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Models for predicting broadleaf vegetable responses to green manures mixtures in semi-arid environment

Modelos para predição de respostas de hortaliças folhosas a misturas de adubos verdes em ambiente semiárido

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ABSTRACT: The broadleaf vegetables require large amounts of nutrients to provide a high productivity, and quality products, mainly due to their short period of development and growth. The green manuring has emerged as a viable alternative to provide these requirements for these vegetables, mainly from spontaneous species in the Caatinga biome. Thus, the aim of this study was to evaluate and estimate the maximum physical and economic efficiencies of lettuce and arugula agro-economic characteristics in monocropping as a function of equitable quantities of *Merremia aegyptia* and *Calotropis procera* biomass mixtures at different growing seasons, using polynomial and exponential models, based on the criteria of biological logic of growth and production of the cultures, of significance of the regression mean square, of high value of the coefficient of determination (R^2), of significance of the regression parameters, and of maximization of productivity and profit. The types of polynomial and exponential models chosen estimated the lettuce and arugula agro-economic characteristics with good precision and high R^2 values. The maximum agronomic (physical) efficiency of the lettuce and arugula was made possible with the incorporation into the soil of 47.38 and 42.23 t ha^{-1} of *M. aegyptia* and *C. procera*, respectively, and the maximum economic efficiency of production for these leafy vegetables was reached with biomass amounts of 45.96 and 33.61 t ha^{-1}, respectively. The rates of return obtained for lettuce and arugula cultivation for the optimized mixture amounts were 2.6 and 1.5 of those achieved in the control treatment (without fertilization), respectively.

Keywords: *Calotropis procera*. *Eruca sativa*. *Lactuca sativa*. *Merremia aegyptia*. Optimized agro-economic doses.

RESUMO: As hortaliças de folhas largas requerem grandes quantidades de nutrientes para proporcionar alta produtividade e produtos de qualidade, principalmente devido ao seu curto período de desenvolvimento e crescimento. A adubação verde tem se mostrado uma alternativa viável para suprir esses requisitos para essas hortaliças, principalmente advinda de espécies espontâneas do bioma Caatinga. Assim, o objetivo deste estudo foi avaliar e estimar as máximas eficiências físicas e econômicas das características agroeconômicas de alface e rúcula em monocultivo em função de quantidades equitativas de misturas de biomassa de *Merremia aegyptia* e *Calotropis procera* em diferentes épocas de cultivos, utilizando modelos polinomiais e exponenciais, baseados nos critérios da lógica biológica de crescimento e da produção das culturas, de significância do quadrado médio de regressão, de alto valor do coeficiente de determinação (R^2), de significância dos parâmetros de regressão e da

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maximização da produtividade e do lucro. Os tipos de modelos polinomiais e exponenciais escolhidos estimaram as características agroeconômicas da alface e da rúcula com boa precisão e elevados valores de R^2. A máxima eficiência agronômica (física) da alface e da rúcula foi possível com a incorporação ao solo de 47,38 e 42,23 t ha^{-1} de *M. aegyptia* e *C. procera*, respectivamente, e a máxima eficiência econômica de produção para essas folhosas foi alcançada com teores de biomassa de 45,96 e 33,61 t ha^{-1}, respectivamente. As taxas de retorno obtidas para o cultivo da alface e da rúcula para as quantidades otimizadas da mistura foram de 2,6 e 1,5 das obtidas no tratamento controle (sem fertilização), respectivamente.

Palavras-chave: *Calotropis procera*. Doses agroeconômicas otimizadas. *Eruca sativa*. *Lactuca sativa*. *Merremia aegyptia*.

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INTRODUCTION

The cycles of development and vegetative growth in the broadleaf lettuce and arugula crops in a semi-arid environment are quite similar, but specific information on nutritional requirements and growing seasons is still scarce in northeastern Brazil, thus not allowing recommendations for the producers of these vegetables to optimize production and their components in order to provide good quality products to the market.

It is known, however, that these vegetables require large amounts of nutrients, mainly due to their short period of development and growth (GRANGEIRO *et al*., 2011). The use of chemical and organic fertilizers (corral manure) has been used in the Brazilian semiarid region in order to supply the nutritional needs of these broadleaf crops. Due to the high cost of these inputs, green manuring has emerged as an alternative, mainly from spontaneous species in the Caatinga biome.

Among the spontaneous species used in green manuring for vegetables are *Merremia aegyptia* and *Calotropis procera* (SOUZA *et al*., 2017), which have all the characteristics of a “good” green manure, such as producing high amounts of phytomass and high levels of N in phytomass, in addition to promoting the recycling of nutrients such as P, K, Ca, and Mg, rapid initial growth, and presenting easy adaptation to the semi-arid climatic conditions (SILVA *et al*., 2018a).

The recommendation of the appropriate amount of biomass mixture of these two spontaneous species must be based on the knowledge obtained in experiments where the effects of different quantities of these green manures during different years on the production and the components of these vegetables were tested. The response obtained can be adjusted by various statistical models seeking to estimate the optimum amount of the mixture of these green manures (BEZERRA NETO *et al*., 2014; SILVA *et al*., 2018b). It is known, however, that adjustment of polynomial and exponential models in research with fertilizers is greatly affected by the model used, coefficient of variation, location of the maximum point, and clustering of experiments (ZIMMERMANN; CONAGIN, 1986).

The literature has shown that the selection of the most appropriate model to describe the relationship between crop productivity and fertilizer application is not standardized (BOCK; SKORA, 1990; ANGUS *et al*., 1993). Generally, in the works on the topic, there is no discussion of how the model was selected, and there is no standardization for the selection of the appropriate model to describe plant responses to fertilization. Therefore, some researchers argue that the choice of a statistical model should be based on criteria such as the biological logic of the phenomenon, significance of the mean square of the regression, a high value of the coefficient of determination (R^2), and significance of the parameters of the regression. In addition to these criteria, it is necessary to consider maximizing of productivity and profit (ALVAREZ, 1994).

Almeida *et al*. (2015) researched the agronomic efficiency of lettuce and arugula intercropping as a function of increasing amounts of *C. procera* biomass using polynomial models, and obtained maximum values of 15.8 and 4.3 t ha^{-1} in lettuce productivity and in the yield of arugula, respectively, with the incorporation of 37 and 38 t ha^{-1} of green manure biomass. Meanwhile, for the economic efficiency of the system, they obtained a maximum value of 28,243.45 R$ ha^{-1} with the addition to the soil of 36.3 t ha^{-1} of this green manure.

The objective of this work was to evaluate and estimate the maximum physical and economic efficiency of lettuce and arugula agro-economic characteristics in monoculture as a function of equitable quantities of biomass mixtures of *M. aegyptia* and *C. procera* in different growing seasons, using polynomial and exponential models, based on the criteria of the biological logic of the growth and production of the cultures, of significance of the mean square of regression, of high value of the coefficient of determination (R^2), of significance of the parameters of the regression, and of the maximization of productivity and profit.

2 MATERIAL AND METHODS

Experiments were conducted in different experimental areas at the 'Rafael Fernandes' Farm of the Federal University of Semi-Arid (UFERSA), in the district of Alagoinha, 20 km from the municipality of Mossoró, RN (5° 03' 37" S, 37° 23' 50" W, 18 m altitude), from August to September of the years 2016 and 2018.

