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AGRONOMIC CHARACTERISTICS AND OPTIMIZED SWEET POTATO ROOT PRODUCTION IN MONOCULTURE UNDER GREEN MANURING

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Abstract
One of the challenges of the scientific research on sweet potatoes in semi-arid environments is to increase biomass amounts of spontaneous species from the Caatinga biome, such as hairy woodrose (*Merremia aegyptia* L.) and roostertree (*Calotropis procera* Ait.), for use as green fertilizers during cultivation. Therefore, this study aimed to agronomically and economically optimize the agronomic characteristics of sweet potato root production in a monoculture, fertilized with equal amounts of biomass mixture of these spontaneous species, over two years of cultivation. The experimental design was complete randomized blocks with five treatments and five replications. The treatments consisted of equal amounts of hairy woodrose and roostertree biomass at 16, 29, 42, 55, and 68 t ha^{-1} on a dry basis. An additional sweet potato treatment was planted in each experiment, one without fertilizers (control) and another with mineral fertilizer, to compare with the treatment of maximum physical or economic efficiency. Sweet potato fertilization obtained the maximum optimized productive efficiency by incorporating 46.97 t ha^{-1} of dry biomass of *M. aegyptia* and *C. procera* into the soil. The maximum optimized agroeconomic efficiency (based on net income) of sweet potato cultivation occurred by adding 41.55 t ha^{-1} of dry biomass of *M. aegyptia* and *C. procera* to the soil. Using biomass from the green fertilizers *M. aegyptia* and *C. procera* is a viable technology for producers who practice sweet potato monocropping in semi-arid environments.

Keywords: *Calotropis procera. Ipomoea batatas. Merremia aegyptia.* Organic fertilization.

1. Introduction

Sweet potato (*Ipomoea batatas* (L)) is a tuberous vegetable (roots) from the Convolvulaceae family, widely accepted and adapted, rustic, highly tolerant to droughts, and easy to cultivate. It is among the significant crops that feed the population and is rich in carbohydrates; proteins; fibers; nutrients such as potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), and copper (Cu); and bioactive compounds. It shows economic relevance and is extensively cultivated in all Brazilian regions. This crop has a high productive potential, and it is mostly cultivated by small producers in agricultural systems with lower use of inputs (Neiva et al. 2011).

Sweet potato presents a high production capacity of 40 t ha^{-1}. The average Brazilian production is around 14.25 t ha^{-1} (Instituto Brasileiro de Geografia e Estatística 2022), which may increase with proper soil management using fertilization techniques to guarantee a high crop yield and product quality (Oliveira et al. 2017). Green manuring incorporates the plant biomass, either produced at the origin or not, to increase the levels of organic matter and nutrients in the soil, improving its structure, aeration, water storage capacity, and physical, chemical, and biological properties (Silva et al. 2020).

Typically, grasses and legumes are the species most used in green fertilizing. Among the types of green fertilizers used are hairy woodrose and roostertree, spontaneous species from the Caatinga biome (Lino et al. 2021). Hairy woodrose is a herbaceous species with an average green and dry phytomass production between 36,000 and 4,000 kg ha^{-1}, respectively, nitrogen and potassium contents around 19.76 and 34.28 g kg^{-1} of dry matter, and a carbon/nitrogen (C/N) ratio of 25/1 (Oliveira et al. 2017). Roostertree is a shrub species with an average phytomass production on a dry basis of around 3,000 kg ha^{-1} per cut (120 days), reaching 9 t ha^{-1} per year (Costa et al. 2009), nitrogen and potassium contents around 18.40 and 24.50 g kg^{-1} in dry matter, and a C/N ratio of 25/1 (Nunes et al. 2018).

These spontaneous species (hairy woodrose and roostertree) have been used as green fertilizers in tuberous crops, such as beetroot and radish, with satisfactory results for yield, product quality, and economic indicators. Lino et al. (2021) fertilized beetroot and radish with different amounts of hairy woodrose and roostertree biomass mixture and obtained optimized yields of 17.58 and 6.21 t ha^{-1} when incorporating 49.87 and 39.43 t ha^{-1}, respectively, of the biomass mixture of green fertilizers, with rates of return of BRL 1.42 and 1.32 for each Brazilian Real (BRL) invested.

