 m x 0.10 m for radish, based on research carried out in the region by Almeida *et al.* (2015) and Pereira *et al.* (2018). Plants were harvested in the 4 central cultivation lines, excluding the sidelines, as well as the first and last plants of each cultivation line, considered borders.

The soil preparation in the experimental areas consisted of mechanical cleaning of the areas using a tractor with a plough attached, followed by harrowing and mechanized lifting of the beds with a rotary harrow. Subsequently, pre-planting solarization was performed with a transparent plastic type Vulca Brilho Bril Flex (30 microns) for 30 days in order to combat phytopathogenic microorganisms in the soil.

The materials used as green manures 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, before the beginning of flowering. After the collections, the plants were crushed into fragments of two to three centimeters, which were dehydrated at room temperature until reaching 10% moisture content and then subjected to laboratory analysis, whose chemical compositions obtained were in 2018: N = 11.40 g kg^{-1}; P = 2.36 g kg^{-1}; K = 2.20 g kg^{-1}; Mg = 9.75 g kg^{-1} and Ca = 8.30 g kg^{-1}, for hairy woodrose and N = 18.40 g kg^{-1}; P = 3.14 g kg^{-1}; K = 4.50 g kg^{-1}; Mg = 13.35 g kg^{-1} and Ca = 16.30 g kg^{-1} for roostertree. In 2019: N = 16.60 g kg^{-1}; P = 2.79 g kg^{-1}; K = 47.80 g kg^{-1}; Mg = 7.07 g kg^{-1} and Ca = 19.35 g kg^{-1}, for hairy woodrose and N = 21.90 g kg^{-1}; P = 1.92 g kg^{-1}; K = 20.90 g kg^{-1}; Mg = 9.22 g kg^{-1} and Ca = 17.00 g kg^{-1} for roostertree.

Cultivars of radish 'Crimson Gigante' and of arugula 'Cultivada' were sown on November 12, 2018 in the first year of cultivation and on July 25, 2019 in the second year of cultivation, in holes approximately 3 cm deep, with three to four seeds per hole, covered with commercial substrate. Thinning of the arugula and radish was carried out by leaving two plants per hole for the arugula and one plant per hole for the radish in intercropped cultivation, while in monocropping only one plant was left for the two crops.

Irrigation was carried out using a micro sprinkler system with a daily watering shift, divided into two applications (morning and afternoon). The amount of water supplied was determined by the values of the radish cultivation coefficient (initial Kc = 0.45; middle Kc = 0.95; and final Kc = 0.65) (Alves *et al.*, 2017), with a blade of irrigation, when necessary, of approximately 8 mm day^{-1}. Weed control was performed, when necessary, by manually plucking the plants. No pest and disease control methods were required, and no other fertilizer input had been used besides green manure. The vegetable cultivation practices used in this research, such as intercropping of crops, soil management with the use of green manure and spontaneous plant management using manual grubbing control, are those recommended for the cultivation of vegetables in the organic system in the region (Silva *et al.*, 2018b).

The harvests of radish and arugula in the first cropping year were carried out at 29 and 30 DAS; and in the second cropping year at 27 and 28 DAS, respectively, proceeding with the evaluations. The characteristics evaluated from the radish culture were plant height, number of leaves per plant, fresh mass of shoots, dry mass of roots, transversal and longitudinal diameter of roots, and productivity of commercial roots (quantified by the fresh mass of roots of radish plants in the harvest area, free of cracks and non-isoporized, with at least 2 cm diameter, expressed in t ha^{-1}). From the arugula culture we evaluated plant height, number of leaves per plant, green mass yield (quantified by the fresh mass of arugula plant shoots in the harvest area and expressed in t ha^{-1}) and dry mass of shoots.

From the intercropped systems of radish and arugula, the agronomic and economic indexes evaluated were:

a) The system productivity index (SPI), calculated by the following expression (Oseni & Aliyu, 2010): SPI = $[(Y_r/Y_a) \times Y_{ar}] + Y_{ra}$, where: Y_r represents the commercial productivity of radish roots and Y_a the green mass yield of arugula in single cropping; Y_{ar} is the green mass yield of arugula in intercropped system with radish; Y_{ra} is the commercial productivity of radish roots in intercropping with arugula. The advantage of this SPI is that it standardizes the productivity of the secondary crop (arugula) based on the main crop (radish). The higher the value of this index, the more efficient the intercropped system is.

b) The land equivalent coefficient (LEC) was determined by the formula used by Diniz *et al.* (2017): LEC = $LER_r \times LER_a$, where: LER_r and LER_a represent the partial land equivalent ratios of radish and arugula land, respectively. For the intercropped system, the minimum value of LEC is 0.25, with that, the intercropped system shows the advantage of production of the index, when it exceeds the value of 0.25.

c) The monetary equivalent ratio (MER) was determined by the formula used by Afe & Atanda (2015): MER = $(GI_{ra} + GI_{ar})/GI_r$, where $GI_{ra} = Y_{ra} \times P_r$, $GI_{ar} = Y_{ar} \times P_a$ and $GI_r = Y_r \times P_r$. GI_{ra} is the gross income of radish in intercropping with arugula; Y_{ra} is the commercial productivity of radish roots in intercropping with arugula; P_r is the radish price paid to the producer at the market level in the region (R$ 4.08 kg^{-1}); GI_{ar} is the gross income of arugula in intercropping with radish; Y_{ar} is the green mass yield of arugula in intercropped system with radish; P_a is the arugula price paid to the producer at the market level in the region (R$ 3.78 kg^{-1}); GI_r is the highest gross income of radish in single cropping, when compared to the arugula and Y_r is the commercial productivity of radish roots in single cropping. This index measures the economic superiority, or not, of the intercropping over single cropping of the more economical crop. The higher value of this index, the more viable is the cropping system.

Univariate analysis of variance for the randomized block design in a factorial scheme was used to evaluate the variables collected. After that, a joint analysis was performed for the two growing years for the characteristics of the two crops using the SISVAR software (Ferreira, 2011). Then, an adjusting procedure of regression curve was performed using the Table Curve software to estimate the behaviour of each variable as a function of the equitable amounts of *M. aegyptia* and *C. procera* biomass and of the arugula population densities studied. For the economic indexes, due to the homogeneity of variances between cropping years, an average of the cropping years was made, and a regression procedure was performed in each index. The response function obtained in each adjusting procedure was based on the following criteria: biological logic of the variable, significance of the mean square of the regression residue (MSRR), high determination coefficient (R^2) and significance of the parameters of the regression function. The F test was used to compare the mean values between the cropping seasons, and between cropping systems.