The region's climate according to the Köppen classification is 'BShw', dry and very hot, with two seasons: one dry season, which usually occurs from June to January and one rainy season from February to May (ALVARES *et al*., 2014). During the experimental period of 2016, the average temperature was 27.2 °C, the average minimum was 22.4 °C, and the average maximum was 33.3 °C. The average air relative humidity was 60.8%, average solar radiation was 23.6 MJ m^{-2}, and there was 0 mm rainfall and wind speeds of 1.0–4.5 ms^{1}. In the experimental period of 2018, the average temperature was 27.4 °C, the average minimum was 20.1 °C, and the average maximum was 37.0 °C. The average air relative humidity was

73.8%, solar radiation was 20.8 MJ m^{-2}, and there was 0 mm rainfall and wind speeds of 1.6–4.5 m s^{-1} (INMET, 2019).

The soils in the experimental areas were classified as Dystrophic Red-yellow Argisol with sandy-loam texture (EMBRAPA, 2013). In each experimental area, simple soil samples were collected at a 0–20 cm layer, and then homogenized to obtain a composite sample. Subsequently, they were sent to the Laboratory of Water, Soil and Plant Analysis of the Department of Environmental Sciences at UFERSA for chemical analysis, whose results in the 2016 growing season were: pH (water) = 6.60, CE = 0.10 dS m^{-1}, organic matter (OM) = 3.65 g kg^{-1}, N = 0.42 g kg^{-1}, P = 34.20 mg dm^{-3}, K = 69.20 mg dm^{-3}, Ca = 3.10 cmol$_c$ dm^{-3}, Mg = 0.80 cmol$_c$ dm^{-3}, Na = 19.0 mg dm$^{-,3}$; Cu = 0.29 mg dm^{-3}, Fe = 2.86 mg dm^{-3}, Mn = 11.40 mg dm^{-3}, and Zn = 7.35 mg dm^{-3}. For the 2018 growing season the values were: pH = 6.10, EC = 0.24 dSm-^{1}, MO = 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 = 13.7 mg dm-^{3}, Cu = 0.10 mg dm^{-3}, Fe = 1.91 mg dm^{-3}, Mn = 11.67 mg dm^{-3}, and Zn = 2.63 mg dm^{-3}.

The design used was in complete randomized blocks, with five treatments and five replications. The treatments consisted of equitable mixtures of *M. aegyptia* and *C. procera* biomass in the following quantities (16, 26, 36, 46, and 56 t ha^{-1} on a dry basis) tested in the 2016 and 2018 growing seasons. In each experiment, one plot with lettuce and another with arugula without fertilization (control) was planted, for the purpose of comparison with the average value of optimized physic efficiency maximum in each characteristic of the broadleaf crops as well as with the average value of the fertilized treatments. Each experimental unit had a total area of 1.44 m^2 and a harvest area of 0.64 m^2 for lettuce and 0.80 m^2 for arugula (Figure 1), with the lettuce planted in the recommended spacing for the region 0.20 m × 0.20 m (SILVA *et al.*, 2000) and the arugula with a spacing of 0.20 m × 0.05 m (MOURA., 2008). Thus, for lettuce, the plot consisted of six rows with 6 plants per row, forming a population of 36 plants per plot, and for the arugula, the experimental plot was composed of six rows with 24 plants per row forming a population of 144 plants per installment.

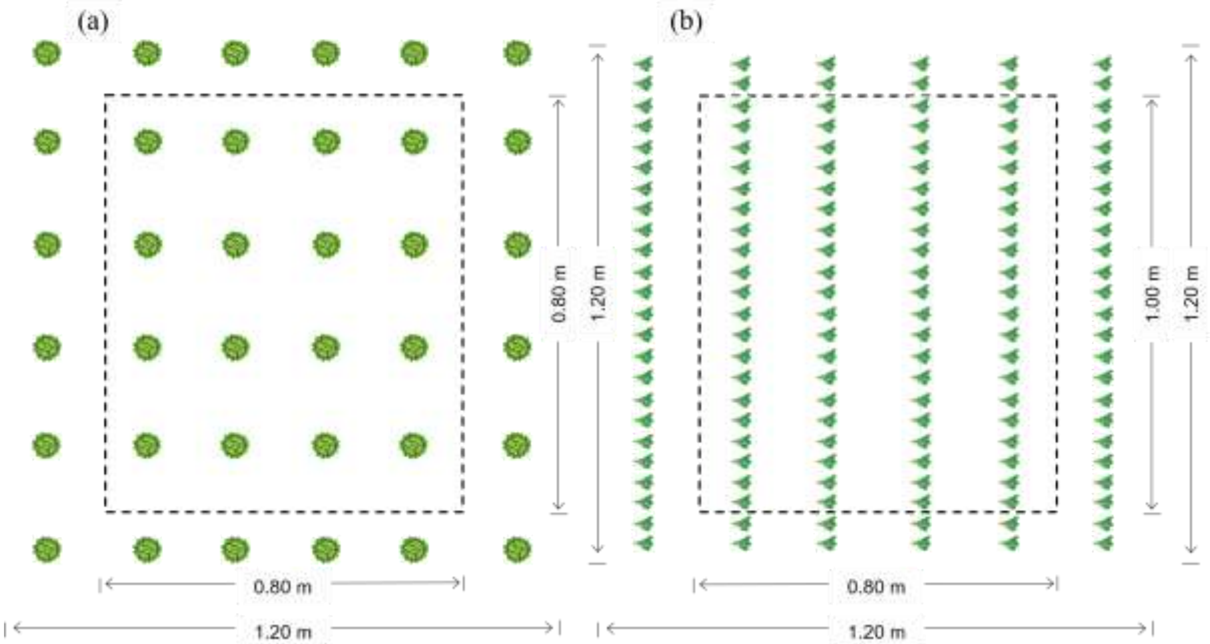

Figure 1. Details of the experimental plots of the broadleaf crops of lettuce (a) and arugula (b) in monocropping.

The soil preparation consisted of mechanical cleaning of the experimental area with the aid of a tractor with a coupled plow, followed by harrowing and raising the beds with the aid of a backhoe. After that, a pre-planting solarization was carried out for 30 days with 30-μm transparent plastic (Vulca Brilho Bril Fles) following the methodology recommended by Silva *et al*. (2006), the purpose of which is to reduce the population of phytopathogens in the soil, which would harm the productivity of broadleaf crops.

The green manures used in the experiments were collected from native vegetation in several locations in the rural area of the municipality of Mossoró, RN before the beginning of flowering. After the collections, the plants were crushed into pieces of two or three centimeters, which were dehydrated at room temperature until reaching a moisture content of 10% and then subjected to laboratory analysis. The chemical composition obtained in the 2016 growing season was: N = 14.80 g kg^{-1}, P = 2.52 g kg^{-1}, K = 11.95 g kg^{-1}, Ca = 8.11 g kg^{-1}, Mg = 8.15 g kg^{-1} and C:N = 21:1 for *M. aegyptia*, and N = 18.40 g kg^{-1}, P = 3.14 g kg^{-1}, K = 4.5 g kg^{-1}, Ca = 16.30 g kg^{-1}, Mg = 13.35 g kg^{-1}, and C:N = 25:1 for *C. procera*. In the 2018 growing season, the chemical composition was N = 16.60 g kg^{-1}, P = 2.79 g kg^{-1}, K = 20.80 g kg^{-1}, Ca = 19.35 g kg^{-1}, Mg = 7.07 g kg^{-1}, and C: N =20:1 for *M. aegyptia*, and N = 21.90 g kg^{-1}, P = 1.92 g kg^{-1}, K = 20.90 g kg^{-1}, Ca = 17.00 g kg^{-1}, Mg = 9.22 g kg^{-1}, and C:N = 27:1 for *C. procera*.