It is worth noting that sweet potato cultivation is considered rustic; therefore, producers tend to grow it in nutritionally poor soils, which does not mean that the response to fertilization is low (Filgueira 2008). This response depends on soil conditions, and fertilization increases sweet potato production in low-fertility soils (Fernandes et al. 2018).

Considering the lack of information about using these spontaneous species as green fertilizers in sweet potato monocropping in semi-arid environments, the present study aimed to agronomically and economically optimize the production of sweet potato and its components when fertilized with equal amounts of biomass of the spontaneous species hairy woodrose and roostertree, in two cropping seasons.

2. Material and Methods

Field experiments were performed from October 2021 to March 2022 and from March to July 2022 at the Rafael Fernandes Experimental Farm of the Federal Rural University of the Semi-Arid Region (UFERSA), in the district of Lagoinha, 20 km from Mossoró, RN, Brazil (5° 03' 37" S, 37° 23' 50" W and altitude of 80 m).

According to the Köppen Geiger classification, the climate in the experimental areas is 'BShw', dry and very hot, with two seasons: a dry season typically from June to January, and a rainy season from February to May (Beck et al. 2018). During sweet potato development and growth periods, the values recorded for minimum, average, and maximum temperatures were 24.7, 29.0, and 35.2°C, respectively, in 2021/2022 and 23.3, 27.1, and 35.2°C, respectively, in 2022. Relative humidity was 67.5 and 79.3%, precipitation was 502.2 and 697.2 mm, solar radiation was 18.8 and 16.5 MJ m^2 day^{-1}, and wind speed was 5.0 and 3.6 m s^{-1}, respectively, in 2021 and 2022, (Laboratório de Instrumentação Meteorologia e Climatologia 2022). Figure 1 shows the data on the average daily minimum and maximum temperatures and average daily relative humidity after sowing sweet potatoes in the two seasons.

The soils of the experimental areas were classified as Dystrophic Red Yellow Latosol with a sandy loam texture (Santos et al. 2018). In each location, single soil samples were collected from the surface layer (0–20 cm) and homogenized to obtain a composite sample representative of the area. Table 1 describes the chemical analyses of the soils according to the methodology of the Brazilian Agricultural Research Corporation (Teixeira et al. 2017).

The experiments were performed in a randomized complete block design with five treatments and five replications. The treatments consisted of equal amounts of hairy woodrose (*Merremia aegyptia*) and roostertree (*Calotropis procera*) biomass at 16, 29, 42, 55, and 68 t ha^{-1} on a dry basis. Each experiment received one sweet potato treatment without fertilization (absolute control) and another with mineral fertilizer (control) to compare with the treatment of maximum physical and economic efficiency.

