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Productivity and optimized economic efficiency of carrot roots in monocropping under green manuring

Produtividade e eficiência econômica otimizada de raízes de cenoura em monocultivo sob adubação verde

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ABSTRACT - A great challenge of scientific research with carrot in semi-arid regions is obtaining the best productive characteristics and economic conditions by optimizing the green manure amounts using spontaneous species from the Caatinga biome, such as hairy woodrose (*Merremia aegyptia* L.) and roostertree (*Calotropis procera* Ait.). Therefore, this work aimed to agronomically and economically optimize the production of carrot roots in monocropping and of their components when fertilized with equitable biomass amounts of these spontaneous species in two cropping seasons in a semi-arid environment. The experimental design was a randomized complete block design, with five treatments and five replications. The treatments consisted of equitable amounts of hairy woodrose and roostertree biomass in amounts of 16, 29, 42, 55, and 68 t ha^{-1} on a dry basis. In each experiment, an additional carrot treatment without fertilizer (absolute control) was planted for comparison with the other treatments to determine maximum physical and economic efficiency. Carrot fertilization was performed with the incorporation of 48.87 t ha^{-1} of *M. aegyptia* and *C. procera* dry biomass into the soil to obtain the maximum optimized productive efficiency (commercial productivity). The maximum optimized agroeconomic efficiency (net income) of carrot cultivation was obtained when 49.64 t ha^{-1} of *M. aegyptia* and *C. procera* dry biomass was added to the soil. The use of biomass from these spontaneous species from the Caatinga biome as green manure is a viable technology for tuberose producers in monocropping in semi-arid environments.

Keywords: *Daucus carota*. *Merremia aegyptia*. *Calotropis procera*. Organic fertilization. Optimized production.

RESUMO - Um grande desafio na pesquisa científica com cenoura em ambiente semiárido é obter as melhores características produtivas e condições econômicas otimizando as quantidades de adubos verdes de espécies espontâneas do bioma Caatinga, como a jitirana (*Merremia aegyptia* L.) e a flor-de-seda (*Calotropis procera* Ait.). Diante disso, esse trabalho teve como objetivo otimizar agronômica e economicamente a produção de raízes de cenoura em monocultivo e de seus componentes, quando adubados com quantidades equitativas de biomassa dessas espécies espontâneas, em duas estações de cultivos em ambiente semiárido. O delineamento experimental utilizado foi em blocos completos casualizados, com cinco tratamentos e cinco repetições. Os tratamentos consistiram de quantidades equitativas de biomassa de jitirana e de flor-de-seda nas doses de 16, 29, 42, 55 e 68 t ha^{-1} em base seca. Em cada experimento foi plantado um tratamento adicional com cenoura sem adubo (testemunha absoluta) para efeito de comparação com os demais tratamentos para determinar a máxima eficiência física ou econômica. A adubação da cenoura foi realizada com a incorporação de 48,87 t ha^{-1} de biomassa seca de *M. aegyptia* e *C. procera* ao solo para obtenção da máxima eficiência produtiva otimizada (produtividade comercial). A máxima eficiência agroeconômica otimizada (renda líquida) do cultivo da cenoura foi obtida quando 49,64 t ha^{-1} de biomassa seca de *M. aegyptia* e *C. procera* foram adicionados ao solo. A utilização da biomassa dessas espécies espontâneas do bioma Caatinga como adubação verde é uma tecnologia viável para produtores de tuberosas em monocultivo em ambientes semiáridos.

Palavras-chave: *Daucus carota*. *Merremia aegyptia*. *Calotropis procera*. Adubação orgânica. Produção otimizada.

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INTRODUCTION

Carrot (*Daucus carota* L.) is a vegetable from the Apiaceae family consumed worldwide, with an edible orange-colored tuberous root, which has social, economic, and nutritional value and contains K, Na, Ca, Fe, Mg, P, and N as mineral sources, in addition to vitamin A and B complexes, beta-carotene, and vitamin C (BEZERRA NETO et al., 2014). Its cultivation in much of the world involves the intensive use of chemical fertilizers and pesticides to obtain high yields, but this vegetable production system has been questioned in recent years, not only because of economic and ecological contradictions, but also for disregarding important qualitative aspects of production (RESENDE; BRAGA, 2011).

However, to counteract this production system due to the need to protect the health of producers and consumers and to preserve the environment, the organic system of vegetable production has been adopted in recent years. This system has been used due to the diversity of products grown in the same area and for less dependence on external resources, with greater absorption of family labor and less need for capital (SEDIYAMA et al., 2014). Among the practices used in the organic production system, green manure can guarantee an adequate quantity and quality for high vegetable crop yields, thus conserving natural resources and providing acceptable standards of sustainability for farmers.

Plant species with potential for use as green manure in the Caatinga biome include black velvet bean (*Stizolobium aterrimum*), one-leaf senna (*Senna uniflora*), *Crotalaria juncea*, cowpea (*Vigna unguiculata*), hairy woodrose (*Merremia aegyptia*), and roostertree (*Calotropis procera*), as they are rustic plants, with efficient vegetative development adapted to conditions of low fertility and high temperatures in northeastern Brazil (FONTANÉTTI et al., 2006; BATISTA et al., 2016). Among these species, hairy woodrose and roostertree are abundant, great producers of phytomass, and easy to obtain in the Caatinga biome, and they can provide an efficient supply of nutrients and a C/N ratio between 20 and 30. Therefore, they have great potential for success in cultivating vegetables in the northeastern semi-arid region.

The hairy woodrose (*Merremia aegyptia L.*) is a species of liana plant that has a climbing habit, annual, herbaceous, belonging to the Convolvulaceae family, with an average production of green and dry phytomass of around 36,000 and 4000 kg ha^{-1}, respectively, with a high nitrogen content, around 26.2 g kg^{-1} in dry matter and a C/N ratio of 18/1 (LINHARES et al., 2012). The roostertree (*Calotropis procera* (Ait) R. Br.) is a shrub species belonging to the Apocynaceae family (RANGEL; NASCIMENTO, 2011), characterized as a prolific ever-green plant with the capacity to provide biomass throughout the year. It has an average dry phytomass production of around 3000 kg ha^{-1} when cut (120 days), reaching 9 t ha^{-1} per year, with a nitrogen content of around 18.4 g kg^{-1} in dry matter and a C/N ratio of 25/1 (EMPARN, 2004; NUNES et al., 2018).

Studies have used these species as green manure in single vegetable crops, with promising results. Bezerra Neto et al. (2011) evaluated different biomass amounts at diverse hairy woodrose decomposition times in lettuce production and observed a 28% increase in productivity as a function of the increasing amounts of hairy woodrose incorporated into the soil. Evaluating the production of lettuce fertilized with roostertree in different amounts and at different times of incorporation, Paula et al. (2017) obtained better lettuce productive performance when fertilized with 15.6 t ha^{-1} of roostertree biomass incorporated 10 days before lettuce transplant. Desravines et al. (2022) evaluated biomass mixtures with equitable amounts of *M. aegyptia* and *C. procera* in cowpea and obtained excellent results for green pod productivity, showing the potential use of these green manures.

