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Agro-economic optimization of radish cultivation fertilized with doses of roostertree in a semi-arid environment

Otimização agroeconômica do cultivo do rabanete adubado com doses de flor-de-seda em ambiente semiárido

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ABSTRACT - The use of spontaneous species from the Caatinga biome as green manure is a promising practice in increasing the productivity of agricultural systems and sustainable exploitation of the environment. This study aimed to estimate the maximum physical and economic efficiencies of radish agroeconomic characteristics in monocropping as a function of roostertree (*Calotropis procera* (Ait.) R. Br) biomass amounts in two cropping seasons in a semi-arid environment. The experimental design was randomized complete blocks with five treatments and five replications. The treatments consisted of different roostertree biomass amounts: 16, 29, 42, 55, and 68 t ha^{-1} on a dry basis, incorporated into the soil. In each block, two additional treatments were added, one without fertilization (control) and the other with mineral fertilizer, for comparison purposes with the maximum efficiency treatment. The radish cultivar planted was 'Crimson Gigante'. The fertilization of the radish to obtain the maximum optimized productive efficiency (9.56 t ha^{-1}) was possible with the incorporation of 50.86 t ha^{-1} of *C. procera* dry biomass into the soil. The maximum optimized agroeconomic efficiency (based on a net income of 37,641.08 R\$ ha^{-1}) of radish cultivation was obtained with 44.39 t ha^{-1} of *C. procera* dry biomass added to the soil. The rate of return and the profit margin obtained were 2.94 R\$ for each real invested, with a profit margin of 62.55%. The use of biomass from the *C. procera* green manure is a viable technology for producers who practice radish monoculture in a semi-arid environment.

Keywords: *Calotropis procera* (Ait.) R. Br. Economic indicators. Green manuring. Productivity. *Raphanus sativus* L.

RESUMO - O uso de espécies espontâneas do bioma Caatinga como adubo verde é uma prática promissora no aumento da produtividade dos sistemas agrícolas e na exploração sustentável do meio ambiente. Este trabalho teve como objetivo estimar as máximas eficiências físicas e econômicas das características agroeconômicas do rabanete em monocultivo, em função de quantidades de biomassa de flor-de-seda em duas estações de cultivos em ambiente semiárido. O delineamento experimental utilizado foi em blocos casualizados com cinco tratamentos e cinco repetições. Os tratamentos consistiram de diferentes quantidades de biomassa de flor-de-seda: 16, 29, 42, 55 e 68 t ha^{-1} em base seca, incorporadas ao solo. Em cada bloco dos experimentos foram adicionados dois tratamentos, um sem adubação (tratamento testemunha) e outro com adubo mineral, para fins de comparação com o tratamento de máxima eficiência. A cultivar de rabanete plantada foi a Crimson Gigante. A adubação do rabanete para obtenção da máxima eficiência produtiva otimizada (9,56 t ha^{-1}) foi possível com a incorporação de 50,86 t ha^{-1} de biomassa seca de *C. procera* ao solo. A máxima eficiência agroeconômica otimizada (baseada na renda líquida de 37.641,08 R\$ ha^{-1}) foi obtida com a quantidade de 44,39 t ha^{-1} de biomassa seca de *C. procera* adicionada ao solo. A taxa de retorno e a margem de lucro obtida foram de R\$ 2,94 para cada real investido com margem de lucro de 62,55%. A utilização da biomassa do adubo verde, *C. procera*, é uma tecnologia viável para produtores que praticam o monocultivo de rabanete em ambiente semiárido.

Palavras-chave: *Calotropis procera* (Ait.) R. Br. Indicadores econômicos. Adubação verde. Produtividade. *Raphanus sativus* L.

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INTRODUCTION

The radish (*Raphanus sativus* L.) is a tuberous vegetable belonging to the Brassicaceae family, with a rapid cycle (around 35 days), and has as its edible part a red-colored root and spicy flavor. It shows medicinal properties, being a natural expectorant and stimulant of the digestive system. It is also rich in phosphorus, calcium, potassium, sulfur, thiamine, and riboflavin, as well as vitamins A, B1, and B2 (FILGUEIRA, 2013; NUNES et al., 2020). Its cultivation occurs in the semi-arid region of northeastern Brazil, where there are 281 production units (IBGE, 2017). One of the strategies to increase its production and productivity per area would be using mineral fertilization or green manure.

Tuberous vegetables require a high concentration of nutrients and, because of the high cost of chemical fertilization, make room for new forms of fertilization, such as green fertilization, with spontaneous species from the Caatinga biome, thus making it possible to reduce mineral fertilizer costs (LINO et al., 2021). Green manuring consists of the practice of preserving and restoring the levels of organic matter and nutrients in the soil, through the incorporation into the soil of non-decomposed plant mass of plants grown on or off-site, favoring the physical, chemical, and biotic conditions of the system and ensuring satisfactory levels in crop development and productivity (ABRANCHES et al., 2021).

Among the spontaneous species of the Caatinga biome is *Calotropis procera* (Ait) R. Br., popularly known in Northeast Brazil as roostertree (FREIRE et al., 2021). Belonging to the *Apocynaceae* family, it is a perennial shrub adapted to the edaphoclimatic conditions of the semi-arid region and can reach 3.5 meters in height (RANGEL; NASCIMENTO, 2011). It stands out for its potential production of phytomass throughout the year from the stem and leaves, reaching nine tons of dry mass per hectare in three cuts during the year (COSTA et al., 2009). It has an excellent C:N ratio of around 25:1 and has a chemical composition rich in important macronutrients, including N, P, K, Ca, and Mg contents of 18.40, 3.10, 25.60, 8.60, and 4.32 g kg^{-1}, respectively (NUNES et al., 2018).

Scientific studies with this spontaneous species from the Caatinga biome have been carried out with some vegetables, with satisfactory results in terms of production and system efficiency. Silva et al. (2018), when studying the performance of lettuce fertilized with different amounts of roostertree, observed maximum lettuce productivity of 18.16 t ha^{-1}, when 40.29 t ha^{-1} of dry biomass of this green manure was added to the soil. Silva et al. (2021), when evaluating carrot performance in amounts of roostertree in the same region of this research, observed better agroeconomic efficiency of carrot when 42.81 t ha^{-1} of roostertree dry biomass was incorporated into the soil.

Currently, green manuring with spontaneous species from the Caatinga biome has become a strategy of capital importance in the production of vegetables. One of the great challenges in the production of tuberous vegetables is to define an optimized quantity that provides a highly productive yield within the economic efficiency of the production system. Thus, given the lack of information on the cultivation of radish fertilized with roostertree in a semi-arid environment, the present work aimed to estimate the maximum physical and economic efficiencies of the agroeconomic characteristics of radish in monoculture as a function of amounts of roostertree biomass in two cropping seasons.