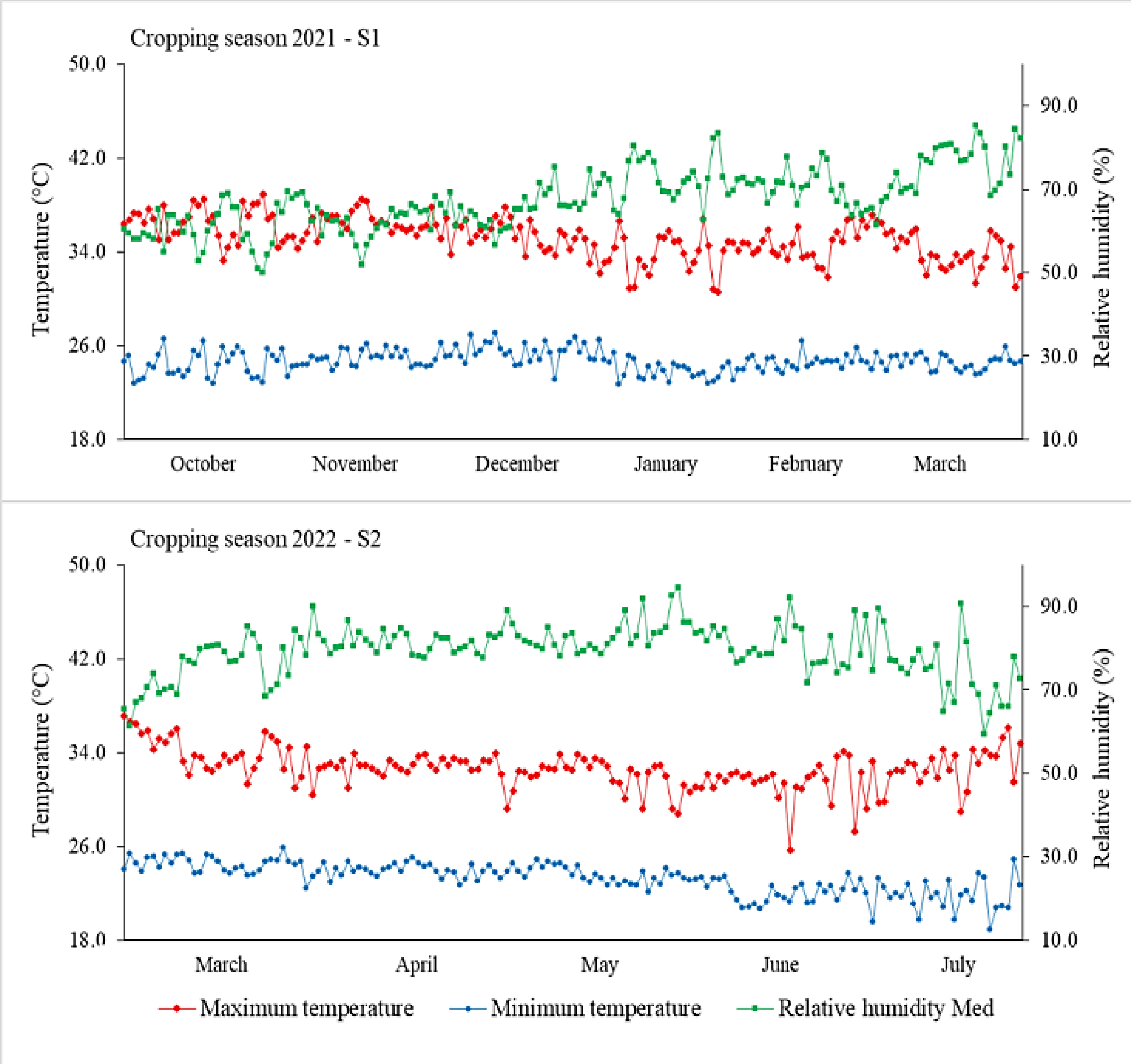

Figure 1. Data on daily temperature and relative air humidity averages during sweet potato growing periods in 2021 (S1) and 2022 (S2).

Table 1. Chemical analysis of the soils before incorporating green manure in the first and second growing seasons, Mossoró, RN, Brazil - UFERSA, 2022.

Before spontaneous species incorporation								
Soil cropping areas	N	C	pH (H_2O)	EC	OM	P	K^+	Na^+
	g kg^{-1}			ds m^{-1}	g kg^{-1}		mg dm^3	
Soil 1	0.70	7.52	6.60	0.56	12.97	32.0	2.59	2.30
Soil 2	0.60	6.90	6.30	0.44	11.90	24.0	2.36	1.73
	Ca^{2+}	Mg^{2+}	Cu	Fe	Mn	Zn	B	
	cmol$_c$ dm^3		mg dm^3					
Soil 1	23.70	6.50	0.30	4.80	6.10	2.7	0.50	
Soil 2	22.50	4.80	0.50	5.70	11.2	3.8	0.58	

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.

Each experimental plot had four sweet potato rows, with 10 plants per row planted in holes spaced at 0.80 m × 0.30 m, producing an estimated population of 41,667 plants per hectare (Empresa Brasileira de Pesquisa Agropecuária 2021). Two branches with eight buds each were transplanted into each hole, four of which were buried, totaling 40 plants per experimental plot (Figure 2). The total area of each plot was 9.60 m^2 (3.00 m x 3.20 m), with a harvest area of 3.84 m^2 (1.60 m x 2.40 m).

The planted sweet potato cultivar Paraná has a branching size, dark green leaves, with a stem base and acute apex, rounded roots with periderm and orange pulp, an early cycle of 120 days, and excellent adaptation to semi-arid conditions due to its low water requirement and tolerance to prolonged water stress (Albuquerque et al. 2019).