Thus, the objective of this work was to agronomically and economically optimize the production of carrot roots in monoculture and to optimize their components when fertilized with equitable amounts of biomass of the spontaneous species hairy woodrose and roostertree from the Caatinga biome in two cropping seasons.

MATERIAL AND METHODS

The experiments were carried out in the field from November 2020 to April 2021 and from August 2021 to January 2022 at the Experimental Farm 'Rafael Fernandes' of the Universidade Federal Rural do Semi-Árido (UFERSA), in the district of Lagoinha, 20 km away from the seat of the municipality of Mossoró, RN (5° 03' 37" S, 37° 23' 50" W, altitude of 80 m).

According to the Köppen climate classification, the climate of the region is 'BShw', dry and very hot, with two seasons: a dry season from June to January and a rainy season from February to May (BECK et al., 2018). During the carrot development and growth periods, the average values recorded for minimum, average, and maximum temperatures, relative air humidity, for precipitation, solar radiation, and wind speed were 24.6, 28.9, and 35.3°C, 65.9%, 242.9 mm, 19.2 MJ m^{-2} day^{-1}, and 5.1 m s^{-1}, respectively, for the 2020/2021 season and 24.9, 29.6, and 36.1°C, 62.6%, 108.2 mm, 19.9 MJ m^{-2} day^{-1}, and 5.6 m s^{-1}, respectively, for the 2021/2022 season (LABIMC, 2022). The data of the daily averages of minimum and maximum temperature, and relative humidity of the air after carrot sowing during the two cropping seasons are presented in Figure 1.

The soils in the experimental areas were classified as Dystrophic Red Yellow Latosol, with a sandy loam texture (SANTOS et al., 2018). Soil samples from each experimental area were collected from the 0–20 cm surface layer, and some of the chemical characteristics of the soil were analyzed. The results of these analyses are shown in Table 1.

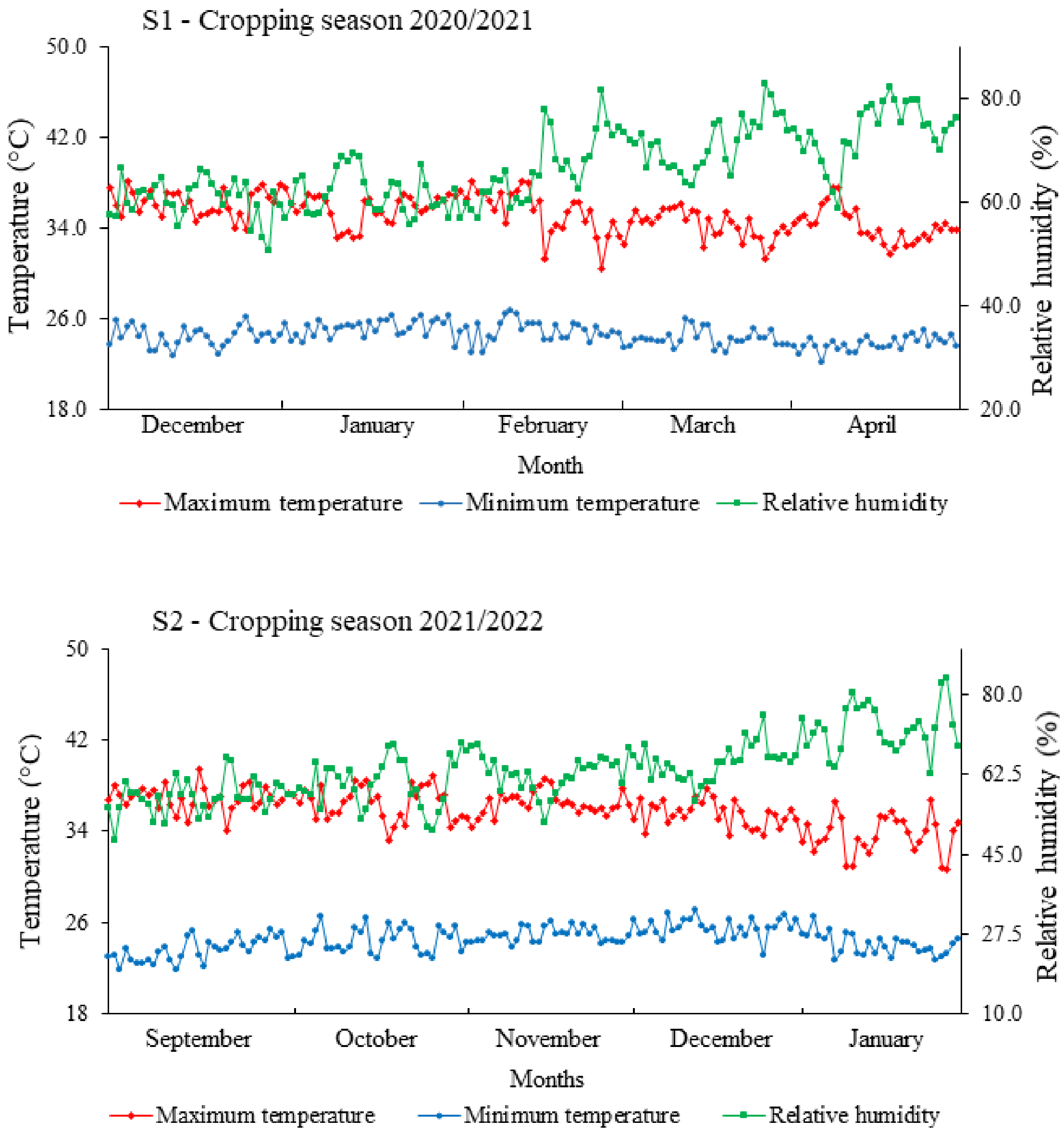

Figure 1. Daily means of temperatures and air relative humidity during the two carrot cropping seasons, S1 (2020/2021) and S2 (2021/2022).

Table 1. Chemical analyses of the soils before the incorporation of green manure in the first and second cropping seasons.

Prior to incorporation of the spontaneous species															
Soils of cropping seasons	N	C	pH (H_2O)	EC	OM	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cu	Fe	Mn	Zn	B
	g kg^{-1}			ds m^{-1}	g kg^{-1}	mg dm^{-3}	cmol$_c$ dm^{-3}				mg dm^{-3}				
Season 1	0.6	6.90	6.30	0.44	11.90	24.0	2.36	1.73	22.50	4.80	0.50	5.7	11.2	3.8	0.58
Season 2	0.7	7.52	6.60	0.56	12.97	32.0	2.59	2.30	23.70	6.50	0.30	4.8	6.10	2.7	0.50

N: nitrogen; C: carbon; pH: hydrogenionic potential; EC: electrical conductivity; OM: organic matter; P: phosphorus; K^+: potassium; Na^+: sodium; Ca^{2+}: calcium; Mg^{2+}: magnesium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; B: boron.