RESULTS AND DISCUSSION

Radish crop

No significant interaction was observed for any of the production factors studied in the agronomic variables: plant height, number of leaves per plant, fresh mass of shoots and dry mass of roots, and in the transversal and longitudinal diameters of radish roots intercropped with arugula (Table 1).

However, the height of the radish plants increased with increasing arugula population densities up to a maximum value of 17.9 cm in a density of 90.2% of arugula RDSC, then decreased until the highest population density studied (Figure 1A).

The number of leaves per plant and the fresh mass of shoots decreased with increasing population densities of arugula, reaching the highest mean values of 5.9 leaves and 1.06 t ha^{-1} in the lowest population density of 40% of the RDSC of arugula (Figures 1A and 1C).

An increase in the longitudinal diameter of the radish roots was observed with the increase of the arugula population densities, reaching the maximum average value of 4.30 cm in the highest arugula density tested (Figure 1E). It was not possible to adjust a response equation for the dry mass and for the radish root transverse diameter as a function of the studied arugula population densities. However, the averages observed for these characteristics were 0.11 t ha^{-1} and 3.26 cm, respectively (Figures 1C and 1E).

Studying the agronomic variables of the radish intercropped with arugula as a function of the green manures amounts, we observed that the height of plants, fresh mass of shoots and transversal diameter of roots increased with equitable biomass amounts of *M. aegyptia* and *C. procera*, where the maximum values of these variables of 19.1 cm, 1.26 t ha^{-1} and 3.4 cm were recorded, in the amounts of 63.66, 61.88 and 55.76 t ha^{-1}, respectively, then decreased until the last tested amount (Figures 1B, 1D and 1F).

The number of leaves per plant, the dry mass of roots and the root longitudinal diameter of radish also increased between the smallest and largest biomass amount in the green manure, reaching the highest mean values of 6.2 leaves per plant, 0.13 t ha^{-1} and 4.5 cm in the largest tested amount (Figures 1B, 1D and 1F).

The results obtained for radish plant height may be associated with intense competition for light, due to the increase in the population density of arugula, which probably promoted radish growth. Lino *et al.* (2021), studying the intercropping of beet and arugula in the same region of this research as a function of arugula population and of green manures amounts, report that with less space, plants grow more in height in search of light, the main climatic element that determines their growth, in addition to water and nutrients available in the soil solution.

Greater shading imposed by the greater number of plants in the area, probably had a negative impact on photosynthesis and consequently, reduced the number of leaves per plant and fresh mass of shoots. In intercropped systems, where the nutritional conditions of the soil are suitable for cultivation, competition for light can be more intense, and the use of higher densities can increase competition for this natural resource (Silva *et al.*, 2015).

The optimization of plant height, fresh mass of shoots and transversal diameter of radish roots with increasing amounts of the green manures incorporated into the soil, where after reaching the maximum point they presented a decrease in their values, can be attributed to the maximum law, where an even greater increase in the dose of a nutrient causes a decrease in these characteristics, after the maximum point (Almeida *et al.*, 2015).

Linhares *et al.* (2010) recorded an increasing polynomial behaviour for the number of leaves and dry mass of radish shoots with the incorporation of increasing amounts of *M. aegyptia* in the soil, behaviour similar to that obtained in this study with the incorporation of the *M. aegyptia* and *C. procera*.

Significant interactions between cropping years and arugula population densities, between cropping years and equitable amounts of *M. aegyptia* and *C. procera* biomass, and between arugula population densities and equitable amounts of *M. aegyptia* and *C. procera* biomass, were observed in the productivity of commercial roots of radish (Table 1).

Studying the interaction of arugula population densities within each cropping year, a growing behaviour of commercial root productivity was recorded up to maximum values of 8.41 and 6.39 t ha^{-1} within the second and first cropping year at densities of 43% and 96.8% of RDSC, respectively, and then decreased until the last studied density (Figure 2A). This superiority of productivity in the second year of cultivation is due in part to the mild climatic conditions of temperature and relative humidity that provided