MATERIAL AND METHODS

Experiments were conducted from August to November 2021 (S_1 - Cropping season 1) and from June to September 2022 (S_2 - Cropping season 2), at the Rafael Fernandes Experimental Farm, belonging to the Universidade Federal Rural do Semi-Árido (UFERSA), located in the district of Alagoinha, 20 km from the headquarters of the municipality of Mossoró, RN (5° 03' 37" S, 37° 23' 50" W, altitude of 18 m). The soil of the experimental area is classified as Dystrophic Red Yellow Latosol with a sandy texture (SANTOS et al., 2018).

The climate of the region where the experiments were carried out, according to the Köppen Geiger classification, is BShw, dry and very hot, with two seasons: a dry season, which generally occurs from June to January, and a rainy season, from February to May (BECK et al., 2018). The meteorological data for the period in which the experiments were carried out are presented in Table 1 (LABIMC, 2022).

The average temperature and the daily air relative humidity after sowing the radish during the two cropping seasons are shown in Figure 1.

Before the installation of the experiments (in temporarily cultivated areas), simple soil samples were collected in the 0–20 cm depth layer, which was homogenized to obtain a composite sample. Subsequently, they were air-dried and sieved in a 2 mm sieve and sent to the Laboratory of Analysis of Water, Soil and Vegetal Tissue of the Federal Institute of Education, Science, and Technology of Ceará – Campus Limoeiro do Norte, to determine the chemical attributes. The results of these analyses are shown in Table 2.

The experimental design used was complete randomized blocks, with five treatments and five replications. The treatments consisted of roostertree biomass amounts of 16, 29, 42, 55, and 68 t ha-1 on a dry basis. In each experiment, a treatment with radish without fertilization (control), and another treatment with mineral fertilization was added for comparison with the treatment of maximum physical and economic efficiency.

Table 1. Meteorological data during the development and growth periods of radish in the 2021 and 2022 cropping seasons.

Cropping seasons	Temperature (ºC)			Relative humidity (%)	Solar radiation (MJ m^{-2})	Wind speed (m s^{-1})
	Minimum	Mean	Maximum			
2021 (S_1)	24.47	29.51	36.45	60.70	274.80	2.80
2022 (S_2)	20.54	27.78	35.73	62.87	256.41	1.71

Source: LABIMC (2022).

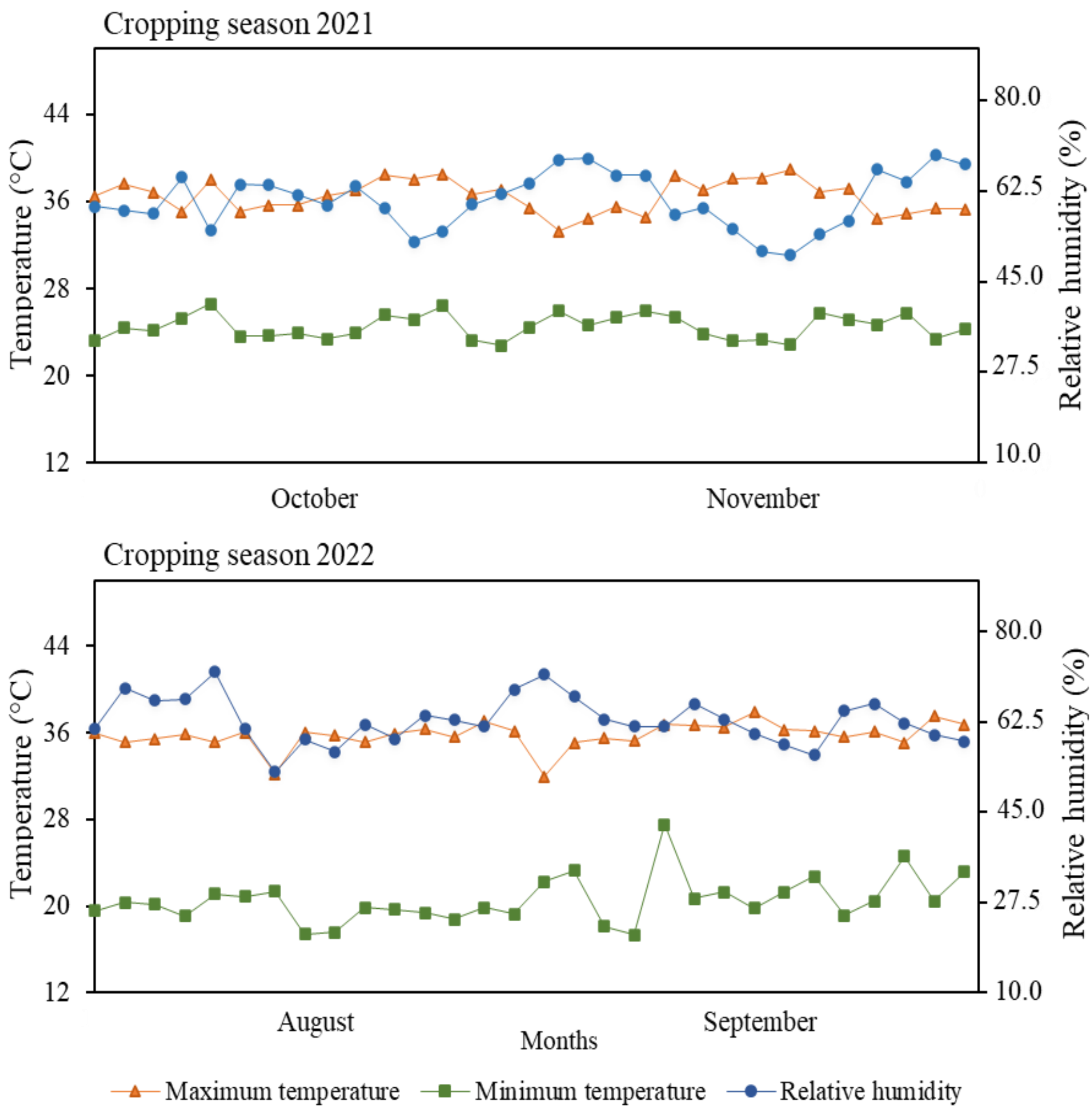

Figure 1. Data of daily mean temperatures and air relative humidity during the radish growing periods in 2021 (S_1) and 2022 (S_2).

Table 2. Chemical analyses of the soils before the incorporation of the green manure in the first and second cropping seasons.