The experimental design used in the experiments was a randomized complete block design, with five treatments and five replications. The treatments consisted of equitable amounts of hairy woodrose (*Merremia aegyptia*) and roostertree (*Calotropis procera*) biomass at 16, 29, 42, 55, and 68 t ha^{-1} at dry basis, that is, with half of each amount of each green manure incorporated. In each experiment, a carrot treatment without fertilization (control treatment) was planted for comparison with the treatments to determine maximum physical and economic efficiency. Each experimental plot consisted of 6 rows with 12 carrot plants per row, planted at a spacing of 0.20 m × 0.10 m, for an estimated population of 500,000 plants per hectare (SILVA et al., 2013). The total area of each plot was 1.44 m^2 (1.20 m × 1.20 m), with a harvest area of 0.64 m^2 (0.80 m × 0.64 m), as shown in Figure 2.

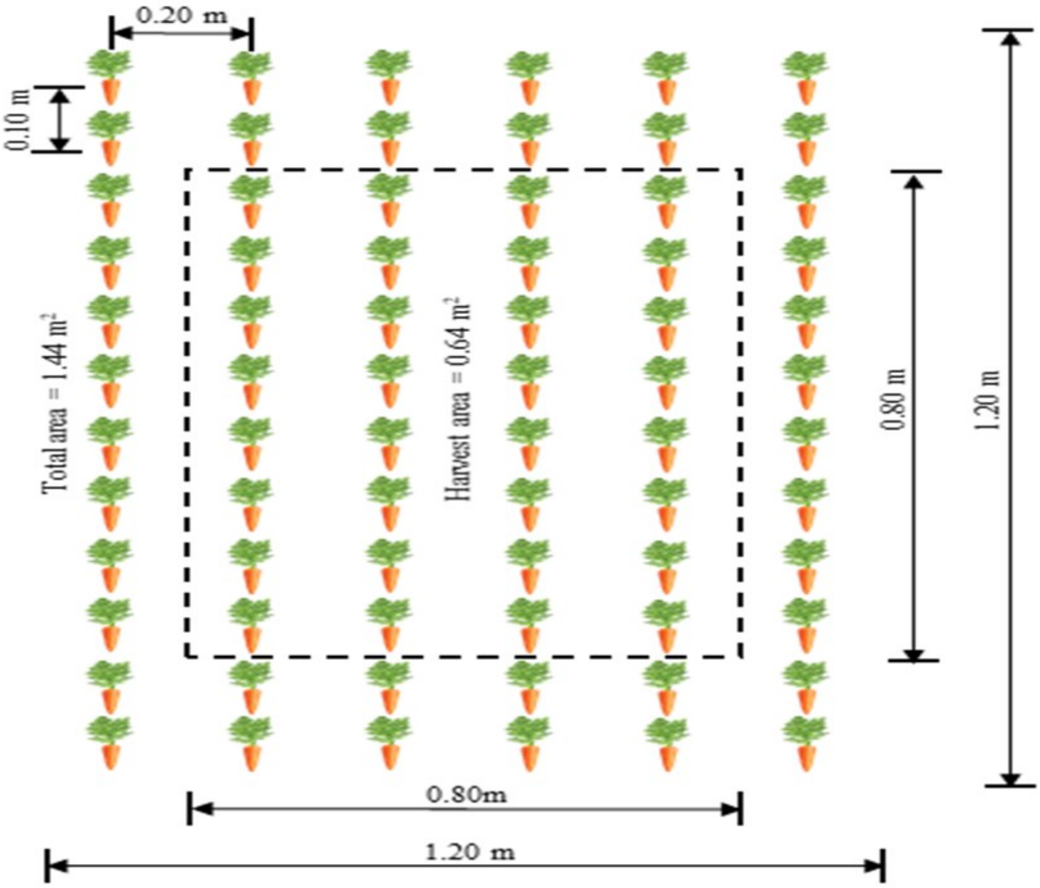

Figure 2. Detail of the experimental plot of monocropped carrot.

The carrot cultivar planted was ‘Brasilia’, which is indicated for cultivation in the semi-arid region of northeast Brazil. It has vigorous dark green foliage, medium size, orange cylindrical roots, and a low incidence of green or purple shoulders, and it ranges from 35 to 40 cm in height, has a cycle of 90 to 100 days, and is resistant to heat, foliar diseases, and premature bolting (OLIVEIRA et al., 2011).

The soil preparation consisted of mechanical cleaning of the experimental areas with the aid of a tractor with a reversible plow. Plowing and harrowing were carried out with a leveling harrow, and the beds were lifted with a rotary tiller. Then, pre-planting solarization was carried out for 30 days with 30 μm transparent plastic (Vulca Brilho Bril Fles), as recommended by Costa (2019), to reduce the population of soil pathogens and weeds that could harm the development of field cultures.

The materials used as green manure in the carrot culture were hairy woodrose and roostertree collected from native vegetation in several locations in the rural area of the municipality of Mossoró, RN, before the beginning of flowering. After collection, the plants were crushed into fragments of two to three centimeters, dehydrated at room temperature until they reached a moisture content of approximately 10%, and subsequently submitted to laboratory analysis. The chemical compositions obtained are shown in Table 2.

The green manure used in the experiments constituted equitable amounts of M. aegyptia and C. procera biomass. After solarization, the incorporation of the dry biomass of the green manure was carried out manually with the aid of hoes in the parcels, with 30% of the amount for each treatment applied 15 days before sowing carrot and the remaining 70% applied 30 days after sowing in the spaces between the planted rows using hoes. Manure was applied at a depth of 0–20 cm in all experimental plots, following the amounts specified for each treatment (SILVA et al., 2013). In the first year of cultivation, this first incorporation was carried out on 12/09/2020 and the second on 01/23/2021, while in the second year, the first incorporation was carried out on 09/13/2021, and the second on 10/29/2021.

Table 2. Chemical analyses of the macronutrients present in the dry biomass of green manures M. aegyptia and C. procera in the first and second season.

Green manures	Green manures macronutrient content (g kg^{-1})					
	N*	P	K	Ca	Mg	C:N
			S1 - 2020/2021			
M. aegyptia	20.56	2.83	37.08	3.17	1.77	25:1
C. procera	15.14	2.96	24.84	1.67	1.93	27:1
			S2 - 2021/2022			
M. aegyptia	18.55	1.89	38.68	2.60	1.53	25:1
C. procera	14.09	1.54	22.72	0.98	1.98	27:1

*N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium and C/N: carbon/nitrogen ratio.