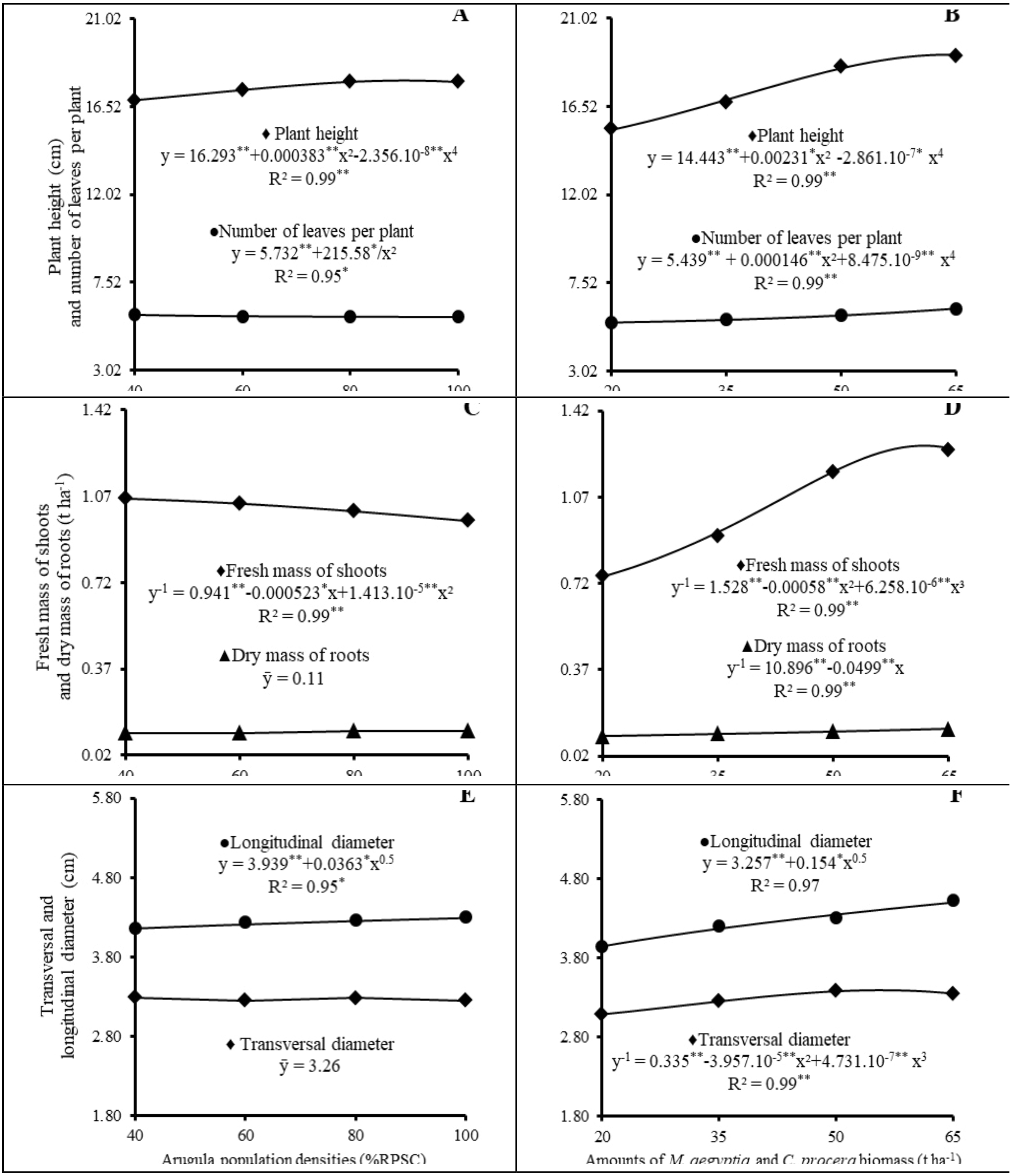

Figure 1. Plant heights and number of leaves per plant (A and B), fresh mass of shoots and dry mass of roots (C and D), and transversal and longitudinal diameter of radish roots (E and F) intercropped with arugula as a function of arugula population densities and biomass mixture amounts of *M. aegyptia* and *C. procera* incorporated into the soil. Mossoró, UFERSA, 2018-2019.

greater development of radish plants, consequently greater productivity. According to Silva (2017), radish develops well in mild conditions of temperature and relative humidity in a semi-arid environment.

On the other hand, studying the equitable amounts of *M. aegyptia* and *C. procera* biomass within each cropping year, an increase was found in the commercial productivity of radish roots with increasing amounts of green manures up to maximum values of 5.93 and 7.50 t ha^{-1} with amounts of 65.00 and 60.8 t ha^{-1} within the first and second cropping year, respectively, decreasing until the last amount incorporated into the soil (Figure 2B).

Studying the arugula population densities' interaction within each amount, an increasing behaviour was observed in the commercial productivity of roots within the amounts of 20 and 35 t ha^{-1} up to the maximum values of 5.97 and 6.87 t ha^{-1} in arugula densities of 77.90 and 76.20% of the RDSC, respectively, decreasing until the last tested density (Figure 2C). In the amount of 50 t ha^{-1}, the commercial productivity increased to a maximum value of 6.82 t ha^{-1} at a density of 100% of the RDSC (Figure 2C).

It was not possible to adjust a response equation for the commercial productivity of radish roots as a function of the arugula population densities in the amount of manures of 65 t ha^{-1} (Figure 2C).

Studying the interaction of equitable amounts of *M. aegyptia* and *C. procera* biomass within each arugula population density, an increasing behaviour was also observed in the commercial productivity of radish roots within the densities of 40% and 60% of the RDSC, with maximum values of 6.48 and 6.61 t ha^{-1}, up to the amount of 65 t ha^{-1} (Figure 2D). On the other hand, within densities of 80 and 100%, commercial productivity reached maximum values of 6.89 and 6.73 t ha^{-1} in the amounts of 41.16 and 52.86 t ha^{-1}, respectively, decreasing up to the last studied amount (Figure 2D).

The first year of cultivation stood out from the second in terms of plant height, number of leaves per plant and fresh mass of the shoots, while, the second year differed from the first in the dry mass and transversal diameter of roots. There was no significant difference between them in the LDR (Table 1). The commercial productivity