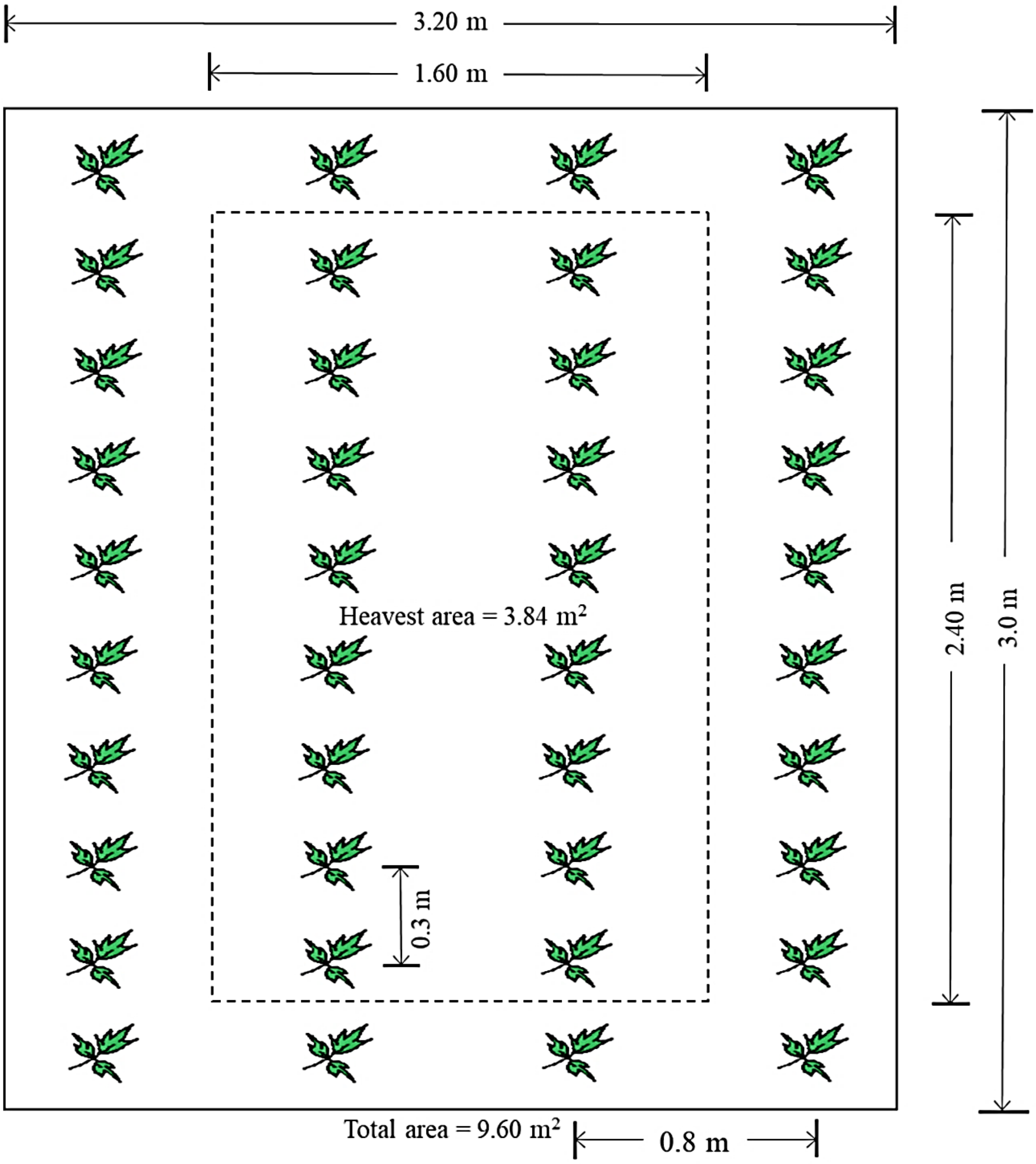

Figure 2*.* Representation of an experimental sweet potato plot planted at a spacing of 0.80 × 0.30 m.

Before installing the experiments, a tractor mechanically cleaned the area by plowing and harrowing. Next, windrows were raised with a moldboard plow and manually corrected with a hoe. Solarization was not required because the soil had no history of the presence of nematodes.

The materials used as green fertilizers in the sweet potato culture were hairy woodrose and roostertree, collected from several locations of the native vegetation in the rural area of Mossoró, RN, Brazil, before flowering started. After the collections, the plants were crushed into two-to-three-centimeter fragments, dehydrated at room temperature until reaching a moisture content of approximately 10%, and then submitted to laboratory analysis. Table 2 shows the resulting chemical compositions.