Cropping seasons	C	OM	pH	EC	K	Ca	Mg	Na	P	Cu	Fe	Mn	Zn	B
	--- g kg^{-1}---		(H_2O)	dS m^{-1}	------------- mmol$_c$ dm^{-3} ------------				---------------------- mg dm^{-3} ------------------------					
2021 (S_1)	7.92	12.97	6.60	0.56	2.59	23.70	6.50	2.30	32.00	0.30	4.80	6.10	2.70	0.50
2022 (S_2)	7.20	12.41	7.10	0.19	1.16	20.10	6.10	0.43	7.00	0.20	6.80	12.70	1.70	0.48

C: Carbon; OM: Organic matter; pH: Hydrogen ionic potential; EC: Electrical conductivity; K: Potassium; Ca: Calcium; Mg: Magnesium; Na: Sodium; P: Phosphorus; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc; B: Boron.

The mineral fertilization treatment was performed as recommended by Trani and Raij (1997). The mineral basic fertilization consisted of the application of N, P_2O_5, and K_2O at a rate of 20, 240, and 120 kg ha^{-1}, respectively. The top-dressing fertilization combines 60 kg ha^{-1} of N and 40 kg ha^{-1} of K_2O, applied at 7, 14, and 21 days after germination. The source of NPK was obtained from urea: 45% of N, single superphosphate (SS): 18% of P_2O_5, and potassium chloride

(KCl): 60% of K_2O.

The total area of each plot of the experiments was 1.44 m^2, with a useful area of 0.80 m^2, with the radish planted at a spacing of 0.20 × 0.10 m (NUNES et al., 2020), making an estimated population of 500,000 plants per hectare. The harvest area consisted of four central rows of plants, with 10 plants in each row, as shown in Figure 2.

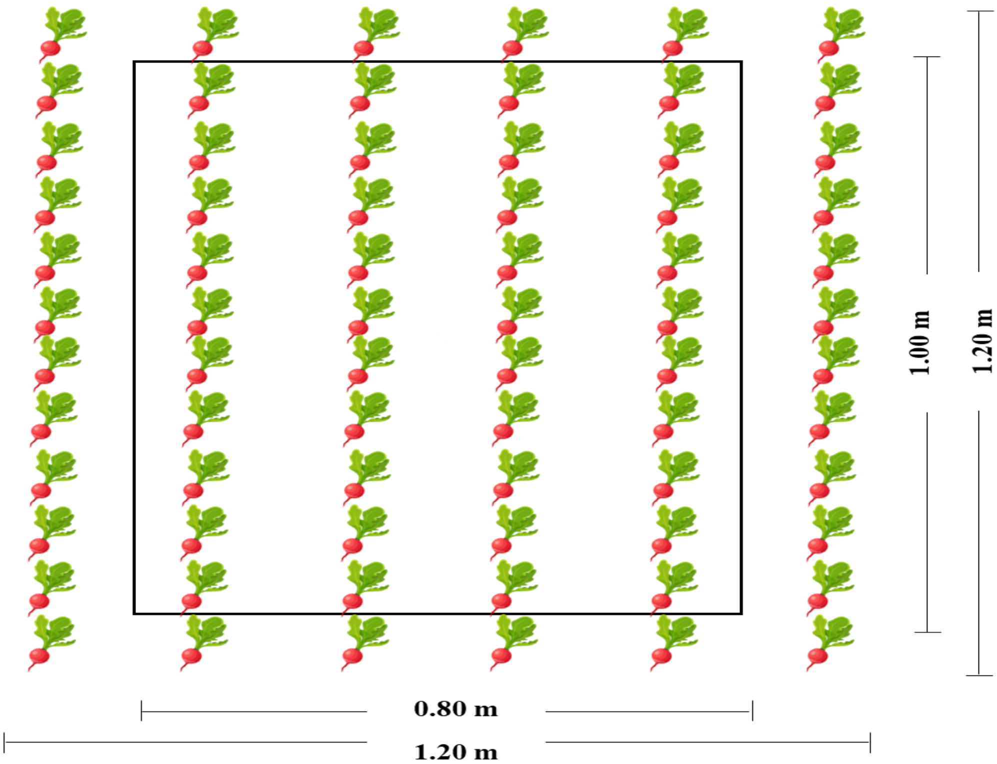

Figure 2. Representation of an experimental plot of radish planted at a spacing of 0.20 m × 0.10 m.

The roostertree used as green manure was collected from native vegetation near the urban and rural areas of the municipality of Mossoró-RN before the beginning of its flowering, a period that coincides with a greater accumulation of fresh matter. Subsequently, the roostertree plants were ground in a conventional forage machine, in fragments of two to three centimeters, and dehydrated under sunlight for a period of 5 to 7 days, until they reached a moisture content of around 10%. From this material, samples were taken and sent for laboratory analysis, and the chemical compositions were 14.09 g kg^{-1} N, 1.54 g kg^{-1} P, 22.72 g kg^{-1} K, 0.98 g kg^{-1} Ca, 1.98 g kg^{-1} Mg, and a 27:1 C: N ratio.

Before the installation of the experiments, soil preparation was carried out, which consisted of mechanical cleaning of the area with plowing and harrowing, followed by lifting the beds, with the aid of a rotary hoe. Pre-planting solarization was carried out for 30 days, with 30 µm transparent plastic (Vulca Brilho Bril Fles), to combat nematodes, phytoparasites, and weeds in the 0–10 cm layer of the soil, which could harm the development of culture (AMARAL; ARAUJO, 2021).

After the solarization period, twenty days before the radish sowing, the biomass amounts of green manure were manually incorporated into the soil in the 0–20 cm layer with the aid of hoes in each plot, following the specified doses in the treatments tested.

The radish cultivar was ‘Crimson Gigante’ (obtained from a seed company), recommended for the conditions of the Brazilian Northeast. It presents plants with large leaves, rounded roots of an intense red color, very white and firm pulp, and a diameter ranging from 4-5 cm.

The planting of the first cropping season was carried out on 10/05/2021 and that of the second season on 08/08/2022. In both seasons, planting was carried out by direct sowing in holes three centimeters deep, placing two to three seeds per hole, and covering with commercial substrate. At seven days after sowing (DAS), thinning was performed, leaving one plant per hole.

The cultural treatments carried out during each cropping consisted of manual weeding to control weeds and radish heap up. Daily micro-sprinkler irrigations were carried out in two shifts (morning and afternoon), providing a water depth of approximately 8 mm day^{-1} (ALVES et al., 2017), to maintain the soil's field capacity and favor the activity of soil microorganisms and mineralization of organic matter. The harvest of the first cropping season was carried out at 30 DAS, while that of the second season was carried out at 29 DAS.