The incorporation of the vegetable biomass of these green manures was carried out at ten days before the transplanting of the lettuce seedlings and the sowing of the arugula in the 0–0.20 m soil layer in the experimental plots with the aid of a hoe, according to the quantities tested in each treatment. Irrigations were carried out daily by microsprinkling in two irrigation shifts (morning and afternoon), providing an 8 mm blade per day, in order to favor the microbial activity of the soil in the process of mineralization of organic matter.

The first cultivation of lettuce was carried out in 100 mL disposable cups, containing as the substrate a mixture of vermiculite and humus in the proportion 1:2 in a greenhouse covered with translucent white plastic. Three to five seeds were sown per container and, at seven days after germination, the first thinning was carried out, leaving three seedlings per container, and at fifteen days, the second thinning was carried out, leaving only one seedling per container. At 20 days after sowing (DAS), the transplants were carried out to the field (08/23/2016), placing a seedling per hole, and harvesting was performed 29 days after transplanting (DAT). The second cultivation of lettuce in the greenhouse was carried out using the same procedure as the first cultivation, and was transplanted to the field at 20 DAS (08/02/2018), with a harvest performed at 29 DAT.

The first cultivation of the arugula was carried out directly in the field on the same day as the lettuce transplant (08/23/2016), at two centimeters of depth, placing four seeds per hole, with thinning carried out eight days after sowing, leaving one plant per hole and harvesting at 39 DAS. The second arugula cultivation was carried out using the same procedure as the first (08/02/2018), with harvest at 39 DAS.

The cultivar of lettuce planted was ‘Tainá’ and the arugula cultivar was ‘Cultivated’. While conducting the experiments, the control of competing plants was carried out through manual weeding.

In the lettuce culture, evaluations were carried out on samples of five plants randomly harvested within the useful area of each plot for the heights and diameters of plants, the numbers of leaves per plant and dry mass of shoots, and for all harvest areas, the lettuce productivity. In the arugula culture, samples of twenty plants were also randomly collected within the harvest area, and the plant heights, numbers of leaves per plant and dry mass of shoots were determined, and in all harvested plots, the green mass yields were obtained.

In addition to these agronomic characteristics, indicators of economic efficiency were also determined, such as gross and net income, rate of return, and profit margin. The gross income (GI) of the tested treatments, expressed in R\$ ha^{-1}, was obtained by multiplying the production per hectare by the value of the product (R\$ 2.00 kg^{-1} for lettuce and R\$ 2.50 kg^{-1} for arugula) paid to the producer at the market level in the region in October 2016 and 2018. Net income (*NI*) was calculated by the following expression: $NI = GI - TC$, where *TC* is the total cost of production, resulting in the sum of all expenses with inputs and labor in each treatment, also expressed in R\$ ha^{-1}. The rate of return (*TR*) was obtained by the expression: $RR = GI/TC$. The profit margin was obtained from the ratio between *NI* and *GI*, expressed as a percentage.

A joint analysis of variance involving the growing seasons was performed for all variables of the broadleaf crops, using Sisvar software (FERREIRA, 2011), looking for a significant interaction between the growing seasons and the amounts of equitable mixtures of *M. aegyptia* and *C. procera* biomass. Where this interaction occurred, it was partitioned, and a polynomial or exponential model response function was adjusted for each variable, depending on the amounts of the equitable mixture of green manure biomass in each growing season using Table Curve software (JANDEL SCIENTIFIC, 1991), where the point of maximum agronomic (physical) or economic efficiency was estimated in its respective amount of mixture of green manure biomass. This response function was obtained based on the following criteria: biological logic of the variable, significance of the mean square of the regression residue (MSRR), high coefficient of determination (R^2) and significance of the parameters of the regression function. The F test was used to compare the mean values between growing seasons, and between the mean value of the maximum agronomic or economic efficiency and the mean value of the control treatment that did not receive green manure.

3 RESULTS

3.1 LETTUCE AGRONOMIC CHARACTERISTICS OPTIMIZATION

Significant interactions between the amounts of equitable *M. aegyptia* and *C. procera* biomass mixtures incorporated into the soil and the growing seasons were observed in the agronomic characteristics, including height and diameter of plants, number of leaves per plant, leaf productivity and mass dry of lettuce shoots (Figure 2).

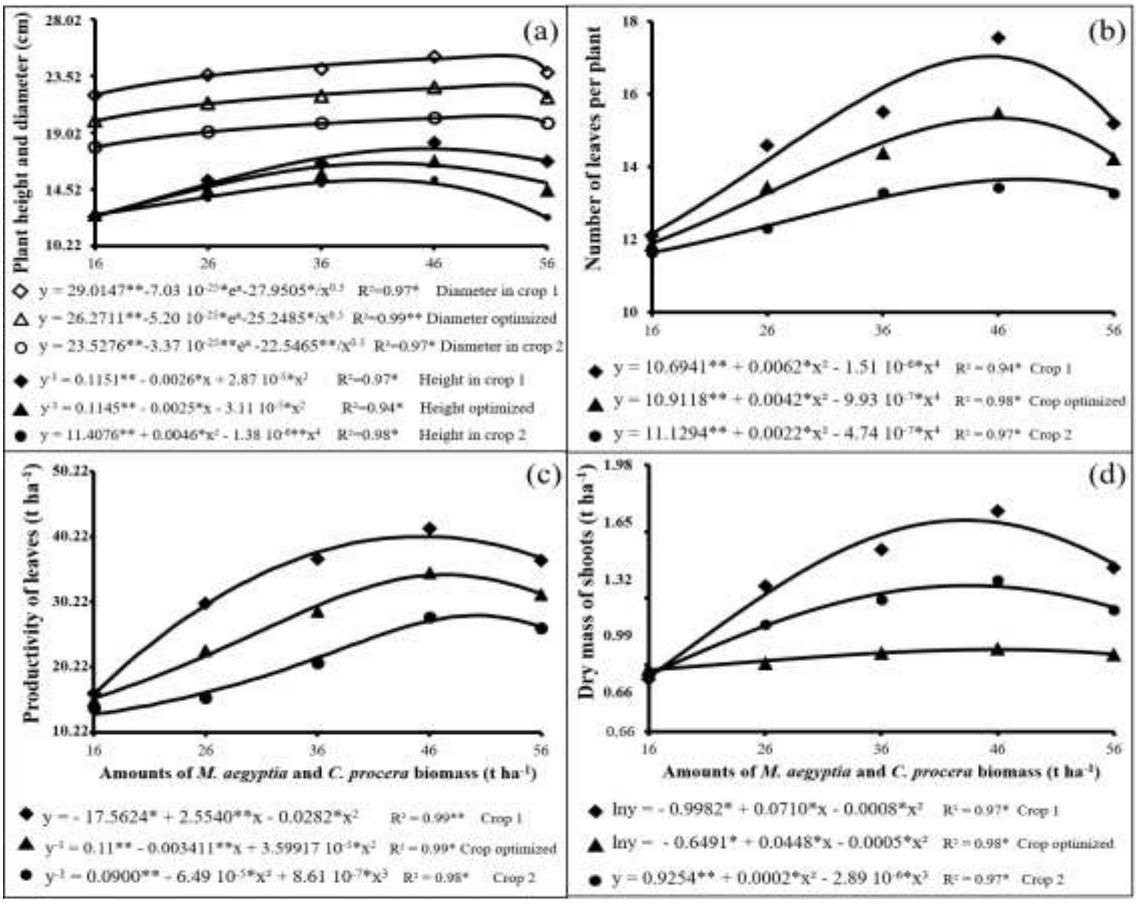

Figure 2. Plant height and diameter (a), number of leaves per plant (b), productivity of leaves (c), and dry mass of lettuce shoots (d) as a function of equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil in two growing seasons.