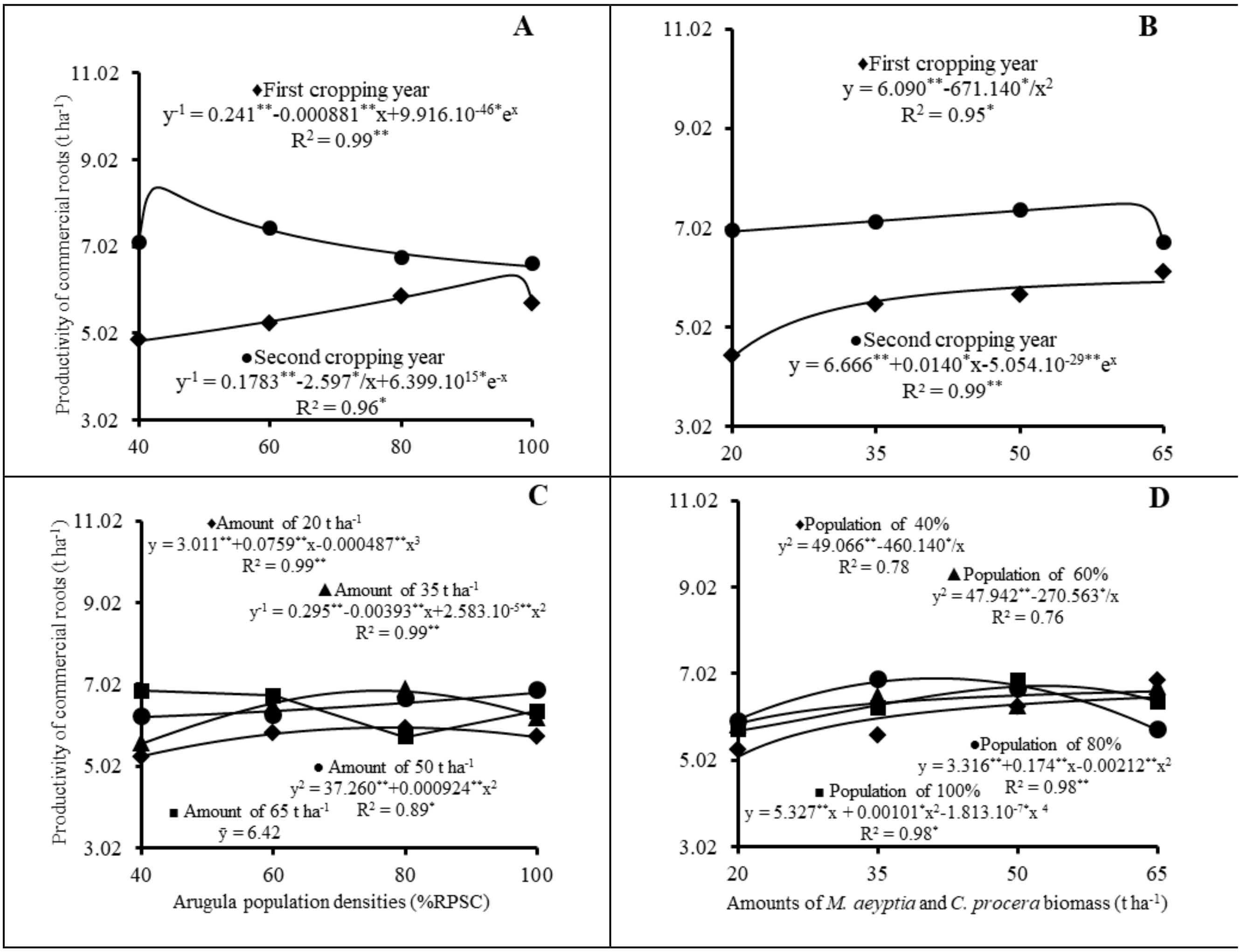

Figure 2. Productivity of commercial roots of radish as a function of cropping years, population densities of arugula and biomass equitable amounts of *M. aegyptia* and *C. procera* incorporated into the soil. Mossoró, UFERSA, 2018-2019.

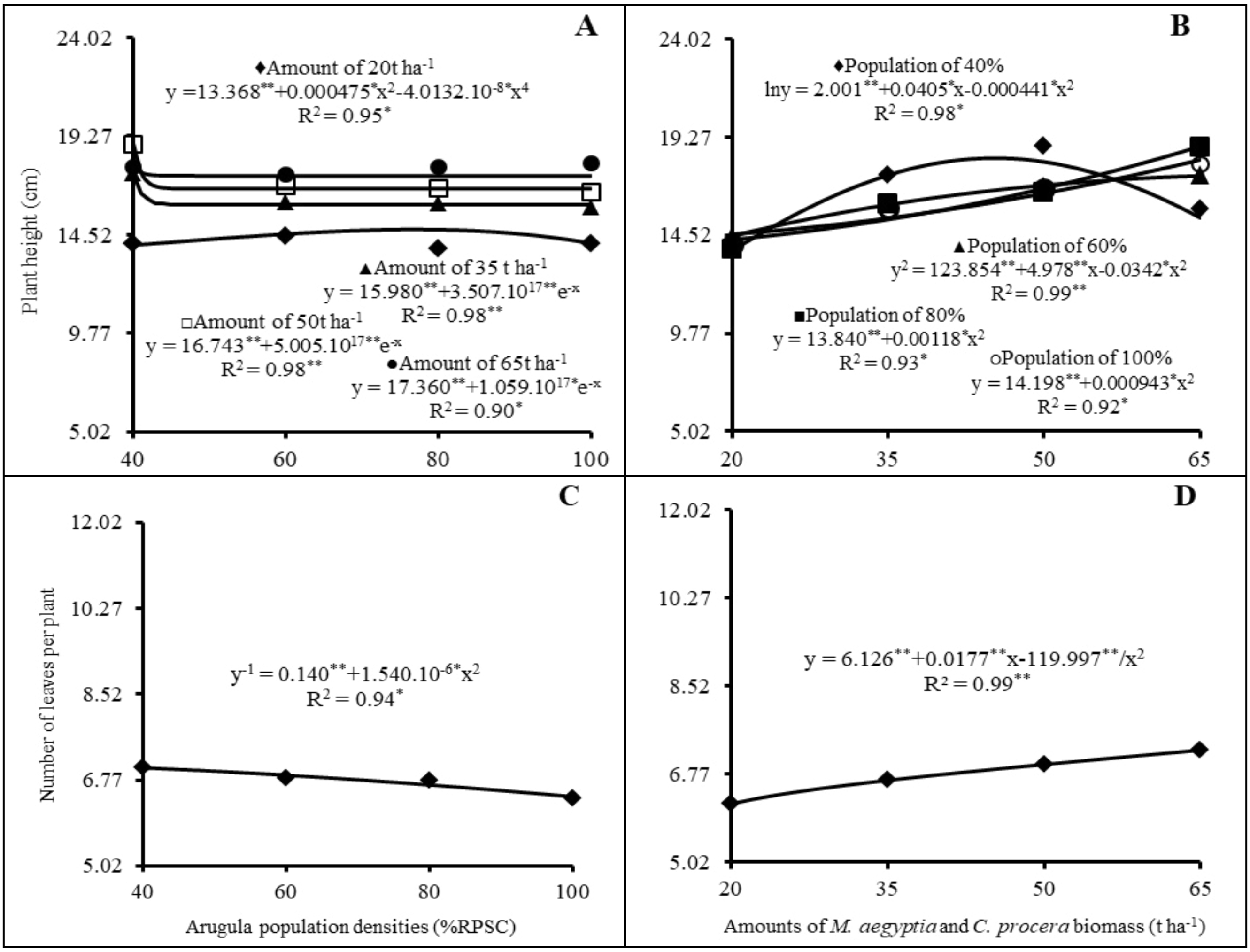

Figure 3. Plant height (A and B) and number of leaves per plant of arugula (C and D) intercropped with radish as a function of arugula population densities and biomass amounts of *M. aegyptia* and *C. procera* incorporated into the soil. Mossoró, UFERSA, 2018-2019.

of roots in the monocropping surpassed that of the intercropping in the first cropping year while, in the second year, these commercial productivities were similar. On the other hand, within the intercropping system, the second cropping year surpassed the first year in terms of commercial productivity, and within the monocropping these productivities were similar.