The agronomic characteristics determined in the radish were carried out in a sample of 16 plants, randomly collected in the harvest area of each plot, which were: plant height (determined using a graduated ruler, considering the distance between the soil surface and the apex of the highest leaf and, estimating the average expressed in centimeters), the number of leaves per plant (determined by directly counting the number of leaves on each plant greater than three centimeters in length, starting from the basal leaves to the last open leaf, and expressing the average number of leaves per plant), root diameter (measured with the aid of a caliper in the longitudinal and transversal directions, estimating the average expressed in centimeters) and dry mass yields of shoots and roots, determined from the drying of the fresh mass, in an oven with circulation forced air at 65°C, until constant weight, thus obtaining the dry masses, expressed in t ha^{-1} (SÁ et al., 2022).

In addition to these characteristics, the total productivity (determined from the fresh mass of roots of all the plants in the useful area, expressed in t ha^{-1}) and the commercial productivity of roots (obtained from the productivity of roots considered commercial of all plants in the useful area, free from cracks, bifurcations, nematodes, and mechanical damage, with a diameter ≥ 20 mm and expressed in t ha^{-1} (SOUZA et al., 2020).

The economic indicators quantified in each treatment studied were: gross income (GI) expressed in R$ ha^{-1} (obtained by multiplying the productivity of commercial roots of each treatment, by the value of the product paid to the producer in the region, in the value of 6.15 R$ kg^{-1} in September 2022; net income (NI) also expressed in R$ ha^{-1} (calculated by subtracting from gross income), total production costs (TPC) of each treatment in the use of inputs and services. The rate of return (RR) was obtained through the relationship between the GI and the production total costs (TPC) of each treatment, corresponding to how many reals would be obtained, for each real invested as a function of the treatment factor studied, and the profit margin (PM), determined by the ratio between NI and GI, expressed as a percentage (FERREIRA et al., 2022).

The production costs calculated in each treatment were obtained based on the coefficients of costs and services used in one hectare of radish, considering the total expenditures made by the producer during the production process per hectare of cultivated area. These costs encompass the services provided by the stable capital and circulation, such as depreciation, acquisition and maintenance costs and repairs of machines, implements, and improvements; labor; machine and implement operations; and inputs, which vary as a function of the green manure amount tested. The total cost for the lowest dose of roostertree used was 14,340.52 R$ ha^{-1}, and that of the highest dose was 25,899.78 R$ ha^{-1}.

Univariate analysis of variance for the design of complete randomized blocks was performed for each characteristic or indicator, using SAS software (SAS, 2015). A joint analysis of each characteristic or indicator was also carried out to determine whether there was an interaction between the tested treatments and the growing seasons. Subsequently, a regression curve adjustment procedure was performed on each variable, using Table Curve software (SYSTAT SOFTWARE, 2022), to estimate the curve patterns of each characteristic or indicator, as a function of the green manure application. The selected models were based on the following criteria: biological logic (BL) of the variable (that is, when it is found that after a certain maximum dose of fertilizer, there is no increase in the variable), the significance of the mean square of the regression residue (MSRR), a high value for the coefficient of determination (R^2), and the significance of the parameters of the regression equation. The F test was used to compare the average values between the cropping seasons, maximum agronomic or economic efficiency, treatments fertilized with green manure, and the treatment fertilized with mineral fertilizer and the control treatment (not fertilized).

RESULTS AND DISCUSSION

Radish agronomic characteristics

The results of the analyses of variance of the agronomic characteristics of the radishes, such as the plant height, number of leaves per plant, and longitudinal and transversal diameter of roots, are presented in Table 3. Significant interactions were found between treatment factors, amounts of *C. procera* biomass, and cropping seasons for all agronomic traits evaluated in the radish crop.

For the green manure amounts within each season (S), the plant height, the number of leaves per plant, and the longitudinal and transversal diameters, an increasing behavior was observed as a function of the increase in the amounts of C. procera incorporated into the soil in a polynomial model for each trait, both in the first (S1) and in the second (S2) cropping season (Figure 3).

The maximum physical efficiency (MPE) values of these characteristics were 14.32 (S1) and 18.83 cm (S2) in the plant height, 7.07 (S1) and 6.42 (S2) in the number of leaves per plant, 5.03 (S1) and 5.03 cm (S2) in the longitudinal diameter, and 4.64 (S1) and 3.97 cm (S2) in the transversal diameter, respectively, for the C. procera biomass amounts of 51.54 (S1) and 51.77 (S2), 51.22 (S1) and 40.95 (S2), 40.95 (S1) and 45.39 (S2), as well as 50.06 (S1) and 47.28 (S2) t ha-1 (Figure 3), then decreasing until the highest amount of green manure incorporated (Figure 3). However, estimating the maximum physical efficiencies of these characteristics over the cropping seasons, an increasing polynomial behavior was also observed as a function of the increase in the amounts of green manure up to the maximum values of 16.54 cm (plant height); 6.72 (number of leaves per plant); 5.01 cm (longitudinal diameter), and 4.25 cm (transversal diameter) in the green manure amounts of 51.68, 50.02, 46.57 and 48.20 t ha^{-1}, then decreasing until the highest amount of fertilizer tested (Figure 3).

Table 3. Mean values of the control treatment (T_c), treatment of maximum physical efficiency (MPE), treatments with green manure (T_{gm}), and treatment with mineral fertilizer (T_{mf}) for plant height, number of leaves per plant, and longitudinal and transversal diameters of radish roots in the 2021 (S_1) and 2022 (S_2) cropping seasons.

Comparison treatments	Plant height (cm)			Number of leaves per plant		
	2021	2022	2021-2022	2021	2022	2021-2022
	(S1)	(S2)	(S1/S2 mean)	(S1)	(S2)	(S1/S2 mean)
Control (without fertilization, T_c)	11.66cA	11.93cA	11.80	6.08bA	5.59bB	5.93
MPE Treatment	14.32bB	18.83bA	16.54$^+$	7.07aA	6.42aB	6.72$^+$
Green manure treatments (T_{gm})	13.71bB	17.48bA	17.48$^+$	6.78aA	6.41aB	6.59$^+$
Mineral treatment (T_{mf})	22.56aB	29.21aA	25.89$^+$	6.55aA	6.94aA	6.74$^+$
CV (%)	6.14	12.21	10.34	7.87	9.44	8.45
	Longitudinal diameter (cm)			Transversal diameter (cm)		
Control (without fertilization. T_c)	3.16cB	3.92cA	3.53	2.62cA	2.82cA	2.72
MPE Treatment	5.03bA	5.03bA	5.01$^+$	4.64aA	3.97bB	4.25$^+$
Green manure treatments (T_{gm})	4.91bA	4.84bA	4.88$^+$	4.51aA	3.79bB	4.15$^+$
Mineral treatment (T_{mf})	5.22aB	6.20aA	5.71$^+$	4.21bA	4.22aA	4.22$^+$
CV (%)	4.31	7.06	5.91	3.69	6.00	4.85