Upon partitioning these interactions, there was an increase in the height and diameter of plants, in the number of leaves per plant, productivity, and dry mass of the lettuce shoots with increases in equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil, in a polynomial or exponential model. The maximum values were 17.79 and 25.11 cm (height and diameter), 17.1 leaves per plant, and 40.26 and 1.07 t ha^{-1} (productivity and dry mass), respectively, in the green manure biomass amounts of 45.36 and 52.32, as well as 45.34, 45.26, and 43.16 t ha^{-1} within the first growing season. Values of 15.24 and 20.40 cm (height and diameter), 13.7 leaves per plant, 28.27 and 1.78 t ha^{-1} (productivity and dry mass) for the manure amounts of 40.96 and 52.82, as well as 47.73, 50.21, and 45.90 t ha^{-1} within the second growing season were registered (Figures 2a-d). On the other hand, when estimating the maximum physical efficiencies of these characteristics over the growing seasons, a polynomial or exponential increasing behavior was also observed, as a function of these amounts up to the maximum values of 16.52 and 22.75 cm (height and diameter), 15.4 leaves per plant, and 34.26 and 1.42 t ha^{-1} (productivity and dry mass), in the amounts of green manures of 41.47 and 52.51, as well as 45.92, 47.38, and 43.41 t ha^{-1}, then decreasing to the largest amount of manure tested (Figures 2a-d).

The mean values of maximum physical efficiency (MPE) of the treatments that received fertilization (T_f) differed from the control in all the agronomic characteristics of the lettuce (T_{wf}) (Table 1). In the growth variables (plant height, number of leaves per plant, and plant diameter), the MPEs were about 1.8 to 3 times the T_{nf} values, and the productive variables (leaf productivity and mass dry of shoots) were around 5 times the T_{wf} values. On the other hand, the growing seasons within the MPE treatment differed in all lettuce agronomic variables, with the first season standing out from the second, except in the dry mass of shoots where the second season stood out from the first. In the control treatment, the second station stood out from the first, except in the diameter of plants where they were similar (Table 1).

Table 1. Mean values for the control (T_{wf}), the treatment of maximum physical or economic efficiency (MPE or MEE) and the treatments fertilized (T_f) in the plant height and diameter, number of leaves per plant, productivity, dry mass of shoots, gross and net incomes, rate of return and in the profit margin of the lettuce over the growing seasons of 2016 and 2018

Comparison treatments	**Plant height (cm)**			**Number of leaves per plant**		
	Growing seasons			**Growing seasons**		
	2016	**2018**	**2016-2018**	**2016**	**2018**	**2016-2018**
Control (without fertilization, T_{wf})	5.46 bB	8.92 bA	7.19 b	7.0 bB	8.7 bA	7.9 b
MPE treatment	17.79 aA	15.24 aB	16.52 a	17.1 aA	13.7 aB	15.4 a
Fertilized treatments (T_f)			14.81 $^{+}$			13.9 $^{+}$
CV (%)			9.85			23.5
	Plant diameter (cm)					
Control (without fertilization, T_{wf})	12.57 bA	12.51 bA	12.54 b			
MPE treatment	25.11 aA	20.40 aB	22.75 a			
Fertilized treatments (T_f)			21.54 $^{+}$			
CV (%)			7.98			
	Productivity (t ha^{-1})			**Dry mass of shoots (t ha^{-1})**		
Control (without fertilization, T_{wf})	6.39 bB	7.27 bA	6.83 b	0.19 bB	0.35 bA	0.27 b
MPE treatment	40.26 aA	28.27 aB	34.26 a	1.07 aB	1.78 aA	1.42 a
Fertilized treatments (T_f)			26.53 $^{+}$			1.22 $^{+}$
CV (%)			23.51			17.85
	Gross income (R$ ha^{-1})			**Rate of return**		
Control (without fertilization, T_{wf})	12,776.80 bB	14,583.60 bA	13,680.20 b	1.21 bB	1.38 bA	1.29 b
MEE treatment	81,209.85 aA	56,285.01 aB	68,747.43 a	3.50 aA	3.07 aB	3.29 a
Fertilized treatments (T_f)			53,052.20 $^{+}$			2.61 $^{+}$
CV (%)			23.51			22.04
	Net income (R$ ha^{-1})			**Profit margin (%)**		
Control (without fertilization, T_{wf})	2,192.29 bB	3,999.09 bA	3,095.69 b	17.13 bB	27.33 bA	22.23 b
MEE treatment	58,786.05 aA	34,561.18 aB	46,673.61 a	74.12 aA	58.93 aB	66.52 a
Fertilized treatments (T_f)			33,033.69 $^{+}$			57.05 $^{+}$
CV (%)			38.97			17.20

***** Means followed by the same small letter in the column and capital letter in the row do not differ by F test at the 5% probability. $^{+}$ Mean of fertilized treatments is significantly different from the control mean by the F test at the 5% probability level.

3.2 LETTUCE ECONOMIC INDICATORS OPTIMIZATION

Significant interactions between the amounts of equitable biomass mixtures of *M. aegyptia* and *C. procera* incorporated into the soil and the growing seasons were also recorded in the economic indicators of lettuce (Figure 3).

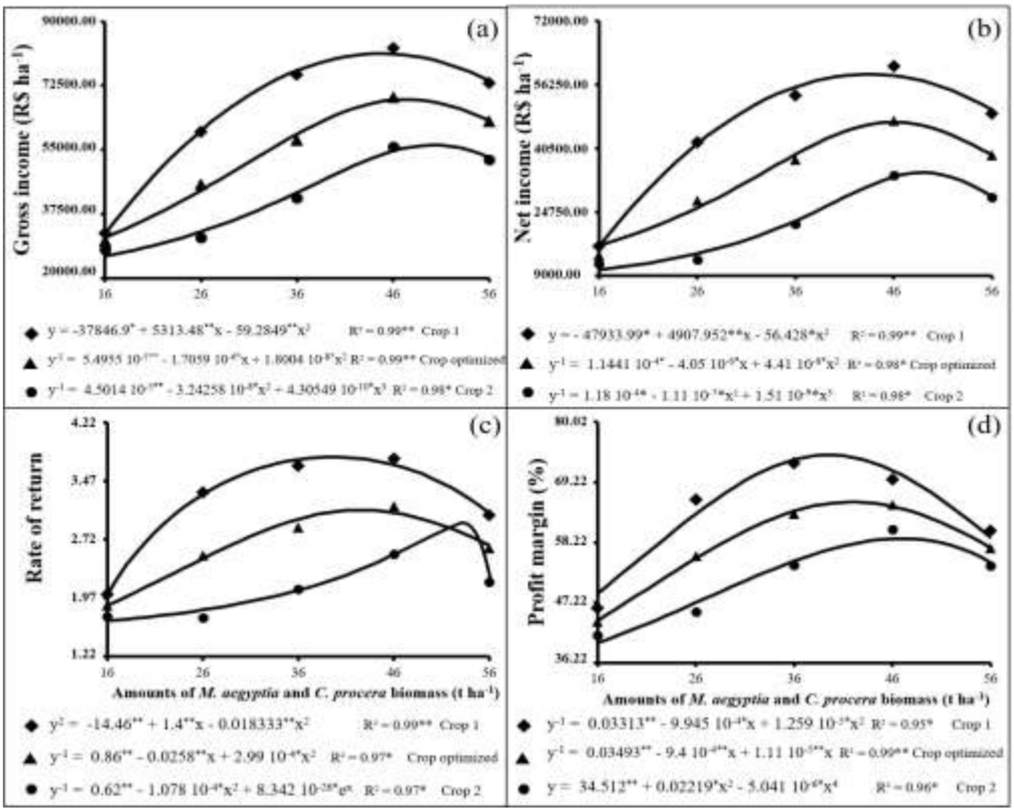

Figure 3. Gross income (a), net income (b), rate of return (c), and profit margin of lettuce as a function of equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil in two growing seasons.