Among the crop systems, monocropping stood out from intercropping in terms of the fresh mass of shoots, dry mass of roots and the transversal diameter of radish roots. There were no significant differences between them in plant height, number of leaves per plant and longitudinal diameter (Table 1).

The results of the interaction between cropping years and arugula population densities in the commercial productivity of radish roots indicate that in the second cropping year, the arugula plants were possibly more efficient in the use of environmental resources, accentuating the interspecific competition with an increase in population density, and consequently, reduced the commercial productivity of radish roots. According to Chaves *et al.* (2020), the efficient use of natural resources by plants can be related to several factors, among them the population densities, amounts of incorporated material, the climatic conditions, among others. In the research in focus, the population densities and climatic conditions were responsible for these results.

The optimization of the commercial productivity of radish roots resulting from the interaction of equitable amounts of *M. aegyptia* and *C. procera* biomass within each cropping year can be attributed to the chemical characteristics of the green manure and the soil fertility in the second cropping year. Thus, this response may be related to the increasing increase in organic matter with increasing amounts of incorporated biomass (Batista *et al.*, 2016b). Thus, an adequate supply of organic matter is important for the formation of commercial roots in tuberous species (Lino *et al.*, 2021). On the other hand, the interaction of the arugula population densities within each amount shows that there was no intense interspecific competition with the increase in arugula densities, since the best productive performance of radish was registered in the largest population of the broadleaf crop within the dose of

50 t ha^{-1}, probably due to the better use of environmental resources.

The interaction of the equitable amounts of *M. aegyptia* and *C. procer*a biomass within each arugula population density can be attributed to the greater availability of nutrients provided by the dynamics of decomposition and mineralization of green manure, as well as by the influence of organic fertilization in improving soil fertility through the promotion of biological activity that favoured the solubilization of nutrients and therefore, the increase in root absorption surface (Filgueira, 2013).

The high temperatures in the first year of cultivation may have contributed to a reduction in the accumulation of biomass by the radish roots (Lino *et al.*, 2021).

Among crop systems, monocropping stood out from intercropping in terms of the fresh mass of the shoots, dry mass of roots and the transversal diameter of radish roots. This shows that, as the number of plants in the area increases, the effect of competition intensifies. Thus, in the intercropped system, plants can present variables with lower values compared to monocropping. However, proper management of production factors such as fertilization and population densities, among others, can reduce competition and increase the efficiency of crops in productive terms. Grangeiro *et al.* (2008), evaluating the yield of intercropping between radish and coriander, found similar results, where a greater fresh mass of radish plant shoots in monocropping in relation to that of intercropping was obtained.

Arugula crop

There was no significant interaction between the production factors, cropping years and population densities of arugula, between cropping years and equitable amounts of *M. aegyptia* and *C. procera* biomass, and among cropping years, equitable amounts of *M. aegyptia* and *C. procera* biomass and population densities of arugula in any agronomic characteristics of arugula (Table 1).

However, a significant interaction between the production factors, densities of arugula and equitable amounts of *M. aegyptia* and *C. procera* biomass was recorded for plant height, green and dry mass yield of arugula shoots intercropped with radish (Table 1).