* Means followed by the same lowercase letter in the column and uppercase in the row do not differ statistically by the F test at the 5% probability level; $^+$mean of manure treatments, MPE treatment, or mineral treatment is significantly different from the control treatment mean by the F test at the 5% probability level

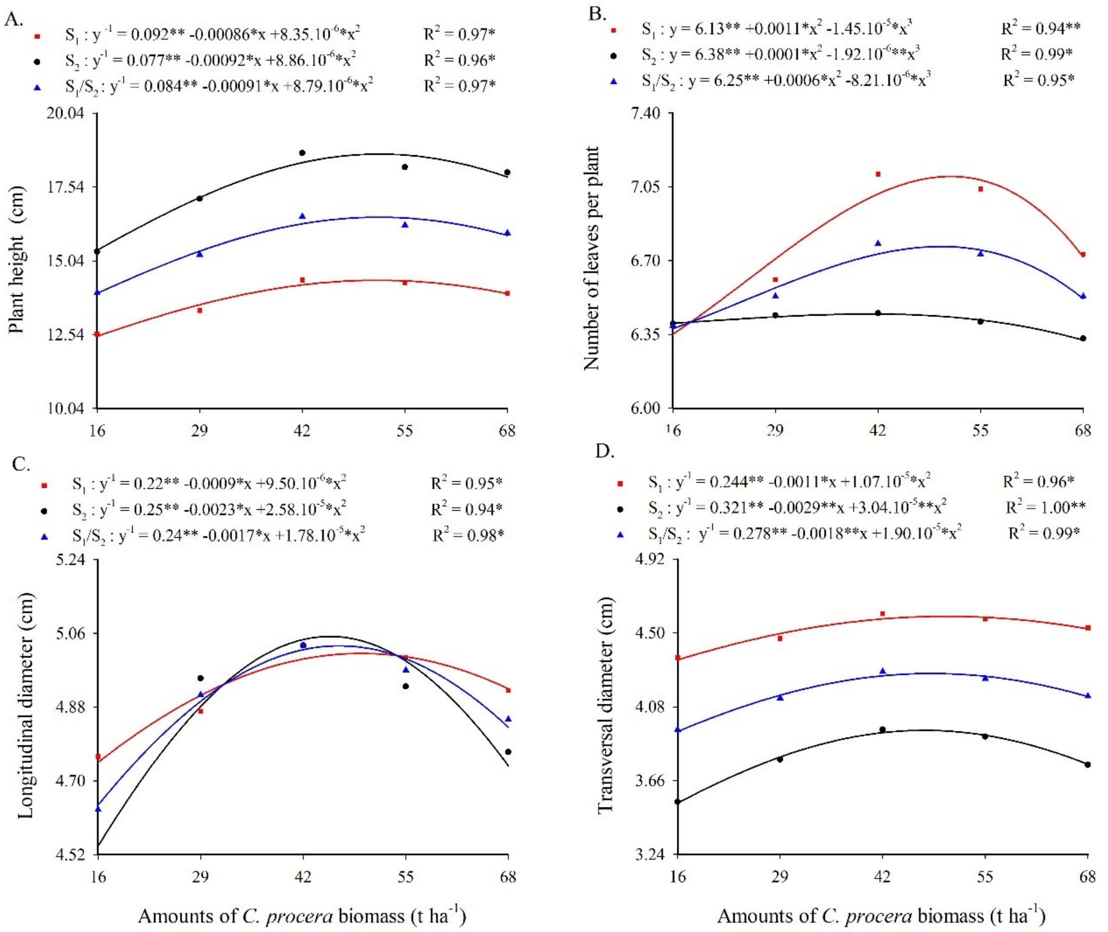

Figure 3. Plant height (A), number of leaves per plant (B), longitudinal (C), and transversal diameter of roots (D) as a function of amounts of *C. procera* dry biomass incorporated into the soil, in the cropping seasons 2021 (S_1) and 2022 (S_2); ** - significant at $p \leq 0.05$ and $p \leq 0.01$ by the F-test.

The average values of MPE of the treatments that received green manure (T_{gm}) and of the mineral treatment (T_{mf}) differed from the control (T_c) in the characteristics of plant height, the number of leaves per plant, and the longitudinal and transversal diameters in the two cropping seasons (Table 3). In these characteristics, the MPE values were 1.4, 1.1, 1.4, and 1.6 times the T_c values. The cropping seasons within the treatments fertilized with green manure differed, with S_1 surpassing S_2 in the number of leaves per plant and the transversal diameter, while the plant height showed the opposite behavior. For the longitudinal diameter, no significant difference was observed between the cropping seasons. In the control treatment, there was also no significant difference between the cropping seasons in plant height and the transversal diameter. In the number of leaves per plant, S_1 surpassed S_2, and in the longitudinal diameter, the opposite behavior was registered. In the mineral treatment, no significant difference was observed between the cropping seasons in the number of leaves per plant and the transversal diameter. However, in the plant height and longitudinal diameter, a significant difference was observed between the cropping seasons, with S_2 surpassing S_1.

Radish productive characteristics

The results of the analyses of variance of the productive characteristics of the radish, including total and commercial productivity of roots, and dry mass of shoots and roots, are shown in Table 4. Significant interactions were detected between the factors-treatments, amounts of *C. biomass,* and cropping seasons for all productive characteristics evaluated.

Table 4. Mean values of the control treatment (T_c), treatment of maximum physical efficiency (MPE), treatments with green manure (T_{gm}), and treatment with mineral fertilizer (T_{mf}) for total and commercial productivity of roots and dry mass of radish shoots and roots in the 2021 (S_1) and 2022 (S_2) cropping seasons.