When partitioning the interactions, there was an increase in gross income, net income, rate of return, and the profit margin as a function of the equitable amounts of *M. aegyptia* and *C. procera* biomass, in a polynomial or exponential model, up to the maximum values of 81,209.85 and 58,786.05 R$ ha^{-1} and 3.50 and 74.12%, respectively, for the green manure biomass amounts of 44.81; 43.49; 39.60 and 39.49 t ha^{-1} within the first growing season and of 56,285.01 and 34,561.18 R$ ha^{-1} (gross income and net income) as well as 3.07 and 58.93% (rate of return and profit margin) for the manure amounts of 50.21, 48.97, 53.28, and 46.92 t ha^{-1} during the second growing season (Figures 3a-d). Upon estimating the maximum economic efficiencies (MEE) of these indicators over the growing seasons, there was also an increasing polynomial or exponential behavior, depending on these amounts up to the maximum values of 68,747.43 and 46,673.61 R$ ha^{-1} (gross income and net income), 3.29 and 66.52% (rate of return and profit margin), for the green manure amounts of 47.38, 45.96, 42.48, and 41.91 t ha^{-1}, then decreasing to the largest amount of manure tested (Figures 3a-d).

The mean values of maximum economic efficiency (MEE) of the treatments that received manuring differed from those of the control (T_{nf}) in all the lettuce indicators (Table 1). The MEE of the economic indicators varied from 2.5 to 15 times that of the T_{nf} values. On the other hand, the cultivation stations within the treatment of maximum economic efficiency differed from each other, with the first station standing out from the second. In the control treatment, the cultivation seasons showed the opposite behavior (Table 1).

3.3 ARUGULA AGRONOMIC CHARACTERISTICS OPTIMIZATION

There were no significant interactions between the equitable amounts of biomass mixtures of *M. aegyptia* and *C. procera* incorporated into the soil and the growing seasons for plant height and the green mass yield of the arugula (Figures 4a and 4c). These characteristics increased as a function of the increasing biomass amounts, in a polynomial model, up to the maximum values of 20.71 cm and 14.81 t ha^{-1}, respectively, for the green manure biomass amounts of 46.96 and 42.23 t ha^{-1}, then decreased until the largest amount of manure tested.

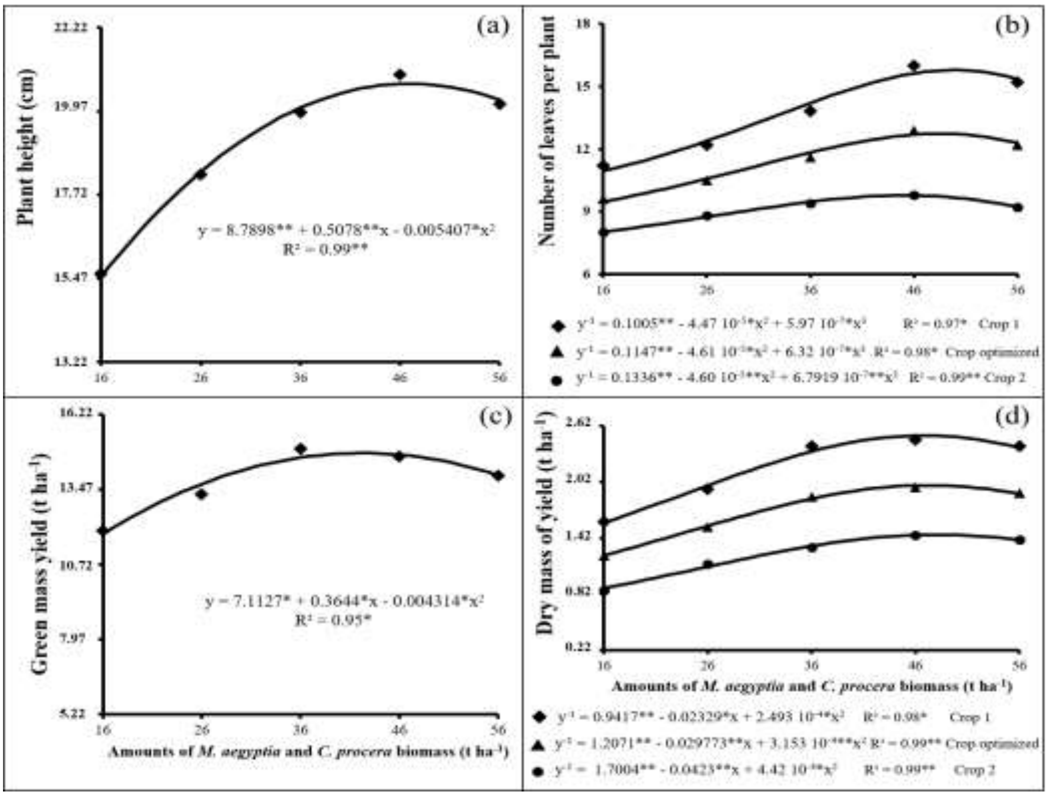

Figure 4. Plant height (a), number of leaves per plant (b), green mass yield (c), and dry mass of arugula shoots (d) as a function of equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated to the soil in two growing seasons.

For the number of leaves per plant and dry mass of arugula shoots, there was a significant interaction between the studied production factors. Upon partitioning this interaction, an increase in these variables was observed with the increasing amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil in a polynomial model up to the maximum values of 15.8 and 9.8 leaves per plant and 2.51 and 1.45 t ha^{-1} in the dry mass of shoots, respectively, within the first and second growing seasons, for the green manure biomass amounts of 49.91, 45.16, 46.71 and 47.91 t ha^{-1}, then they decreased until the last amount incorporated (Figures 4b and 4d). When estimating the maximum physical efficiencies of these characteristics over the growing seasons, there was also a polynomial ascending behavior as a function of these amounts up to the maximum values of 12.8 leaves per plant and 1.98 t ha^{-1} for the green manure amounts of 48.53 and 47.22 t ha^{-1}, then a decrease to the largest amount of manure tested (Figures 4b and 4d).

The mean values of MEF and T_f treatments for all agronomic characteristics of the arugula differed from those of control (T_{wf}) (Table 2). In the growth variables (plant height and number of leaves per plant), the MEFs were about 1.8 to 2 times the T_{wf} values, and in the productive variables (green mass yield and dry mass of shoots), they were around 2.5 to 3.6 times the T_{wf} values. The growing seasons within the maximum physical efficiency treatment differed in the number of leaves per plant and in the dry mass of arugula shoots with the first season standing out from the second. This same behavior was recorded for plant height and green mass yield. In the control treatment, the first season also stood out from the second in the dry mass of shoots and presented a behavior similar to that of the second season in the number of leaves per plant (Table 2).