The tested amounts of these materials were incorporated into the middle of the windrows, which were made by the tractor and then reopened in a 40-cm-deep furrow, subsequently closed, and assembled for planting. The first cultivation year received this incorporation on October 1, 2021, and the second year on March 8, 2022. Then, the windrows were irrigated daily with a micro-sprinkler for 20 days before planting the branches.

Table 2. Chemical analysis of macronutrients in the dry mass of green fertilizers *M. aegyptia* and *C. procera* in two growing seasons - 2021 (S1) and 2022 (S2). Mossoró, RN, Brazil - UFERSA, 2022.

Green fertilizer	Macronutrient content g kg^{-1}					
	N	P	K	Ca	Mg	C/N
	2021/2022					
M. aegyptia	18.55	1.89	38.68	9.30	7.03	25:1
C. procera	14.09	1.54	22.72	16.30	13.50	27:1

N: Nitrogen; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; C/N: Carbon/Nitrogen ratio.

The mineral fertilization of sweet potatoes was performed in two chemical fertilizer applications. Foundation fertilization occurred seven days before planting, at 20-60-50 kg ha^{-1} of ammonium nitrate, simple superphosphate, and potassium chloride, respectively. Topdressing fertilization was performed at 45 days with 40 and 30 kg ha^{-1} of ammonium nitrate and potassium chloride, respectively (Holanda et al. 2017). Foundation fertilization was made in 30-cm-deep holes in the middle of the furrows, and topdressing fertilization in 15-cm-deep holes in the furrows, spaced at 60 cm between potato plants (Empresa Brasileira de Pesquisa Agriculture 2021).

Irrigation was conducted with micro-sprinklers in two shifts a day for the first 15 days to favor the sticking of branches. Later, it occurred once a day in shifts from four to 60 days. Irrigation met soil requirements, allowing the mineralization of the incorporated organic matter.

The first experiment was sown on October 21, 2021, and the second on March 29, 2022. In both experiments, planting was performed in holes with branches that were multiplied. Replanting was required where the branches did not settle. Manual weeding was performed in the experiments when needed. There was no chemical treatment against pests and diseases. The sweet potato was harvested 122 days after sowing (DAS) in the first cultivation year, and 120 DAS in the second one.

The following agronomic characteristics were evaluated for sweet potatoes: Total and commercial yields, obtained by weighing the roots of 16 holes in the harvest area of each plot, expressed in t ha^{-1}; Non-standard roots (thin, greenish, cracked, and insect-affected), considered non-commercial roots; Shoot fresh mass, obtained from branch harvesting (at 3.0 cm from the ground) from a sample of four holes in the harvest area of each plot, expressed in t ha^{-1}; Shoot dry mass, determined in the same plant sample, placed in a forced air circulation oven at 65°C until reaching constant weight, and weighed, expressed in t ha^{-1}. Root dry mass, determined with the same methodology as the shoot dry mass, expressed in t ha^{-1}.

The following economic indicators were also quantified: Gross income (GI), expressed in BRL ha^{-1}, obtained by multiplying the sweet potato commercial yield in each treatment by the average product value paid to the producer in the region during the experiments (BRL 2.20 per kilogram); Net income (NI), obtained by subtracting the gross income and production costs from inputs and services of each treatment, expressed in BRL ha^{-1}. This study considered the average prices of inputs and services in March and July 2022 in Mossoró, RN, Brazil. The rate of return (RR) per Brazilian Real (BRL) invested was obtained through the relationship between the gross income and production costs of each treatment, and the profit margin (PM) resulted from the relationship between the net and gross incomes, expressed in percentages.

Univariate analysis of variance was applied to the complete randomized block design for each sweet potato crop, crop characteristics, and economic indicators after fulfilling the assumptions of normality, homoscedasticity, and additivity. Tukey's test at ($p<0.05$) compared the means between the tested treatments using SISVAR software (Ferreira 2011). Then, a joint analysis of these characteristics and indicators was also performed to investigate a potential interaction between the tested treatments and potato-growing seasons. Before this analysis, the assumption was verified as to whether there was homogeneity of the residual mean squares of the experiments, through the relationship between the highest and lowest mean square value, which was lower than 7. Therefore, the experiment variances were homogeneous (Pimentel-Gomes 2009). Then, a regression curve fitting was performed with Table Curve software (Systat Software 2022) to estimate the behavior of each characteristic or indicator according to the studied equal amounts of *M. aegyptia* and *C. procera* biomass, based on the following criteria: Biological logic (BL) of the variable, meaning that the variable does not increase after a given fertilizer dose; Significance ($p<0.05$) of the mean square of the regression residual (MSRR); High coefficient of determination (R^2); Significance of parameters of the regression equation; Variable maximization. The F test at $p<0.05$ compared the averages between cropping seasons, the average of maximum agronomic or economic efficiency, and the averages of the mineral and control (not fertilized) treatments.