Comparison treatments	Productivity of total roots (t ha^{-1})			Productivity of commercial roots (t ha^{-1})		
	2021	2022	2021-2022	2021	2022	2021-2022
	(S1)	(S2)	(S1/S2 mean)	(S1)	(S2)	(S1/S2 mean)
Control (without fertilization (T_c)	4.73cB	6.98bA	5.86	3.31cB	5.81cbA	4.56
MPE Treatment	8.64aB	13.51aA	11.07$^+$	6.94aB	12.16aA	9.56$^+$
Green manure treatments (T_{gm})	7.80bB	12.28bA	9.99$^+$	5.89bB	10.74bA	8.32$^+$
Mineral treatment (T_{mf})	8.73aB	14.36aA	11.55$^+$	6.60aB	12.00aA	9.30$^+$
CV (%)	6.90	7.17	7.28	8.64	7.43	8.05
	Dry mass of shoots (t ha^{-1})			Dry mass of roots (t ha^{-1})		
Control (without fertilization (T_c)	0.34cA	0.42cA	0.38	0.58aA	0.49cA	0.53
MPE Treatment	0.65bB	0.87bA	0.75$^+$	0.69aB	0.81bA	0.74$^+$
Green manure treatments (T_{gm})	0.55bB	0.77bA	0.66$^+$	0.64aB	0.77bA	0.70$^+$
Mineral treatment (T_{mf})	0.99aB	1.49aA	1.24$^+$	0.55aB	1.11aA	0.84$^+$
CV (%)	14.26	14.17	14.40	16.81	11.11	13.68

* Means followed by the same lowercase letter in the column and uppercase in the row do not differ statistically by the F test at the 5% probability level; $^+$mean of manure treatments, MPE treatment, or mineral treatment is significantly different from the control treatment mean by the F test at the 5% probability level.

Studying the amounts of green manure within each cropping season (S), an increasing polynomial behavior was observed in the first (S_1) and second (S_2) cropping seasons, up to the respective maximum values of 8.64 and 13.51 t ha^{-1} in total productivity, 6.94 and 12.16 t ha^{-1} in commercial productivity, 0.65 and 0.87 t ha^{-1} in the dry mass of shoots and 0.69 and 0.81 t ha^{-1} in the dry mass of roots, in the biomass amounts of 51.31 and 52.71; 48.08 and 53.24; 43.78 and 44.65; 39.57 and 33.53 t ha^{-1} of *C. procera*, decreasing these values until the highest dose of green manure incorporated into the soil (Figure 4).

Estimating the MPE of these productive characteristics over the cropping seasons, an increasing polynomial behavior was also observed as a function of the increase in the amounts of the green manure up to the maximum values of 11.07 t ha^{-1} (total productivity of roots); 9.56 t ha^{-1} (commercial productivity of roots); 0.75 t ha^{-1} (dry mass of shoots) and 0.74 t ha^{-1} (dry mass of roots) in the green manure amounts of 52.15, 50.86, 44.26 and 41.69 t ha^{-1}, then decreasing until the largest amount of tested fertilizer (Figure 4).

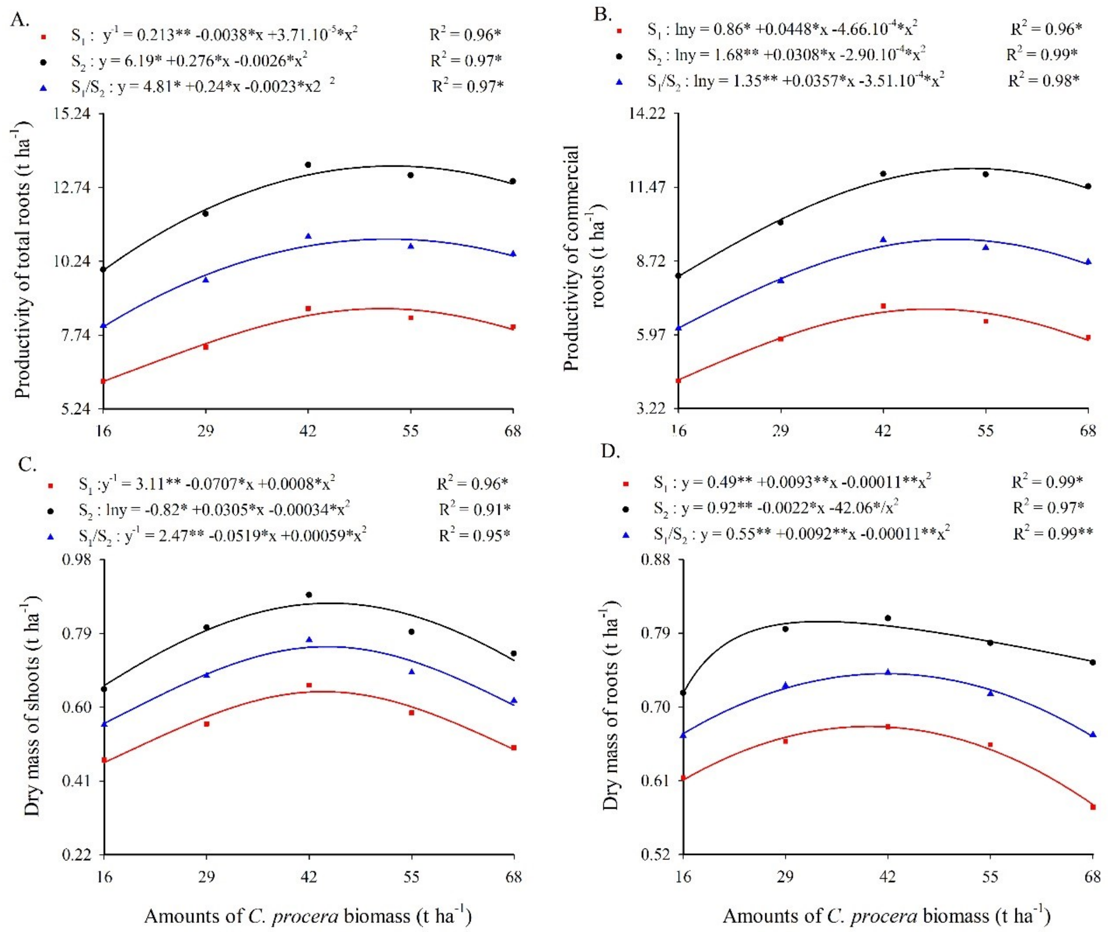

Figure 4. Total productivity (A), commercial productivity (B), dry mass of shoots (C), and dry mass of roots (D) of radish as a function of amounts of *C. procera* dry biomass incorporated into the soil, in the 2021 cropping seasons (S_1) and 2022 (S_2); ** - significant at $p \leq 0.05$ and $p \leq 0.01$ by the F-test.

The average values of MPE of the treatments that received green manure (T_{gm}) and of the mineral treatment (T_{mf}) differed from the control (T_c) in all the productive characteristics of the radish, except for the dry mass of roots in the first season where all these treatments were like the control (Table 4). In these characteristics, the MPE values were 1.9, 2.1, 2.0, and 1.4 times the values of the control treatment.

The cropping seasons within the treatments fertilized with green manure and mineral fertilizer differed, with S_2 surpassing S_1 in all radish productive characteristics. In the control treatment, there was a significant difference between the cropping seasons in the total and commercial productivity of roots, with S_2 surpassing S_1, while in the dry mass of shoots and roots, no significant difference was observed between the cropping seasons (Table 4).