Table 2. Mean values for the control (T_{wf}), the treatment of maximum physical or economic efficiency (MPE or MEE) and the treatments fertilized (T_f) in the plant height, number of leaves per plant, green mass yield, dry mass of shoots, gross and net incomes, rate of return, and in the profit margin of the arugula over the growing seasons of 2016 and 2018

Comparison treatments	**Plant height (cm)**	**Number of leaves per plant**		
		Growing seasons		
		2016	**2018**	**2016-2018**
Control (without fertilization, T_{wf})	10.53 b	7.2 bA	7.0 bA	7.1 b
MPE treatment	20.71 a	15.8 aA	9.8 aB	12.8 a
Fertilized treatments (T_f)	18.98 $^{+}$			11.4 $^{+}$
Season of 2016	18.81 a			
Season of 2018	16.34 b			
CV (%)	13.02			10.27
	Green mass yield (t ha^{-1})	**Dry mass of shoots (t ha^{-1})**		
Control (without fertilization, T_{wf})	5.90 b	0.60 bA	0.49 bB	0.55 b
MPE treatment	14.81 a	2.51 aA	1.45 aB	1.98 a
Fertilized treatments (T_f)	13.78 $^{+}$			1.70 $^{+}$
Season of 2016	14.24 a			
Season of 2018	10.69 b			
CV (%)	20.68			18.61
	Gross income (R\$ ha^{-1})	**Rate of return**		
Control (without fertilization, T_{wf})	14,758.00 b	1.40 bA	1.43 bA	1.42 b
MEE treatment	37,019.15 a	2.62 aA	1.61 aB	2.11 a
Fertilized treatments (T_f)	34,439.50 $^{+}$			1.77 $^{+}$
Season of 2016	35,591.00 a			
Season of 2018	26,728.00 b			
CV (%)	20.68			17.47
	Net income (R\$ ha^{-1})	**Profit margin (%)**		
Control (without fertilization, T_{wf})	4,349.00 b	27.95 bB	29.92 bA	28.93 b
MEE treatment	16,913.59 a	59.55 aA	43.64 aB	51.59 a
Fertilized treatments (T_f)	14,247.92 $^{+}$			41.11 $^{+}$
Season of 2016	17,030.00a			
Season of 2018	8,166.00b			
CV (%)	31.15			21.03

***** Means followed by the same small letter in the column and capital letter in the row do not differ by F test at the 5% probability. $^{+}$ Mean of fertilized treatments is significantly different from the control mean by the F test at the 5% probability level.

3.4 ARUGULA ECONOMIC INDICATORS OPTIMIZATION

There were no significant interactions between the equitable amounts of biomass mixtures of *M. aegyptia* and *C. procera* incorporated into the soil, the growing seasons, and the gross and net incomes (Figures 5a-b). However, an increase in these indicators was observed with growing equitable amounts of *M. aegyptia* and *C. procera* biomass in a polynomial model, up to the maximum values of 37,019.15 and 16,913.59 R\$ ha^{-1}, for the green manure biomass amounts of 42.22 and 33.61 t ha^{-1}, and then they decreased until the last amount incorporated (Figures 5a-b).

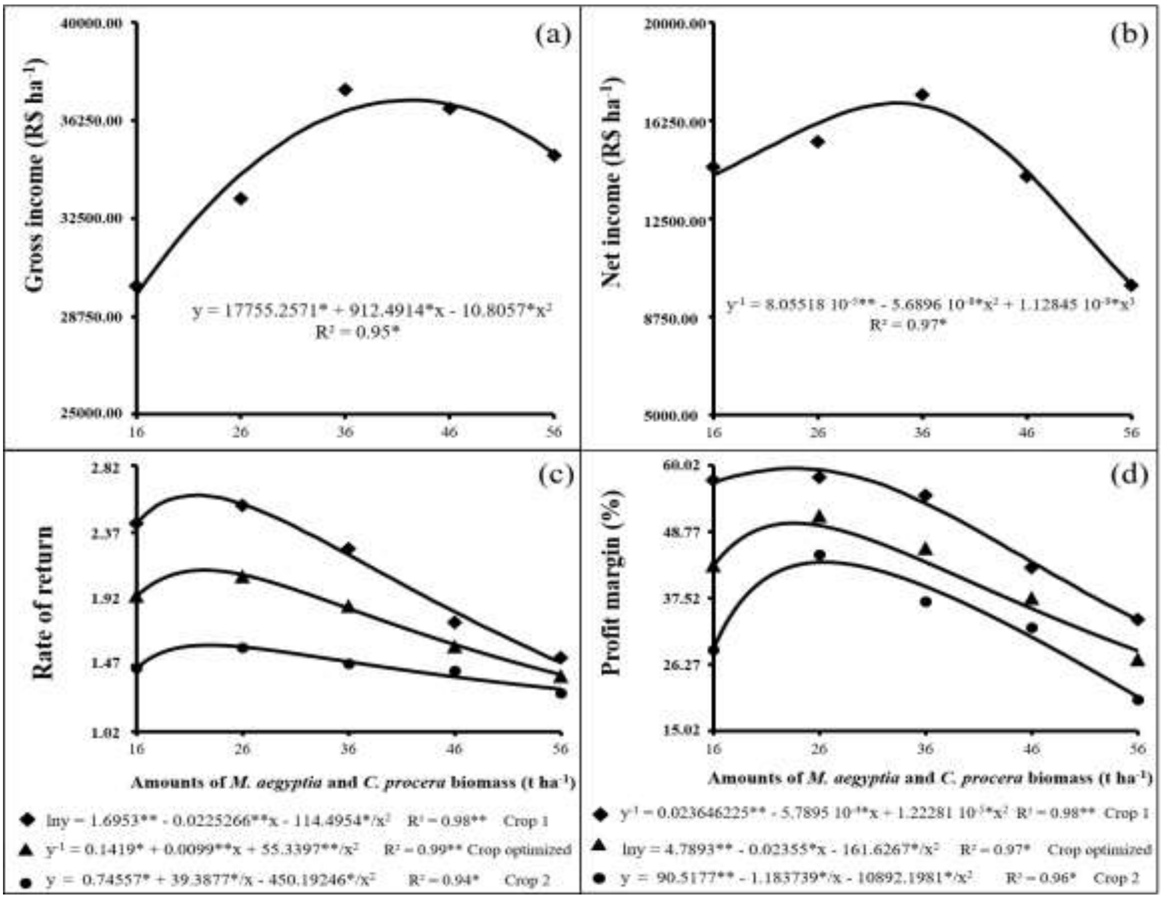

Figure 5. Gross income (a), net income (b), rate of return (c), and profit margin of arugula as a function of equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil in two growing seasons.

In contrast, for rate of return and profit margin, a significant interaction was observed between the production factors. Upon partitioning this interaction, there was an increase in these indicators with the increasing equitable amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil in a polynomial model up to the maximum values of 2.62 and 1.61 (rate of return) and 59.55 and 43.64% (profit margin), respectively, within the first and second growing seasons, for the green manure biomass amounts of 21.66, 22.86, 23.67, and 26.40 t ha^{-1}, then they decreased until the last amount incorporated (Figures 5c-d). When estimating the maximum economic efficiencies of these indicators over the growing seasons, there was also a polynomial crescent behavior as a function of these quantities up to the maximum values of 2.11 and 51.59%, for the of green manure amounts of 22.38 and 23.57 t ha^{-1}, then they decreased to the largest amount tested (Figures 5b and 5d).

The mean values of MEE and T_f treatments for all arugula indicators differed from those of the control (T_{wf}) (Table 2). The growing seasons within the maximum economic efficiency treatment differed in the rate of return and in the profit margin of the arugula, with the first season standing out from the second. In the control treatment, the first season also stood out from the second for the profit margin and presented a behavior similar to that of the second in the rate of return (Table 2). The first season also surpassed the second in terms of gross and net incomes.