3. Results

Agronomic and production characteristics of sweet potato

Table 3 describes the analysis of variance of agronomic and production characteristics of sweet potato: shoot fresh mass, shoot dry mass, root dry mass, total and commercial yields, and productivity of scrap roots. All these traits showed significant interactions ($p<0.05$) between treatment factors, amounts of *Merremia aegyptia* and *Calotropis procera* biomass, and cropping seasons. Studying the cropping seasons (S) within each amount of green fertilizers, it was observed that the first cropping season (S1) differed from the second season (S2) in all treatments tested for agronomic and productive characteristics of sweet potato, except for total productivity of roots in the mineral treatment and for commercial productivity of roots in the control treatment, which did not show significant differences between seasons (Table 3).

Table 3. Mean values of the control treatment (T_{wf}), maximum physical efficiency treatment (MPE), fertilized treatments (T_f) with green manure, and the mineral treatment (T_{mf}) with chemical fertilizer, in shoot fresh and dry mass, total and commercial root yields, root dry mass, and productivity of sweet potato scrap roots, in two growing seasons - 2021 (S1) and 2022 (S2). Mossoró, RN, Brazil, 2022.

Comparison between treatments	Shoot fresh mass (t ha^{-1})			Shoot dry mass (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_{wf})	11.77^{bA}	3.91^{bB}	7.84	1.86^{bA}	0.62^{cB}	1.25
MPE Treatment	13.94^{aA}	7.19^{aB}	10.64^{+}	2.07^{aA}	0.98^{aB}	1.53^{+}
Fertilized treatments (T_f)	12.73^{aA}	6.18^{aB}	9.45^{+}	1.83^{bA}	0.83^{bB}	1.33^{+}
Mineral treatment (T_{mf})	10.36^{cA}	4.72^{bB}	7.54	1.60^{bA}	0.73^{cB}	1.16
CV (%)	10.10	13.86	11.57	10.78	17.43	12.98
Standard deviation	1.24	0.78	1.04	0.19	0.14	0.17
	Total root yield (t ha^{-1})			Commercial root yield (t ha^{-1})		
Control (without fertilization. T_{wf})	11.90^{cB}	16.46^{bA}	14.18	8.96^{cA}	8.85^{bA}	8.90
MPE Treatment	46.57^{aA}	37.90^{aB}	41.11^{+}	43.03^{aA}	26.91^{aB}	34.57^{+}
Fertilized treatments (T_f)	38.00^{aA}	31.62^{aB}	34.81^{+}	34.47^{aA}	21.96^{aB}	28.21^{+}
Mineral treatment (T_{mf})	20.78^{bA}	19.49^{bA}	20.14^{+}	17.64^{bA}	10.01^{bB}	13.83^{+}
CV (%)	7.96	10.48	9.16	9.21	12.18	10.41
Standard deviation	2.53	2.91	2.73	2.62	2.24	2.44
	Root dry mass (t ha^{-1})			Productivity of scrap roots (t ha^{-1})		
Control (without fertilization. T_{wf})	3.08^{bA}	1.35^{bB}	2.22	2.93^{cB}	7.61^{cA}	5.27
MPE Treatment	8.56^{aA}	2.63^{aB}	5.44^{+}	4.67^{aB}	10.28^{aA}	7.40^{+}
Fertilized treatments (T_f)	7.74^{aA}	2.29^{aB}	5.02^{+}	3.54^{bB}	9.66^{bA}	6.60^{+}
Mineral treatment (T_{mf})	3.96^{bA}	2.20^{aB}	3.08^{+}	3.14^{cB}	9.48^{bA}	6.31^{+}
CV (%)	13.51	10.81	14.87	23.43	19.19	21.78
Standard deviation	0.88	0.63	0.65	0.80	1.79	1.39

*Means followed by the same lowercase letter in the column and capital letter in the row do not differ by the F test at $p<0.05$. $^{+}$Significant difference between fertilized and control (T_{wf}) treatments.