The ascending responses and optimizations (MPE values) of the agronomic and productive characteristics of radish in polynomial models can be attributed to the Law of Maximum, where the excess of a nutrient in the soil provided by the amount of *C. procera* can have a toxic effect, and/or decrease the effectiveness of other elements, resulting in the reduction of the characteristic under analysis after the maximum point (ALMEIDA et al., 2015). Another factor that may be related to this behavior of tuberous vegetables is the synchrony between the decomposition and mineralization of *C. procera* biomass added to the soil and the time of greatest nutritional demand for the crop (SILVA et al., 2021).

The polynomial models tested in the agronomic and productive characteristics of the radish plant met the selection and adjustment criteria used to express the behavior of each evaluated characteristic, where the increase in nutrient availability was due to the increase in the amount of roostertree added to the soil, resulting in greater plant height, number of leaves per plant, greater root diameter, shoot, and root dry mass, and the root productivity. The lower productive potential of total and commercial roots of the radish observed in the first cropping season may be related to the climatic conditions of the cropping season and the soil characteristics of the place since the culture is sensitive to water stress and high temperatures.

The decomposition process of green manure is influenced by the carbon/nitrogen (C:N) ratio, which determines the rate of degradation of the waste mass, the predominance of nitrogen immobilization and mineralization, with the ideal range of the C: N ratio being between 20:1 and

30:1 (VALE et al, 2004). The C:N ratio of the plant material used in the research is 27:1, thus providing accelerated decomposition and availability of nutrients.

The significant effects of mineral treatment compared to the fertilized green manure treatment may be related to the concentration of NPK that inorganic fertilizers provide. Despite this, the MPE of the green manure for total and commercial productivity of roots did not differ statistically from T_{mf}, presenting in the first cropping season (S_1) commercial productivity close to the productive average of the Northeast region of 8 t ha^{-1} of radish roots (IBGE, 2017), exceeding this average in the second growing season (S_2).

These results demonstrate that the amounts of macronutrients provided by the tested green manure met, in a balanced way, the nutritional demand of radish plants in the long cycle. It is known that the concentration of nitrogen favors the growth and development of plants, thus increasing the weight of roots and the number of leaves per plant. Potassium greatly influences plant photosynthesis, and phosphorus affects root formation, directly influencing the productivity and quality of radish roots (TAIZ et al., 2017).

Radish economic performance

The results of the analyses of variance of the economic indicators of radish: gross incomes, net income, rate of return, and profitability index are shown in Table 5. Significant interactions were detected between the treatment factors, amounts of *C. procera* biomass, and cropping seasons for all these economic indicators evaluated.

Table 5. Mean values of the control treatment (T_c), treatment of maximum physical efficiency (MEE), treatments with green manure (T_{gm}), and treatment with mineral fertilizer (T_{mf}) for gross income, net income, rate of return, and profit margin of radish roots in the 2021 (S_1) and 2022 (S_2) cropping seasons.

Comparison treatments	Gross income (R$ ha^{-1})			Net income (R$ ha^{-1})		
	2021	2022	2021-2022	2021	2022	2021-2022
	(S1)	(S2)	(S1/S2 mean)	(S1)	(S2)	(S1/S2 mean)
Control (without fertilization, T_c)	20341.13bB	35709.98bA	28025.55	9759.68bB	25128.53bA	17444.10
MEE Treatment	42477.85aB	74442.90aA	58708.70$^+$	23069.77aB	53130.67aA	37641.08$^+$
Green manure treatments (T_{gm})	36226.15aB	66070.99aA	51148.57$^+$	16068.38aB	45913.23aA	30990.81$^+$
Mineral treatment (T_{mf})	40574.62aB	73852.28aA	57213.45$^+$	18968.92aB	52247.57aA	35607.74$^+$
CV (%)	8.64	7.43	8.05	19.18	10.65	13.20
	Rate of return			Profit margin (%)		
Control (without fertilization, T_c)	1.92bB	3.37bA	2.65	46.72bB	69.30bA	58.01
MEE Treatment	2.13aB	3.72aA	2.94$^+$	52.61aB	72.76aA	62.55$^+$
Green manure treatments (T_{gm})	1.83bB	3.33bA	2.58	43.83bB	69.51bA	56.67
Mineral treatment (T_{mf})	1.88bB	3.42bA	2.65	46.51bB	70.71bA	58.61
CV (%)	10.14	8.74	9.46	12.18	4.64	7.82

* Means followed by the same lowercase letter in the column and uppercase in the row do not differ statistically by the F test at the 5% probability level $^+$mean of manure treatments, MPE treatment, or mineral treatment is significantly different from the control treatment mean by the F test at the 5% probability level.

For the amounts of green manure within each cropping season (S), an increasing polynomial behavior was observed in the first (S_1) and second (S_2) cropping seasons, up to the respective maximum values of 42,477.85 (S_1) and 74,442.90 R$ ha^{-1} (S_2) for gross income, 23,069.07 (S_1) and 53,130.67 R$ ha^{-1} (S_2) for net income; of 2.13 R$ (S_1) and 3.72 R$ (S_2) for each R$ invested in the rate of return and 52.61(S_1) R$ and 72.76% (S_2) for the profit margin in the biomass amounts of 48.08 and 53.24, 40.43 and 47.55, 35.02 and 31.33, in addition to 34.74 and 31.01 t ha^{-1} of *C. procera*, decreasing these values up to the highest dose of green manure incorporated into the soil (Figure 5).

Estimating the maximum economic efficiencies (MEE) of these economic indicators over the cropping seasons, an increasing polynomial behavior was also observed, as a function of the increase in the amounts of green manure up to the maximum values of 58,708.70 and 37,641.08 R$ ha^{-1} for income gross and net income, respectively, and of 2.94 and 62.55% for the rate of return and profit margin in the green manure amounts of 50.86, 44.39, 33.18 and 33.86 t ha^{-1}, decreasing then up to the largest amount of tested fertilizer (Figure 5).