Irrigation was performed daily using the micro-sprinkler system in two shifts, morning and afternoon, throughout the experiments, providing a water depth of 8.54 mm each day to maintain the soil at its field capacity and supply microorganisms, thus favoring the processes of mineralization of the incorporated organic matter, together with the low C/N ratio of the green manure. The amount of water supplied daily to the plants was based on the average Kc (cultivation coefficient) of the carrot crop of 1.35 (SANTOS et al., 2009).

The first experiment was sown on 12/24/2020, and the second experiment was sown on 09/23/2021. In both experiments, planting was carried out with direct sowing in holes two centimeters deep, with 2 to 3 seeds per hole. Thinning was carried out manually nine days after sowing (DAS), leaving only one plant per hole. Whenever necessary, manual weeding was performed in both experiments. No chemical treatment was carried out against pests or diseases. In the first year of cultivation, carrot was harvested 100 days after sowing (DAS), and in the second year of cultivation, 102 DAS.

The following agronomic characteristics were evaluated in carrot: plant height (cm), taken from a sample of 16 plants from the useful area, measuring the height from the ground level to the tip of the highest leaf; number of stems per plant (also obtained in the same sample of plants, counting the number per plant); shoot dry mass (determined in the same plant sample, placed in a forced air circulation oven at 65°C until reaching a constant weight, weighed, and expressed in t ha^{-1}); root dry mass (determined by the same methodology as the dry mass of the shoot and expressed in t ha^{-1}); commercial root productivity (quantified by the fresh mass of roots that were long, medium, and short, harvested in the harvest area of the plot, that were free from cracks, bifurcations, nematodes, and mechanical damage, expressed in t ha^{-1}); and classified root productivity (obtained according to the length and largest transversal diameter in long (length from 17 to 25 cm and diameter smaller than 5 cm), medium (length from 12 to 17 cm and diameter greater than 2.5 cm), short (5 to 12 cm in length and greater than 1 cm in diameter) and scrap roots (roots that do not fit the previous measurements) (LANA; VIEIRA, 2000). The total root productivity was quantified using the fresh mass of roots of all plants in the harvest area of the plot.

In addition to agronomic characteristics, the following economic indicators were quantified. Gross income (GI), expressed in R$ ha^{-1}, was obtained by multiplying the commercial productivity of carrot roots in each treatment by the average value of the product paid to the producer in the region during the period of the experiments (R$ 2.70 per kilogram). The net income (NI) was obtained by subtracting the production costs from the gross income from the inputs and services performed in each treatment, expressed as R$ ha^{-1}. The average prices of inputs and services in April 2021 and January 2022 in the city of Mossoró, RN, were considered. The rate of return (RR) per real investment was obtained through the relationship between gross income and production costs for each treatment, and the profit margin (PM), obtained from the ratio between net income and gross income, was expressed as a percentage.

A univariate analysis of variance for a randomized complete block design was performed in each cropping season to evaluate the carrot characteristics using *SISVAR* software (FERREIRA, 2011). Subsequently, a joint analysis of these same characteristics was also performed to determine whether there was an interaction between the tested treatments and the cropping seasons. Then, a regression curve fitting procedure was performed using the *Table Curve* software (SYSTAT SOFTWARE, 2022) to estimate the behavior of each characteristic or indicator as a function of the equitable amounts of biomass of *M. aegyptia* and *C. procera* studied, based on the following criteria: on the biological logic (BL) of the variable, that is, when after a certain amount of fertilizer, there was no increase in the variable; on the significance of the mean square of the regression residue (MSRR); at high value of the coefficient of determination (R^2); in the significance of the parameters of the regression equation and in the maximization of the variable. The F test was used to compare the average values between the growing seasons, between the average value of maximum agronomic or economic efficiency, and the average value of the control treatment (not fertilized).

RESULTS AND DISCUSSION

Agronomic characteristics and performance of carrot root production

The results of the analysis of variance of the agronomic characteristics of carrot are presented in Table 3. Significant interactions among treatment factors, biomass amounts of *M. aegyptia* and *C. procera*, and cropping seasons were observed for all traits evaluated in the carrot crop.

Studying the interaction of the green manure amounts within each cropping season (S), an increasing polynomial behavior was observed up to the maximum values of 57.69 cm for plant height and 10 stems per plant in the first season (S1), with 46.54 and 55.17 t ha^{-1} of green manure, respectively. The highest dry mass was 4.15 and 5.87 t ha^{-1} for shoots and 4.16 and 5.71 t ha^{-1} for the roots in the first (S1) and second (S2) cropping seasons, respectively (Figures 3A–D), with green manure applications of 55.52, 52.78, 55.57, and 55.37 t ha^{-1}, respectively. These values decreased until the last amount of green manure incorporated into the soil. However, an increasing behavior was also recorded between the lowest (16 t ha^{-1}) and highest amount of green manures (68 t ha^{-1}) in the second growing season (S2) for plant height and the number of stems per plant, reaching maximum values of 63.79 and 14 stems per carrot plant with 68 t ha^{-1} green manure (Figures 3A and 3B).

Estimating the maximum physical efficiencies of these agronomic characteristics over the cropping seasons (S1–S2), an increasing polynomial behavior was also observed as a function of the increase in the green manure amount up to the maximum values of 58.73 cm in plant height, 4.96 t ha^{-1}in the shoot dry mass, and 4.94 t ha^{-1} in the dry root mass with the green fertilizer at 60.34, 52.86, and 55.77 t ha^{-1} and decreasing until the highest fertilizer amount tested (Figures 3A, 3C, and 3D). For the number of stems per plant over the cropping seasons, the maximum value of 12.14 stems per plant was obtained with 68 t ha^{-1} green manure (Figure 3B).

In these agronomic traits (plant height, number of stems per plant, dry mass of shoots and roots), the mean values of the MPE treatment were 1.28, 1.33, 2.35, and 1.64 times the mean values of the control treatment (T_{wf}). The cropping seasons within the MPE treatment differed in these agronomic characteristics, with S2 surpassing S1. In the control treatment, the average number of stems per plant and dry root mass in S2 stood out from S1, but the height of plants and dry shoot mass were similar. In the fertilized treatments, S2 stood out from S1 only in the number of stems per plant and dry shoot and root masses (Table 3). The highest values of the soil chemical characteristics recorded in the second cropping season provided better nutritional condition of the soil for carrot growth and development compared to the first cropping season.

The upward responses and optimizations (MPE values) of the carrot agronomic traits in polynomial models can be attributed to the Law of Maximum, where excess nutrients in the soil provided by equitable amounts of *M. aegyptia* and *C. procera* can have a toxic effect and/or decrease the effectiveness of other factors, 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 green manure added to the soil and the time of greatest nutritional demand for the crop (FONTANÉTTI et al., 2006).

Table 3. Mean values of plant height, number of stems per plant, and dry mass of shoots and roots over the 2020 (S1) and 2021 (S2) cropping seasons for the control treatment (T_{wf}), maximum efficiency treatment (MPE), and green manure treatments (T_f).