Studying the interaction of arugula population densities within each quantity

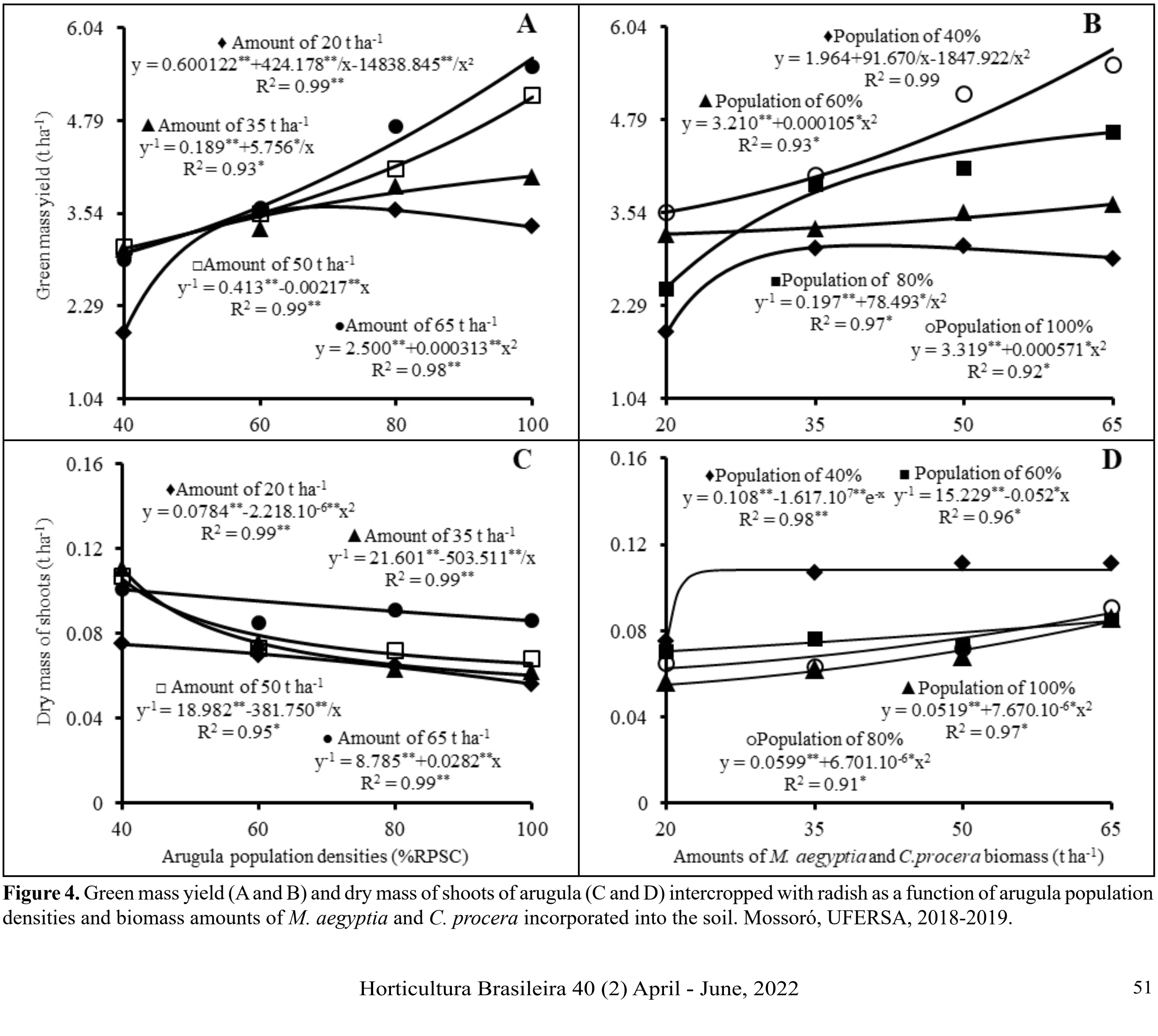

Figure 4. Green mass yield (A and B) and dry mass of shoots of arugula (C and D) intercropped with radish as a function of arugula population densities and biomass amounts of *M. aegyptia* and *C. procera* incorporated into the soil. Mossoró, UFERSA, 2018-2019.

of *M. aegyptia* and *C. procera* biomass incorporated into the soil, an increasing behaviour of plant height and green mass yield of arugula was registered within the amount of 20 t ha^{-1} up to a maximum value of 14.8 cm and 3.63 t ha^{-1} at population densities of 76.8 and 69.7% of the RDSC, respectively, which then decreased until the last studied density (Figures 3A and 4A).

In the amounts of 35, 50 and 65 t ha^{-1}, a decreasing behaviour of plant height was registered between the lowest and highest population density studied, with maximum values of 17.5, 18.9 and 17.8 cm, respectively, obtained at a density of 40% of the RDSC (Figure 3A), while the green mass yield presented an increasing behaviour between the lowest and highest density studied, with maximum values of 4.05, 5.11 and 5.64 t ha^{-1}, respectively at a density of 100% of the RDSC (Figure 4A).

Studying the interaction of equitable

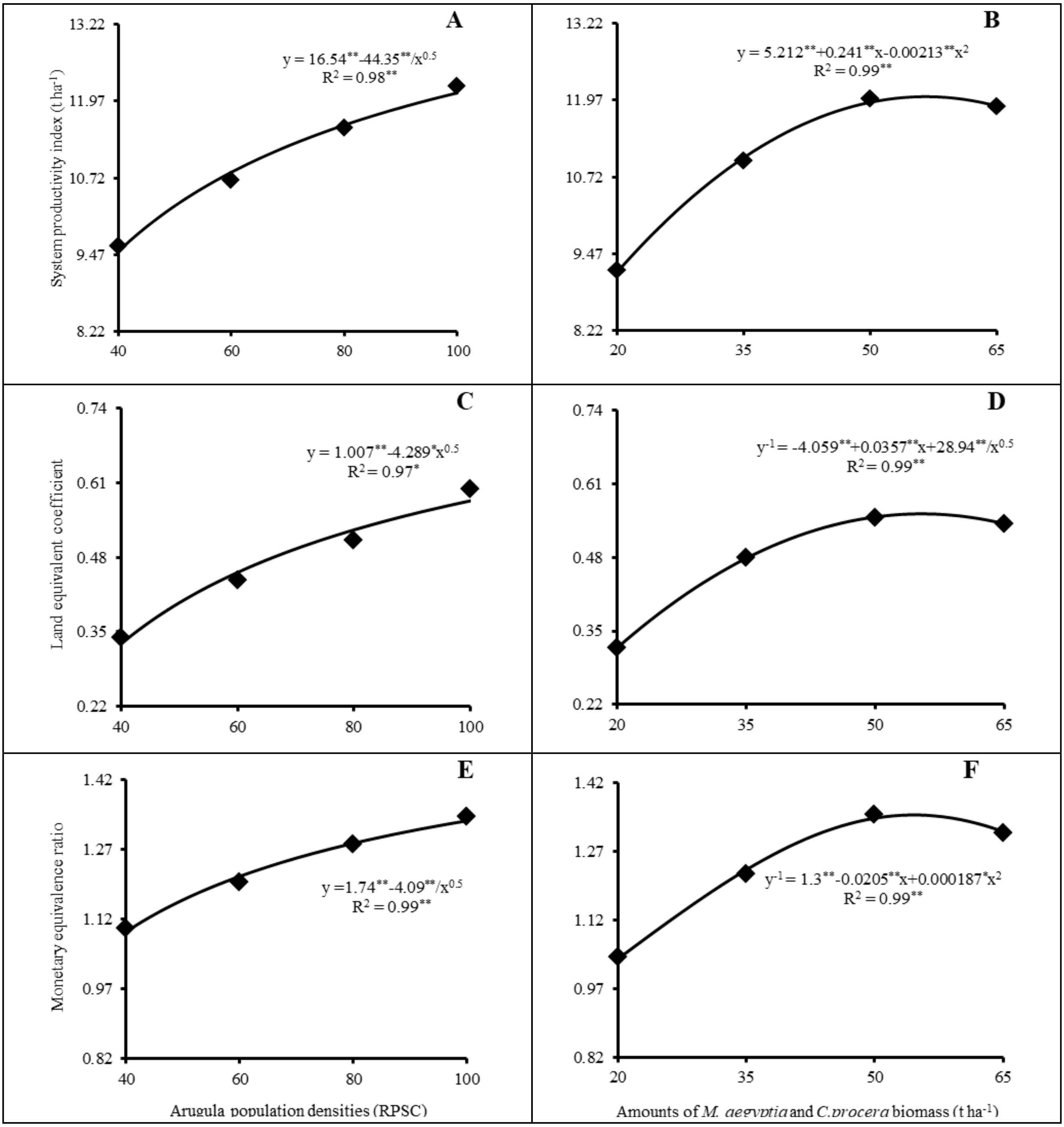

Figure 5. System productivity index (A and B), land equivalent coefficient (C and D) and monetary equivalence ratio (E and F) of radish intercropped with arugula as a function of arugula population density and biomass amounts of *M. aegyptia* and *C. procera* incorporated into the soil. Mossoró, UFERSA, 2018-2019.

quantities of *M. aegyptia* and *C. procera* biomass within each arugula population density, an increasing behaviour of plant height and green mass yield was observed within a population density of 40% of the RDSC until the maximum values of 18.7 cm and 3.10 t ha^{-1} in the biomass amounts of the fertilizers of 45.84 and 40.32 t ha^{-1}, respectively, which then decreased until the last tested amount (Figures 3B and 4B). At densities of 60, 80 and 100%, an increasing behaviour of plant height and green mass yield was also recorded between the smallest and largest studied amounts, with maximum values of 17.4, 18.8 and 18.2 cm and 3.65, 4.62 and 5.73 t ha^{-1}, respectively, obtained in the biomass amount of 65 t ha^{-1} (Figures 3B and 4B).