4 DISCUSSION

It is known that polynomial models have been very popular to describe a crop's response to fertilization (NEETESON; WADMAN, 1987; CERRATO; BLACKMER, 1990; COLWELL, 1994) and exponential models have also been used to describe the response of food and vegetable crops for fertilization (NEETESON; WADMAN, 1987).

The types of polynomial or exponential models tested in the characteristics of the lettuce and arugula fulfilled the selection criteria used to express the behavior of each evaluated characteristic. These were the biological logic (LB) of the variable, that is, when it turns out that after a certain dose of fertilizer there is no increase in productivity, the significance of the mean square of the regression residue (QMRR), a high value of the determination coefficient (R^2), the significance of the parameters of the regression equation, and the maximization of productivity and profit (Table 1).

In addition, in the analysis of each characteristic, the variation coefficient was measured. The results obtained for the agronomic characteristics of both cultures showed “good” experimental precision. Almeida *et al*. (2015), evaluating the agronomic characteristics of lettuce and arugula in intercropping systems in a semi-arid environment, obtained coefficients of variation for these characteristics in their experiments that also showed good experimental precision. On the other hand, the results obtained with the evaluated economic indicators showed experimental precision of medium to good. These results are perfectly justified, because these indicators depend on the nature of their calculations and the types of costs for each treatment, leading to an increase in the variability of their values, consequently increasing the experimental variability.

The upward responses and the optimizations (obtaining MPE values) of the agronomic characteristics evaluated in both lettuce and arugula in polynomial or exponential models can be attributed to the Maximum Law, where the excess of a nutrient in the soil provided by equitable amounts of the *M. aegyptia* and *C. procera* mixture can cause a toxic effect and/or decrease the effectiveness of other factors, thus resulting in the reduction of the characteristic under analysis after the maximum point (VOISIN, 1973). Another factor that may be related to this behavior of the broadleaf crops is the proper synchrony between the decomposition and mineralization of the mixture of green manures added to soil and the time of the greatest nutritional demand of the culture (FONTANÉTTI *et al*., 2006).

These green manures used in this research have a C:N ratio between 20:1 and 30:1, which contributed to a faster decomposition and release of nutrients, evidenced by the incorporation at 20 days before transplanting lettuce or before planting arugula in evaluated characteristics. However, it is known that the rate of decomposition of organic residues is linked to the carbon: nitrogen ratio (C: N) of the material under this process, which in the case of *M. aegyptia* is 20:1, and 25:1 for *C. procera*, and that the mineralization of N was also greatly influenced by the C:N ratio of the decomposing material (VALE *et al*., 1997).

The upward responses of the economic indicators evaluated in both broadleaf crops in polynomial or exponential form and the economic optimizations as a function of the equitable amounts of the mixture of *M. aegyptia* and *C. procera* was because the broadleaf crops responded very well to green manures. The environmental resources, provided by the quantities of the mixtures tested, were better used by lettuce and arugula plants, whose use was translated into economic efficiency. Green manuring is known to improve fertility, increase organic matter content, decrease erosion rates, increase soil water retention and soil microbiota activity, increase nutrient availability, and reduce the amount of invasive plants (GRAHAM; HAYNES, 2006).

These optimizations of agronomic characteristics together with economic indicators allow the producer of these broadleaf crops to decide on the recommendation of the amounts of mixtures of the green manures *M. aegyptia* and *C. procera* that could be used both in agronomic and in economic terms. If the producer decides based on the agronomic aspect, as can be seen from the results obtained, the recommendation for lettuce fertilization would be with the incorporation of 47.38 t ha^{-1} of the biomass mixture, whereas for arugula it would be 42.23 t ha^{-1} of the biomass mixture.

On the other hand, in economic terms (expressed by net income), the recommendation of fertilizer for lettuce would be with the incorporation of 45.96 t ha^{-1} of biomass mixture, whereas for arugula this amount would be 33.61 t ha^{-1} of biomass mixture. According to Beltrão *et al*. (1984), net income is one of the indicators that better expresses the economic value of a farming system than gross income, because production costs are deducted. Bezerra Neto *et al*. (2019), evaluated quantities of *C. procera* incorporated into the soil during carrot × cowpea intercropping in a semiarid environment through polynomial models that would provide maximum economic efficiency of the gross income, net income, rate of return and profit margin, and they obtained values for MEF of 37,815.33 and 17,856.43 R$ ha^{-1} and 1.89

and 46.81%, respectively, in these indicators for the optimized quantities of 44.31, 40.60, 38.28, and 39.60 t ha^{-1} of *C. procera* added to the soil. These optimized amounts of green manure were slightly different from those obtained in this research with manure mixtures. This difference is perfectly justified, because in the current research, mixtures of green manures and different types of crops were tested.

5 CONCLUSIONS

The types of polynomial and exponential models chosen estimated the behavior of the agronomic and economic characteristics of the lettuce and arugula in a semiarid environment with good precision and high R^2 values.

The fertilization of lettuce and arugula to obtain maximum agronomic efficiency was made possible with the incorporation into the soil of the amounts of 47.38 and 42.23 t ha^{-1} of *M. aegyptia* and *C. procera* optimized equitable biomass, respectively.

The maximum economic efficiency of lettuce and arugula cultivation was obtained when the amounts of 45.96 and 33.61 t ha^{-1} of *M. aegyptia* and *C. procera* optimized equitable biomass mixture of were incorporated into the soil.

The rates of return obtained with lettuce and arugula crops with the incorporation of the amounts of *M. aegyptia* and *C. procera* optimized equitable biomass mixture of were about 2.6 and 1.5 of those obtained in the control treatment (without fertilizing).

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REFERENCES

ALMEIDA, A. E. S.; BEZERRA NETO, F.; COSTA, L. R.; SILVA, M. L.; LIMA, J. S. S.; BARROS JÚNIOR, A. P. Eficiência agronômica do consórcio alface-rúcula fertilizado com flor-de-seda. **Revista Caatinga**, Mossoró, v. 28, n. 3, p. 79-85, 2015. DOI: 10.1590/1983-21252015v28n309rc.

ALVARES, C. A.; STAPE, J. L.; SENTELHA, P. C.; GONÇALVES, J. L. M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, Germany, v. 22, n. 6, p.711-728, 2014. DOI: 10.1127/0941-2948/2013/0507.

ALVAREZ, V. H. **Avaliação da fertilidade do solo (Superfície de resposta – modelos aproximativos para expressar a relação fator resposta)**. Viçosa: UFV, 1994. 75p.

Disponível em: https://www.scienceopen.com/document?vid=657c6d49-352e-43fb-895e-6d8578fa3cfc.

ANGUS, J. F.; BOWDEN, J. W.; KEATING B. A. Modelling nutrient responses in the field. **Plant and Soil**, Netherlands, v. 155, n. 1, p. 57-66, 1993. Disponível em: https://www.jstor.org/stable/4293 9262.

BELTRÃO, N. E. M.; NOBREGA, L. B.; AZEVEDO, D. M. P.; VIEIRA, D. J. **Comparação entre indicadores agroeconômicos de avaliação de agroecossistemas consorciados e solteiros envolvendo algodão “upland” e feijão “caupi”**. Campina Grande: CNPA, 1984. 21 p. (Boletim de Pesquisa, 15). Disponível em: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/262650.

BEZERRA NETO, F.; OLIVEIRA, L. J.; SANTOS, A. P.; LIMA, J. S. S.; SILVA, I. N. Agronomic and economic optimization of the carrot when fertilized with different dosages of jitarana. **Revista Ciência Agronômica**, Fortaleza, v. 45, n. 2, p. 305-311, 2014. DOI: 10.1590/S1806-66902014000 200011.