Comparison treatments	Plant height (cm)			Number of stems per plant		
	2020	2021	2020-2021	2020	2021	2020-2021
	(S1)	(S2)	(S1/S2 mean)	(S1)	(S2)	(S1/S2 mean)
Control (without fertilization, T_{wf})	47.25Ab	44.16Ab	45.71	8.16Bb	10.10Ab	9.13
MPE Treatment	57.69Ba	63.78Aa	58.73^{+}	10.01Ba	14.31Aa	12.14^{+}
Fertilized treatments (T_f)	56.00Aa	55.94Aa	55.97^{+}	9.36Ba	12.27Aa	10.82^{+}
CV (%)	8.02	4.06	6.04	10.25	5.61	7.95
	Dry mass of shoots (t ha^{-1})			Dry mass of roots (t ha^{-1})		
Control (without fertilization. T_{wf})	1.80Ab	2.41Ab	2.11	2.46Bb	3.58Ab	3.02
MPE Treatment	4.15Ba	5.87Aa	4.96+	4.16Ba	5.71Aa	4.94+
Fertilized treatments (T_f)	3.63Ba	5.52Aa	4.57+	3.59Ba	5.18Aa	4.38+
CV (%)	15.02	3.10	9.09	13.33	6.88	10.06

*Means followed by the same lowercase letter in the column and capital letter in the row do not differ by the F test at 5% probability. +Significant difference between the maximum efficiency treatment (MPE) and fertilized treatments (T_f) and the control treatment (T_{wf}).

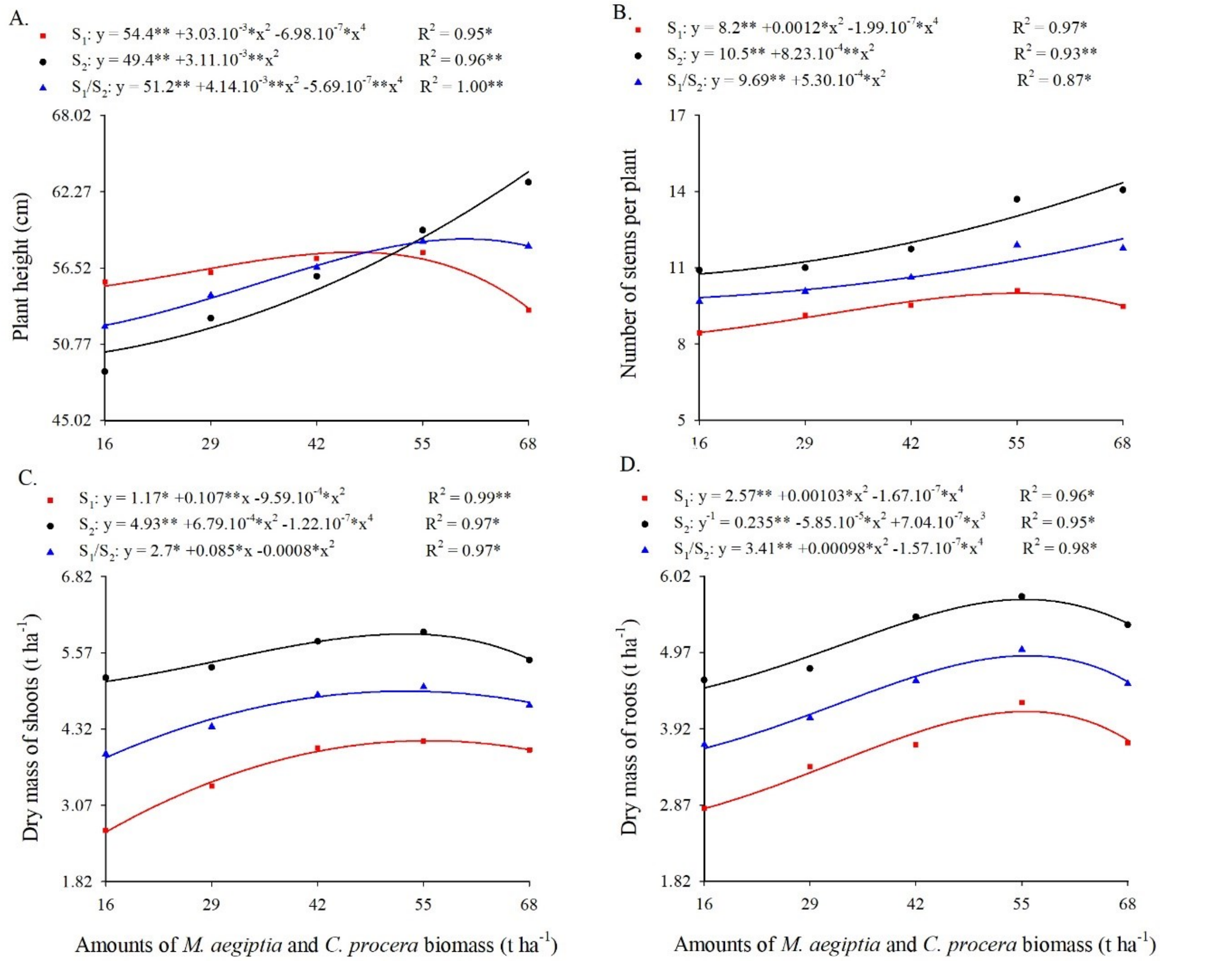

Figure 3. Plant height (A), number of stems per plant (B), and dry mass of shoots (C) and roots (D) of carrot as a function of equitable amounts of *Merremia aegyptia* and *Calotropis procera* biomass incorporated into the soil in the 2020 (S1) and 2021 (S2) cropping seasons.

The green manure used in this research had a C/N ratio between 25/1 and 27/1, which contributed to the decomposition and faster release of nutrients, as evidenced by the incorporation 15 days before carrot sowing in the evaluated characteristics. However, it is known that the rate of decomposition of organic residues is linked to the C/N ratio, which was 25/1 in *M. aegyptia* and 27/1 in *C. procera*. N mineralization is strongly influenced by the C/N ratio of the decomposing material (VALE et al., 1997).

The results of the analysis of variance of the carrot yield performance in terms of total and commercial productivity of roots and productivities of long, medium, short, and scrap roots are presented in Table 4. Significant interactions between the treatment factors, biomass amounts of *M. aegyptia* and *C. procera*, and cropping seasons were recorded for all productive traits evaluated.