The number of leaves per plant decreased with the increasing population density of arugula, reaching the highest average value of seven leaves at the lowest population density of 40% of the RDSC of arugula, while this number increased with the increasing amount of biomass of the green fertilizers, reaching a maximum number of 7.2 leaves per plant in the quantity of 65 t ha^{-1} (Figures 3C and 3D).

Regarding the dry mass of shoots as a function of the population densities of arugula within each equitable amount of *M. aegyptia* and *C. procera* incorporated in the soil, a decreasing behaviour was registered for the dry mass between the lowest and highest densities studied in the amounts of 20, 35, 50 and 65 t ha^{-1}, with maximum values of 0.07, 0.11, 0.11 and 0.10 t ha^{-1} obtained at a density of 40% of the RDSC (Figure 4C).

In relation to the interaction of equitable amounts of *M. aegyptia* and *C. procera* biomass within each arugula population density, an increasing behaviour of the dry mass of shoots was observed within a population density of 40% of the RDSC up to a maximum value of 0.11 t ha^{-1} in the fertilizer biomass amount of 64.47 t ha^{-1}, which then decreased until the last tested amount (Figure 4D). At densities of 60, 80 and 100%, an increasing behaviour of the dry mass of shoots was also registered between the smallest and largest amount studied, with the maximum values of 0.08, 0.09 and 0.08 t ha^{-1} obtained in the biomass amount of 65 t ha^{-1} (Figure 4D).

There was no significant interaction between the cropping years and cropping systems for any agronomic characteristics of arugula. However, a significant difference between cropping years was observed in the following characteristics of arugula: plant height, number of leaves per plant and dry mass of shoots, with the second cropping year standing out from the first (Table 2).

Regarding the cropping systems, monocropping surpassed intercropping in plant height, green mass yield and dry mass of shoots (Table 2).

The behaviour related to the reduction in plant height with the increase of the arugula population in the area is possibly due to the effects of intraspecific competition, notably for light. A result similar to that obtained in this study, for green mass yield, was obtained by Batista *et al.* (2016a) studying the efficiency of arugula and carrot intercropping under different populations. These authors state that the increase in green mass yield of arugula with the increase in population density of the broadleaf vegetable is due to the greater number of plants per area.

The increasing behaviour of the

Table 1. F and mean values for plant height (PH), number of leaves per plant (NLP), fresh mass of shoots (FMS) and dry mass of roots (DMR), transversal (TDR) and longitudinal (LDR) diameters, and productivity of commercial roots (PCR) of radish intercropped with arugula as a function of cropping years and cropping systems. Mossoró, UFERSA, 2018-2019.

Sources of variation	PH	NLP	FMS	DMR	TDR	LDR	PCR	
Y	17.61^{**}	47.41^{**}	8.16^{**}	49.01^{**}	0.57^{ns}	37.41^{**}	90.64^{**}	
Y x A	0.24^{ns}	0.20^{ns}	2.63^{ns}	1.50^{ns}	0.08^{ns}	1.32^{ns}	5.91^{*}	
Y x D	1.05^{ns}	0.90^{ns}	1.33^{ns}	0.50^{ns}	1.32^{ns}	0.72^{ns}	4.50^{*}	
A x D	1.38^{ns}	1.26^{ns}	1.76^{ns}	0.33^{ns}	0.59^{ns}	0.86^{ns}	2.03^{*}	
Y x A x D	0.65^{ns}	0.69^{ns}	1.57^{ns}	0.83^{ns}	0.40^{ns}	1.07^{ns}	1.30^{ns}	
M vs I	0.18^{ns}	1.03^{ns}	343.22^{**}	305.22^{**}	1.03^{ns}	8.26^{**}	23.82^{**}	
Y x M vs I	0.50^{ns}	2.96^{ns}	3.18^{ns}	2.66^{ns}	0.29^{ns}	1.55^{ns}	11.00^{**}	
Cropping seasons				**Mean values**				
2018	18.38 a	6.14 a	1.08 a	0.10 b	3.14 b	4.27 a	5.42 b	
2019	16.50 b	5.45 b	0.96 b	0.13 a	3.40 a	4.21 a	7.05 a	
Cropping systems							**Cropping years**	
							1	**2**
Intercropping	17.26 a*	5.79 a	1.02 b	0.11 b	3.27 b	4.24 a	5.45 bB	7.16 aA
Monocropping	17.44 a	6.00 a	2.40 a	0.27 a	3.53 a	4.40 a	8.16 aA	7.57 aA
CV (%)	15.55	9.43	18.49	19.58	10.33	7.65	14.43	

† ** = P <0.01; * = P <0.05; ns = P >0.05. *Means followed by different lowercase letters in a column or uppercase in a row differ statistically from each other by the F test at 5% probability level. A: Amounts of *M. aegyptia* and *C. procera* biomass; D: Population densities of arugula; Y: Cropping years; M vs I: Monocropping vs Intercropping.

Table 2. F and mean values for plant height (PH), number of leaves per plant (NLP), green mass yield (GMY) and dry mass of shoots (DMS) of arugula intercropped with radish as a function of the cropping years and cropping systems. Mossoró, UFERSA, 2018-2019.