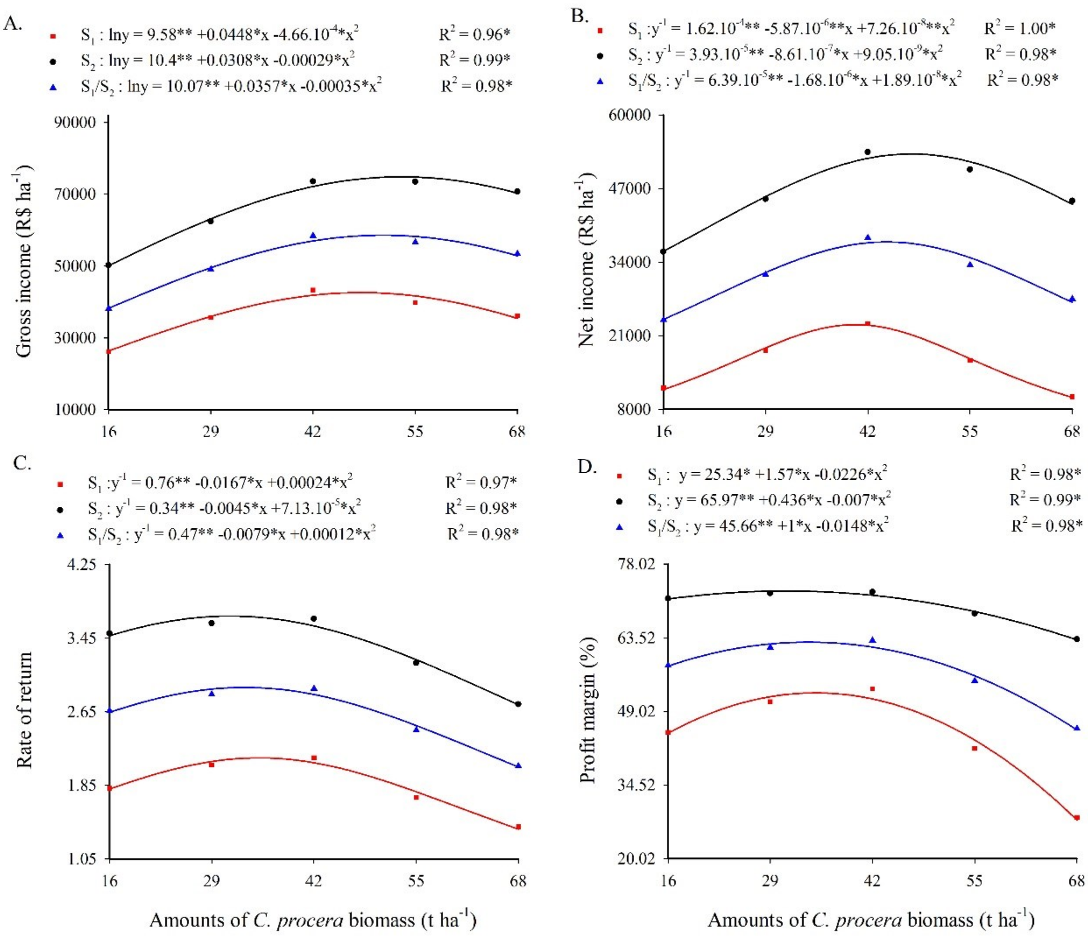

Figure 5. Gross income (A), net income (B), rate of return (C), and profit margin (D) of radish as a function of amounts of *C. procera* dry biomass incorporated into the soil, in the cropping seasons 2021 (S_1) and 2022 (S_2); ** - Significant at $p \leq 0.05$ and $p \leq 0.01$ by the F-test.

The average values of MEE of the treatments that received green manure (Tgm) and of the mineral treatment (Tmf) differed from the control (Tc) in the gross and net income (Table 5). For the rate of return and profit margin, the average values of MEE differed from the control (Tc). In these indicators, the MEE values were 2.1, 2.2, 1.1, and 1.1 times the values of the control treatment. The cropping seasons within the treatments fertilized with green and mineral manure and within the control treatment also differed, with S2 surpassing S1 in all radish economic indicators (Table 5).

The increasing responses of the economic indicators evaluated in the radish crop and the economic optimizations achieved, with a decrease after the maximum point in the form of a polynomial model, as a function of the amounts of *C. procera* biomass, result from the gradual availability of nutrients from the green manure throughout the radish cycle and the biological and physical-chemical improvement of the soil (PAIVA et al., 2017), promoting favorable conditions for the development of the crop. However, it is known that green manure is known to improve soil fertility and increase its organic matter content, decrease erosion rates, to increase soil water retention, microbial activity, and nutrients availability of soil, in addition to reducing the amounts of invasive plants (GRAHAM; HAYNES, 2006).

Given the behavior recorded in these economic indices, it becomes evident that the agronomic efficiency obtained in the productive characteristics of the radish was translated into economic efficiency, thus showing that the use of this fertilization practice provides a financial return compatible with the capital invested. Based on the results obtained, we can safely say that the producer who practices the cultivation of radish in monoculture in a semi-arid environment has the option of strategically choosing the optimal amount of green manure that results in the best cost-benefit, given the productivity that they intend to obtain.

Other collaborative factors for the adoption of this practice of fertilization with spontaneous plants of the Caatinga biome involve the local availability of the species, the supply of phytomass throughout the year, and the feasibility of storing the fertilizer in the form of hay, conserving its nutritional qualities (ALMEIDA; SOUZA; BATISTA, 2019), in addition to the possibility of reducing production costs regarding labor, especially for family farming, which does not structurally depend on hired labor for its full functioning (SILVA NETO, 2014).

Given this evident agroeconomic potential, and the significant increase in the costs of agricultural inputs in conventional cultivation, especially mineral fertilizers (NICOLOSO; MARTINS, 2021), the adoption of the practice of green manuring in agricultural production units becomes a strategic tool in reducing the cost of production, thus reducing dependence on chemical markets and, consequently, the operational and productive costs of vegetables, providing the opportunity to reach new markets, with the offer of products without the addition of agrochemicals.

The results of the economic indicators obtained agree in part with those reached by SILVA et al. (2021) when they fertilized the carrot crop with different doses of *C. procera* green manure and obtained economic efficiency indicators in the order of 62,704.94 and 33,744.07 R$ ha^{-1} for gross and net income, and of 2.27 R$ and 56.63% for the rate of return and profit margin, respectively, at doses of 47.60, 42.81, 31.69, and 31.85 t ha^{-1} of biomass from this green manure. These results show the economic efficiency of green manure on the performance and development of tuberous crops, such as radish and carrot.

CONCLUSIONS

The fertilization of the radish to obtain the maximum optimized productive efficiency (9.56 t ha^{-1}) was possible with the incorporation of 50.86 t ha^{-1} of *C. procera* dry biomass into the soil. The maximum optimized agroeconomic efficiency (based on a net income of 37,641.08 R$ ha^{-1}) of radish cultivation was obtained with the amount of 44.39 t ha^{-1} of *C. procera* dry biomass added to the soil. The rate of return and the profit margin obtained were 2.94 R$ for each real invested, with a profit margin of 62.55%. The use of biomass from the *C. procera* green manure is a viable technology for producers who practice radish monocropping in a semi-arid environment.

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