Studying the interaction of the amount of green manure and the cropping season (S), an increasing polynomial behavior was observed in both cropping seasons, up to the maximum values of 35.88 and 53.79 t ha^{-1} for total productivity, 31.65 and 49.38 t ha^{-1} for commercial productivity, 10.41 and 27.53 t ha^{-1} for long root productivity, and 18.03 and 20.29 t ha^{-1} for medium root productivity in S1 and S2, respectively, and 3.84 t ha^{-1} for short root productivity in S1 green manure amounts of 54.07, 49.09, 53.20, 51.06, 52.56, 51.21, 55.05, 50.03, and 39.48 t ha^{-1}, respectively. These values decreased until the highest amount of green manure incorporated into the soil (Figures 4A–E). In the second season (S2), the maximum short root productivity was 2.28 t ha^{-1} with 68 t ha^{-1} green manure (Figure 4E). However, an increasing polynomial behavior was also recorded between the lowest (16 t ha^{-1}) and highest amounts of green manure (68 t ha^{-1}), both in the first (S1) and second cropping seasons (S2) for the productivity of scrap roots, reaching values of 4.09 and 6.28 t ha^{-1} with 68 t ha^{-1} green manure (Figure 4F).

Table 4. Mean values of total and commercial productivity of roots, productivity of long roots, productivity of medium roots, productivity of short and scrap roots over the 2020 (S1) and 2021 (S2) cropping seasons for the control treatment (T_{wf}), for the maximum efficiency treatment (MPE), and for green manure treatments (T_f).

Comparison treatments	Productivity of total roots (t ha^{-1})			Productivity of commercial roots (t ha^{-1})		
	2020	2021	2020-2021	2020	2021	2020-2021
	(S1)	(S2)	(S1/S2 mean)	(S1)	(S2)	(S1/S2 mean)
Control (without fertilization (T_{wf})	16.50Ab	21.19Ab	18.84	15.98Ab	20.19Ab	18.08
MPE Treatment	35.88Ba	53.79Aa	44.96$^+$	31.65Ba	49.38Aa	40.27$^+$
Fertilized treatments (T_f)	30.67Ba	44.49Aa	37.58$^+$	27.32Ba	40.17Aa	33.75$^+$
CV (%)	7.51	8.03	7.80	8.61	8.97	8.83
	Productivity of long roots (t ha^{-1})			Productivity of medium roots (t ha^{-1})		
Control (without fertilization (T_{wf})	2.77Bb	7.64Ab	5.21	10.60Ab	11.16Ab	10.88
MPE Treatment	10.41Ba	27.53Aa	18.71+	18.03Bb	20.29Aa	19.03+
Fertilized treatments (T_f)	7.07Ba	22.87Aa	14.97+	16.77Aa	15.75Aa	16.26+
CV (%)	17.67	17.37	17.52	14.33	12.11	13.22
	Productivity of short roots (t ha-1)			Productivity of scrap roots (t ha-1)		
Control (without fertilization (T_{wf})	2.60Ab	1.38Bb	1.99	0.52Ab	1.01Ab	0.76
MPE Treatment	3.84Aa	2.28Ba	2.84+	4.09Ba	6.28Aa	5.37+
Fertilized treatments (T_f)	3.48Aa	1.56Bb	2.52+	3.35Ba	4.32Aa	3.83+
CV (%)	32.62	38.47	35.55	25.02	22.87	23.95

*Means followed by the same lowercase letter in the column and capital letter in the row do not differ by the F test at 5% probability. $^+$Significant difference between the maximum efficiency treatment (MPE) and fertilized treatments (T_f) and the control treatment (T_{wf}).

Estimating the maximum physical efficiencies of the total and commercial productivity of the roots and the productivity of long and medium roots over the cropping seasons (S1–S2), an increasing polynomial behavior was also observed, as a function of the increase in the amount of green fertilizers up to the maximum values of 44.96 t ha^{-1} for total productivity, 40.27 t ha^{-1} for commercial productivity, 18.71 t ha^{-1} for long root productivity, and 19.03 t ha^{-1} for medium root productivity with green fertilizer amounts of 50.69, 48.87, 52.56, and 47.08 t ha^{-1}, respectively, but decreasing until the highest amount of fertilizer tested (Figures 4A–D). For the productivity of short and scrap roots over the cropping seasons, the maximum values were 2.84 and 5.37 t ha^{-1} with 68 t ha^{-1} green manure (Figures 4E and 4F).

For these root yield traits on the Table 4, the mean values of the MPE treatment were 2.39, 2.23, 3.59, 1.75, 1.43, and 7.07 times the mean values of the control treatment (T_{wf}). The cropping times within the MPE treatment differed for these yield traits, with S2 surpassing S1, except for the short root yield, where S1 surpassed S2. In the control treatment, the average total and commercial productivity of the roots and medium and scrap root productivity in S1 were similar to those of S2. In the productivity of long roots, S2 surpassed S1, and in the productivity of short roots, S1 differed from S2. In the fertilized treatments, S2 stood out from S1 in the total and commercial productivity of roots and long and scrap root productivity. In the productivity of short roots, the average value of S1 stood out from that of S2, and in the productivity of medium roots, they were similar (Table 4).

Silva et al. (2021) evaluated the agroeconomic efficiency of carrot in the same region of this research as a function of different amounts of *C. procera* and obtained total and commercial root productivities of 38.50 and 35.90 t ha^{-1}, respectively, and long and medium root productivities of 21.06 and 12.46 t ha^{-1}, respectively, when 47.32, 47.60, 53.15, and 48.06 t ha^{-1} of *C. procera* biomass, respectively, were added to the soil. These results were lower than those achieved in this study. This difference is due to the mixture of green manure used in the research, which proved to be much more efficient when compared to the study that worked with only one of the green manure crops.

The types of polynomial models tested on the agronomic traits of the carrot plant and on root productivity met the selection and adjustment criteria used to express the behavior of each trait evaluated. These criteria were described previously. This behavior was due to the greater availability of nutrients released by increasing the equitable amounts of *M. aegyptia* and *C. procera* added to the soil, thus increasing plant height, number of stems per plant, dry mass per area, and root productivity. In addition, this behavior also depends on the synchrony between the release and absorption of nutrients by carrot plants (SILVA et al., 2021). The amounts of macronutrients contained in the tested green manure met the nutritional needs of carrot plants. According to Taiz et al. (2017), nitrogen concentration favors the growth and development of plants, thus increasing the weight and number of stems per plant. Potassium greatly influences plant photosynthesis, and phosphorus affects root formation, directly influencing productivity and the quality of harvested products.