BEZERRA NETO, F.; SILVA, M. L.; LIMA, J. S. S.; BARROS JÚNIOR, A. P.; SILVA, I. N.; CHAVES, A. P. Productive viability and profitability of carrot-cowpea intercropping using different amounts of *Calotropis procera*. **Revista Caatinga**, Mossoró, v. 32, n. 1, p. 62-71, 2019. DOI: 10.15 90/1983-21252019v32n107rc.

BOCK, B. R.; SKORA, F. J. Modified quadratic/plateau model for describing plant responses to fertilizer. **Soil Science Society of America Journal**, Madison, v. 54, n. 6, p. 1784-1789, 1990. DOI: 10.2136/sssaj1990.03615995005400060047x.

CERRATO, M. E.; BLACKMER, A. M. Comparison of models for describing; corn yield response to nitrogen fertilizer. **Agronomy Journal**, Madison, v. 82, n. 1, p. 138-143, 1990. DOI: 10.2134/agronj 1990.00021962008200010030x.

COLWELL, J. D. **Estimating fertilizer requirements**: a quantitative approach. Wallingford: CAB International, 1994. 262p. DOI: 10.1017/S0021859600074748.

EMBRAPA - EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. (2013). **Sistema brasileiro de classificação de solos.** 3. ed. rev. amp. Brasília: EMBRAPA, 2013. 353 p. Disponível em: https://www.embrapa.br/en/solos/sibcs.

FERREIRA, D. F. Sisvar: a computer statistical analysis system. **Ciência e Agrotecnologia**, Lavras, v. 35, n. 6, p. 1039-1042, 2011. DOI: 10.1590/S1413-70542011000600001.

FONTANÉTTI, A.; CARVALHO, G. J.; GOMES, L. A. A.; ALMEIDA, K.; MORAES, S. R. G.; TEIXEIRA, C. M. Adubação verde na produção orgânica de alface americana e repolho. **Horticultura Brasileira**, Brasilia, v. 24, n. 2, p. 146-150, 2006. DOI: 10.1590/S0102-05362006000200004.

INMET - Instituto Nacional de Meteorologia. **Dados meteorológicos**. Brasilia: Ministério da Agricultura, Pecuária e Abastecimento, 2019. Disponível em: https://portal.inmet.gov.br.

GRAHAM, M. H.; HAYNES, R. J. Organic matter status and the size, activity and metabolic diversity of the soil microbial community in the row and inter-row of sugar cane under burning a trash retention. **Soil Biology & Biochemistry**, England, v. 38, n. 1, p. 21-31, 2006. DOI: 10.1016/j.soilbio. 2005.04.011.

GRANGEIRO, L. C.; FREITAS, F. C. L.; NEGREIROS, M. Z.; MARROCOS, S. T. P.; LUCENA, R. R. M.; OLIVEIRA, R. A. Crescimento e acúmulo de nutrientes em coentro e rúcula. **Revista Brasileira de Ciências Agrárias**, Recife, v. 6, n. 1, p. 11-16, 2011. DOI:10.5039/agraria.v6i1a634.

JANDEL SCIENTIFIC. **Table Curve**: curve fitting software. Corte madeira, CA: Jandel Scientific, 1991. DOI: doi.org/10.1177/089443939201000316.

MOURA, K. K. C. F.; BEZERRA NETO, F.; PONTES, F. S. T.; LIMA, J. S. S.; MOURA, K. H. S. Avaliação econômica de rúcula sob diferentes espaçamentos de plantio. **Revista Caatinga**, Mossoró, v. 21, n. 2, p. 113-118, 2008. Disponível em: http://www.redalyc.org/articulo.oa?id=237117611014.

NEETESON, J. J.; WADMAN, W. P. Assessment of economically optimum application rates of fertilizer N on the basis of response curves. **Fertilizer Research**, Dordrecht, v. 12, n. 1, p.37-52, 1987. Disponível em: https://link.springer.com/article/10.1007%2FBF01049419.

SILVA, I. N.; BEZERRA NETO, F.; BARROS JÚNIOR, A. P.; LIMA, J. S. S.; BATISTA, T. M. V.; LINS, H. A. Green manure and spatial arrangement in the sustainability improvement of lettuce-beet intercrops. **Revista Brasileira de Engenharia Agrícola Ambiental**, Campina Grande, v. 22, n. 7, p. 451-457, 2018a. DOI: 10.1590/1807-1929/agriambi.v22n7p451-457.

SILVA, I. N.; BEZERRA NETO, F.; BARROS JÚNIOR, A. P.; LIMA, J. S. S.; CHAVES, A. P.; ALBUQUERQUE, J. R.T.; LINS, H. A.; SANTOS, M. G.; SOARES, E. B. Agronomic performance and economic profitability of lettuce fertilized with *Calotropis procera* as a green manure in a single crop. **Australian Journal of Crop Science**, St. Lucia, v. 12, n. 10, p. 1573-1577, 2018b. DOI: 10.21475/ajcs.18.12.10.p1114.

SILVA, M. G.; SHARMA, R. D.; JUNQUEIRA, A. M. R.; OLIVEIRA, C.M. Efeito da solarização, adubação química e orgânica no controle de nematóides em alface sob cultivo protegido. **Horticultura Brasileira**, Brasilia, v. 24, n. 4, p. 489-494, 2006. DOI: 10.1590/S0102-05362006000400019.

SILVA, V. F.; BEZERRA NETO, F.; NEGREIROS, M. Z.; PEDROSA, J. F. Comportamento de cultivares de alface em diferentes espaçamentos sob temperatura e luminosidade elevadas. **Horticultura Brasileira**, Brasilia, v. 18, n. 3, p. 183-187, 2000. DOI: 10.1590/S0102-05362000000300008.

SOUZA, E. G. F.; LIMA, E. F.; BARROS JÚNIOR, A. P.; SILVEIRA, L. M.; BEZERRA NETO, F.; CRUZ, E. A. Production of lettuce under green manuring with *Calotropis procera* in two cultivation seasons. **Revista Caatinga**, Mossoró, v. 30, n. 3, 391-400, 2017. DOI: 10.1590/1983-21252017v30 n214rc.

VALE, F. R.; GUILHERME, L. R. G.; GUEDES, G. A. A.; FURTINI NETO, A. E. **Fertilidade do solo**: dinâmica e disponibilidade dos nutrientes de plantas. Lavras: UFLA FAEPE, 1997. 171p. Disponível em: https://www.bdpa.cnptia.embrapa.br/consulta/busca?b=ad&id=911649&biblioteca=vazio&busca=autoria:%22GUILHERME,%20L.%20R.%22&qFacets=autoria:%22GUILHERME,%20L.%20R.%22&sort=&paginacao=t&paginaAtual=3.

VOISIN, A. **Adubos**: novas leis científicas de sua aplicação. São Paulo: Mestre Jou, 1973. 130 p. Disponível em: https://biblioteca.incaper.es.gov.br/busca?b=ad&id=3152&biblioteca=vazio&busca=autoria:%22VOISIN,%20A.%22&qFacets=autoria:%22VOISIN,%20A.%22&sort=&paginacao=t&paginaAtual=1.

ZIMMERMANN, F. J. P.; CONAGIN, A. Ajuste de modelos polinomiais do 2º grau em pesquisas com fertilizantes. **Pesquisa Agropecuária Brasileira**, Brasilia, v. 21, n. 9, p. 971-978, 1986. Disponível em: https://seer.sct.embrapa.br/index.php/pab/article/view/15012/8726.