Sources of variation	PH	NLP	GMY	DMS
Y	123.64**	33.16**	2.04^{ns}	37.39**†
Y x A	2.25^{ns}	0.27^{ns}	0.61^{ns}	1.50^{ns}
Y x D	0.68^{ns}	1.42^{ns}	1.61^{ns}	1.50^{ns}
A x D	2.22**	0.29^{ns}	2.36**	2.50*
Y x A x D	1.67^{ns}	1.74^{ns}	1.57^{ns}	1.28^{ns}
M vs I	4.42**	0.01^{ns}	51.14**	10.50**
Y x M vs I	0.60^{ns}	1.99^{ns}	1.37^{ns}	3.50^{ns}
Cropping seasons		**Mean values**		
2018	14.52 b	6.35 b	3.78 a	0.057 b
2019	17.74 a	6.92 a	3.51 a	0.076 a
Cropping systems				
Intercropping	13.50 b	7.02 a*	3.65 b	0.070 b
Monocropping	14.85 a	7.32 a	6.06 a	0.150 a
CV (%)	10.34	12.06	24.37	25.96

† ** = P <0.01; * = P <0.05; ns = P >0.05. *Means followed by different lowercase letters in a column differ statistically from each other by the F test at the 5% probability level. A: Amounts of *M. aegyptia* and *C. procera* biomass; D: Population densities of arugula; Y: Cropping years; M vs I**:** Monocropping vs Intercropping.

plant height and green mass yield can be attributed, both to the adequate nutrient content present in the manures, as well as the better use of environmental resources promoted by green manure. It is important to note that this result indicates the efficient response of arugula to green manure, corroborating the observations made by Filgueira (2013), who reported that the efficiency of organic manure use is related to the increase in shoots and the yield of green mass of plants due to increased availability of nutrients and thus, favouring the physical properties and activities of soil organisms.

The reduction in the number of leaves as a function in the increase in arugula densities is probably due to the marked intraspecific competition for water, light and nutrients. However, the addition of *M. aegyptia* and *C. procera* into the soil contributed to an increase in the number of leaves due to the greater availability of nutrients provided by green manure.

The decreasing behaviour registered in dry mass between the lowest and highest densities studied in the amounts of 20, 35, 50 and 65 t ha^{-1}, is due, in part, to increased competition as a result of an increase in the total population of arugula plants intercropped with radish, sufficient to alter the dry matter behaviour of shoots. According to Duarte & Peil (2010), a change in the strength of the sources, through a change in the planting density or through an increase in the availability of radiation, directly affects the distribution of dry matter among a plant's organs.

A possible explanation for the arugula response to fertilization with *M. aegyptia* and *C. procera* within each arugula population density is the fact that the biomasses of these species had adequate amounts of N and K in their composition, considering that the crop has a high demand for these nutrients, as found in previous research (Grangeiro *et al.* 2011).

In the first year of cultivation, the plants showed, in general, less development compared to the second year, which may have occurred due to climatic variations, mainly of temperature, between the cropping years, since, according to Gonçalves-Trevisoli *et al.* (2017), the culture is sensitive and responsive to the climate. There was no difference between the years of cultivation in green mass yield.

It must be considered that the proximity of the cultures in intercropping predisposes to interspecific competition, that is, more competition for light and space. This behaviour explains the better performance of arugula in monocropping compared to intercropping in this study. Cecílio Filho *et al.* (2003), evaluating the production of beet and arugula as a function of the times of establishment of intercropping, found that, regardless of the time of establishment of the intercropping system, the highest green mass yield and dry mass of shoots of arugula were obtained with monocropping. There was no significant difference between the cropping systems in the number of leaves per plant.

Agro-economic efficiency indicators

There was no significant interaction between the production factors, arugula population densities and equitable amounts of *M. aegyptia* and *C. procera* biomass in the agro-economic indexes evaluated in the intercropped systems (Figure 5).

However, an increasing behaviour as a function of arugula population density was observed in the agronomic efficiency indicators, SPI and LEC, where the maximum values obtained were in the order of 12.11 t ha^{-1} and 0.58, respectively, in a population density of 100% of the RDSC of arugula (Figures 5A and 5C).

The indicator of economic efficiency, MER, also increased with the increasing population densities of arugula, reaching a maximum value of 1.33 in the highest arugula density studied (Figure 5E). This index measures the economic superiority of the intercropping over single cropping of the more economical crop. The higher value of this index, the more viable is the cropping system.

Regarding these same indexes as a function of the equitable biomass amounts of *M. aegyptia* and *C. procera*, an increasing behaviour of SPI, LEC and MER was observed up to maximum values of 12.03 t ha^{-1}, 0.55 and 1.35, respectively, in amounts of 56.53, 54.75 and 54.55 t ha^{-1}, which then decreased up to the greatest studied amount (Figures 5B, 5D and 5F).

The increasing behaviour of the

agro-economic efficiency indicators of the radish-arugula intercropping system, as a function of arugula population density, can be attributed to the greater use of environmental resources with the combination of increasing population densities. Diniz *et al.* (2017) found a stability of intercropping systems indicated by an SPI value higher than that of their monocropping counterparts.

The LEC, SPI and MER values of 0.58 (greater than 0.25), 12.11 and 1.33 obtained as a function of the arugula population densities, are an indication of the superiority of the intercropping system in relation to monocropping (Afe & Atanda, 2015). These results indicate that, in this cropping system, there was no negative effect of very high population density in the crops due to competition for sun light under dense situations for these indexes. It is known that plant population depends on type and growth habit of crops, soil fertility, rainfall and other growth requirements.

In relation to these same indexes as a function of the equitable biomass amounts of *M. aegyptia* and *C. procera*, the optimized values for LEC, SPI and MER of 0.55, 12.03 and 1.35 are due to the incorporation of an amount that contributed efficiently to the supply of nutrients. According to Tivelli *et al.* (2010), green fertilizers can also provide nutrient cycling in the soil, bringing nutrients that are at a greater depth to the surface.

When MER is greater than 1.0, intercropping systems are considered more productive or profitable in relation to monocropping (Afe & Atanda, 2015). This superiority of MER can be attributed to the complementary nature of the cultures involved. In addition, it is possible to observe that the agronomic efficiency of intercropping expressed by SPI and LEC was translated into economic terms by MER.

Finally, the highest agro-economic advantages of radish and arugula intercropping were obtained for LEC and MER of 0.55 and 1.35, respectively, for *M. aegyptia* and *C. procera* biomass amounts of 54.75 and 54.55 t ha^{-1} added to the soil. The arugula population density of 100% of the RDSC provided the greatest agro-economic efficiency of the intercropped system of radish with arugula with LEC and MER of 0.58 and 1.33, respectively. 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 arugula in intercropped systems in a semi-arid environment. The option of an intercropping system can provide vegetable producers in a semi-arid environment with viable alternatives to optimize the planted area, in addition to greater productivity and economic stability of activities on rural properties.

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