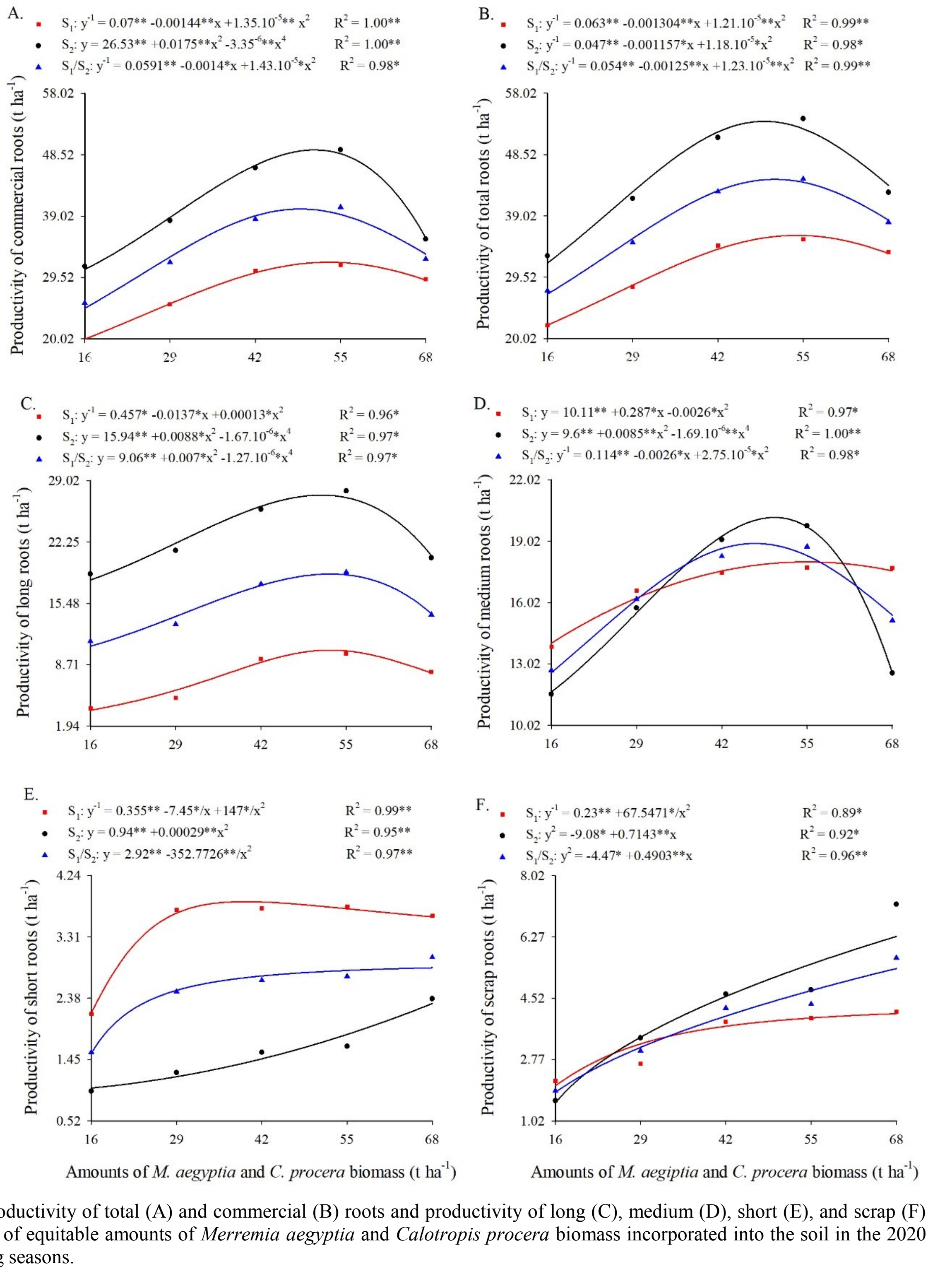

Figure 4. Productivity of total (A) and commercial (B) roots and productivity of long (C), medium (D), short (E), and scrap (F) roots of carrot as a function of equitable amounts of *Merremia aegyptia* and *Calotropis procera* biomass incorporated into the soil in the 2020 (S1) and 2021 (S2) cropping seasons.

Carrot economic performance

The results of the analysis of variance of the performance of the carrot economic indicators in terms of gross income, net income, rate of return, and profit margin are shown in Table 5. Significant interactions between treatment factors, *M. aegyptia* and *C. procera* biomass amounts, and cropping seasons were recorded for these economic indicators.

Table 5. Mean values of the control (Twf), for the treatment of maximum economic efficiency (MEE), and for fertilized treatments (T_f) in the gross income, net income, rate of return, and carrot profit margin in the two cropping seasons (2020 and 2021).

Comparison treatments	Gross income (R$ ha^{-1})			Net income (R$ ha^{-1})		
	2020	2021	2020-2021	2020	2021	2020-2021
	(S1)	(S2)	(S1/S2 mean)	(S1)	(S2)	(S1/S2 mean)
Control (without fertilization, T_{wf})	43143.00Bb	54505.58Ab	48824.29	25226.00Bb	36588.93Ab	33907.47
MEE Treatment	86029.63Ba	133325.31Aa	108187.55$^+$	50926.23Ba	97852.51Aa	74324.27$^+$
Fertilized treatments (T_f)	73769.68Ba	108466.30Aa	91117.99$^+$	41583.37Ba	76279.97Aa	58931.67$^+$
CV (%)	8.62	8.97	8.82	15.22	12.81	14.02
	Rate of return			Profit margin (%)		
Control (without fertilization, T_{wf})	2.41Bb	3.04Ab	2.73	57.98Bb	66.35Ab	62.17
MEE Treatment	2.55Ba	3.90Aa	3.21+	61.02Ba	75.08Aa	67.75+
Fertilized treatments (T_f)	2.31Bb	3.44Aa	2.88	56.14Ba	69.74Aa	62.94
CV (%)	9.98	10.67	10.33	6.95	5.16	6.10

*Means followed by the same lowercase letter in the column and capital letter in the row do not differ by the F test at 5% probability. $^+$Significant difference between the maximum efficiency treatment (MPE) and fertilized treatments (T_f) and the control treatment (T_{wf}).

Studying the amount of green manures within each cropping season (S), an increase in gross income, net income, rate of return, and profit margin was observed, both in the first (S1) and second (S2) cropping seasons, as a function of increasing equitable amounts of *M. aegyptia* and *C. procera* biomass added to the soil in a polynomial model (Figure 5). The maximum amounts recorded were R$ 86,029.63 (S1) and R$ 133,325.31 ha^{-1} (S2) for gross revenue, R$ 50,926.23 (S1) and R$ 97,852.51 ha^{-1} (S2) for net revenue, 2.55 (S1) and 3.90 (S2) for each real invested in the rate of return, and 61.02 (S1) and 75.08% (S2) for the profit margin with green manure biomass amounts of 53.20, 51.06, 51.43, 48.89, 36.76, 41.13, 36.25, and 40.81 t ha^{-1}, respectively; the values decreased until the highest amount incorporated (Figures 5A–D).

Estimating the maximum economic efficiencies (MEE) of these indicators over the cropping seasons, polynomial behavior was also recorded as a function of the amount of green manure (Figure 5). The maximum values were R$ 108,187.55 and R$ 74,324.27 ha^{-1} for gross income and net income, respectively, and 3.21 and 67.75% for the rate of return and profit margin, respectively, with green manure biomass amounts of 48.87, 49.64, 41.55, and 41.19 t ha^{-1}, respectively, which decreased until the highest amount of tested fertilizers (Figures 5A–D).

These results agree with those obtained by Silva et al. (2021) when fertilizing carrot with different amounts of *C. procera*, obtaining economic efficiency indicators of R$ 62,704.94 and 33,744.07 ha^{-1} for gross income and net income, respectively, and 2.27 and 56.63% for the rate of return and profitability index, respectively, with green manure biomass amounts of 47.60, 42.81, 31.69, and 31.85 t ha^{-1}, respectively. These results show the efficiency of green manure in carrot performance and development.

The average values of MEE and treatments that received green manure (T_f) differed from the control (T_{wf}) in all economic indicators of carrot (Table 5). The cropping seasons within the MEE treatment differed for all economic indicators, with an emphasis on the second season. In the control treatment, there was a difference between S1 and S2 in all evaluated indicators (Table 5).

These upward responses of the economic indicators evaluated in carrot, with a decrease after the maximum in the form of a polynomial model as a function of the equitable amounts of biomass of *M. aegyptia* and *C. procera*, were due to the good response of carrot to the incorporation of green fertilizer. However, green manure is known to improve fertility, decrease erosion rates and the amount of invasive plants, and increase soil organic matter content, soil water retention, microbial activity, and soil nutrient availability (GRAHAM; HAYNES, 2006).

The maximum physical efficiency (MPE) of the carrot treatments that received green manure was translated into economic terms for all evaluated indicators, providing optimized economic efficiency over the cropping seasons (Table 5). This behavior allows the carrot producer to choose the optimal amount of green manure for incorporation, and the economic indicator that best suits them in terms of commercial root productivity. In view of these results, the cultivation of carrots with the combination of the two green manure crops provides a financial return compatible with the capital invested, making it a viable alternative, especially for small producers who do not have a high investment capital (SOUZA et al., 2017).

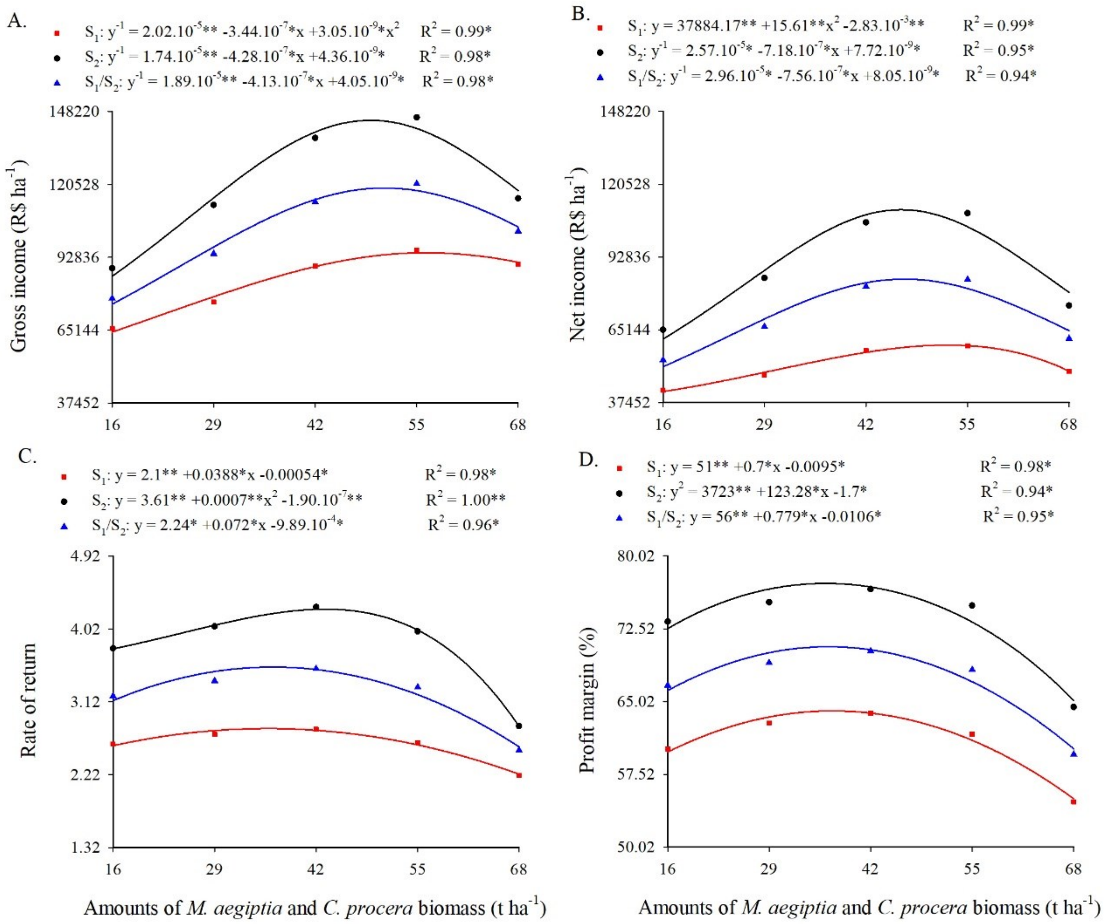

Figure 5. Gross income, net income, rate of return, and profit margin of carrot as a function of equitable biomass amounts of *Merremia aegyptia* and *Calotropis procera* incorporated into the soil in the 2020 (S1) and 2021 (S2) cropping seasons.

These spontaneous species from the Caatinga biome used as green manure are readily available in the region in large populations due to their qualities as “good fertilizers”. They provide nutrients and have excellent biomass with a low C:N ratio, which provides faster decomposition and nutrient release for plants (SILVA et al., 2019). *Merremia aegyptia* can produce 36 t ha^{-1} of green biomass or 4.00 t ha^{-1} of dry biomass (LINHARES et al., 2008), containing 2.62% N, 0.17% P, 1.20% K, 0.90% Ca, and 1.08% Mg on a dry basis. *Calotropis procera* can produce an average of 3 t ha^{-1} of dry biomass per cut, with the potential for three cuts per year (9 t ha^{-1} dry biomass). On a dry basis, this species contains 1.53% N, 4.0% P, 1.57% K, 0.93% Ca, and 0.73% Mg (BEZERRA NETO et al., 2019). Given these amounts, these species have enormous potential for use as green manure in crop production, especially vegetables.

CONCLUSIONS

Carrot fertilization to obtain the maximum optimized productive efficiency (commercial productivity) was made possible with the incorporation of 49.87 t ha^{-1} of *M. aegyptia* and *C. procera* dry biomass into the soil. The maximum agroeconomic efficiency (net income) of carrot cultivation was obtained when 46.64 t ha^{-1} of optimized *M. aegyptia* and *C. procera* dry biomass was added to the soil. The rate of return obtained for the cultivation of carrots was R$ 3.21 for each real invested, and the profit margin was 67.70%. The use of *M. aegyptia* and *C. procera* biomass as green manure is a viable technology for producers of monocropped carrot in semi-arid regions, considering that the significant increase of the total and commercial root productivity and economic indicators presented significantly higher values when compared to other treatments with green manure used in semi-arid environments.

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