The mean values of green fertilizers treatments (T_f) over the cropping seasons were 1.36, 1.22, 2.90, 3.88, 2.45, and 1.40 times the means of the control treatment (T_{wf}) (Table 3).

Albuquerque (2016) evaluated sweet potato cultivation with chemical fertilization at different harvest times and found values for commercial and total root yields and root dry mass of 17.67, 18.89, and 4.5 t ha^{-1}, 150 DAS when the author verified the best yield values. These results are much lower than the present study, which were 28.21, 34.81, and 5.02 t ha^{-1}, respectively, for commercial and total root yields and root dry mass, under green manuring. The highest values for the shoot fresh and dry mass variables were 10.27 and 3 t ha^{-1}, higher than the present study, which were 9.45 and 1.33 t ha^{-1}.

The interaction of green fertilizer amounts in each cropping season (S) showed an increasing polynomial behavior in the first (S1) and second (S2) cropping seasons, up to the maximum values of 13.94 (S1) and 7.19 (S2), and 2.07 (S1) and 0.98 (S2) t ha^{-1} for shoot fresh and dry mass, with 59.40 and 53.12, and 41.88 and 56.23 t ha^{-1} of green fertilizers, respectively. For total and commercial root yields, the highest values were 46.57 (S1) and 37.90 (S2), and 43.03 (S1) and 26.91 (S2), respectively, with 48.77 and 28.13, and 49.28 and 32.89 t ha^{-1} of green fertilizers. For root dry mass and productivity of scrap roots, the maximum values were 8.56 and 2.63, and 4.67 and 10.28 t ha^{-1}, with 49.03 and 27.49, and 26.80 and 27.10 t ha^{-1} of green fertilizers, respectively. All these results decreased up to the last green fertilizer amount incorporated into the soil (Figures 3A to 3F).

The estimation of maximum physical efficiencies of these agronomic characteristics and sweet potato production over the 2021 (S1) and 2022 (S2) cropping seasons also showed an increasing polynomial behavior according to the increase in green fertilizer amounts up to the highest values of 10.64 and 1.53 t ha^{-1} in shoot fresh and dry mass in the fertilizers amounts of 56.70 and 46.12 t ha^{-1}; of 41.11 and 34.57 t ha^{-1} in total and commercial root yields in the amounts of fertilizers of 46.32 and 46.97 t ha^{-1} and 5.44 and 7.40 t ha^{-1} in root dry mass and productivity of scrap roots with 37.86 and 26.68 t ha^{-1} of green fertilizers, decreasing afterward up to the highest tested fertilizer amount (Figures 3A to 3F).

Santos et al. (2006) evaluated the effect of organic fertilization on the total and commercial production of sweet potato roots in the semi-arid region of Paraíba (Brazil) at 0, 10, 20, 30, 40, and 50 t ha^{-1} of bovine fertilizers and obtained a polynomial behavior between the production and the tested doses, with the highest total and commercial production of optimized roots of 18.5 and 14.2 t ha^{-1} at the bovine fertilizer doses of 32 and 30 t ha^{-1}. These results were lower than our research, which showed total and commercial root yields of 41.11 and 34.57 t ha^{-1} in 46.32; 46.97 t ha^{-1} of green fertilizers incorporated into the soil. These differences are essentially due to the type of organic fertilizer.

However, Desravines et al. (2022) worked with green fertilizers with the *M. aegyptia* and *C. procera* species on the production and agronomic characteristics of cowpea, also showing a beneficial effect of such fertilizers on these characteristics and achieving polynomial models for optimizing plant height, green pod length, the number of grains per pod, and green pod production. Therefore, the number of nutrients offered by the green fertilizers hairy woodrose and roostertree were sufficient to optimize agronomic and production characteristics of sweet potato.

Economic performance of sweet potato

Table 4 describes the analysis of variance of sweet potato economic indicators according to gross income, net income, rate of return, and profit margin. Significant interactions ($p<0.05$) between the treatment factors, amounts of *Merremia aegyptia* and *Calotropis procera* biomass, and cropping seasons were recorded for all these economic indicators. Regarding each green fertilizer amount, the first cropping season (S1) differed from the second one (S2) in all tested treatments for these indicators, except for the control treatment, in which they were similar. The averages of maximum economic efficiency (MEE) for treatments under green manuring and mineral fertilizers differed statistically from the control treatment (T_{wf}) in all the economic indicators evaluated for sweet potatoes over the cropping seasons (Table 4).

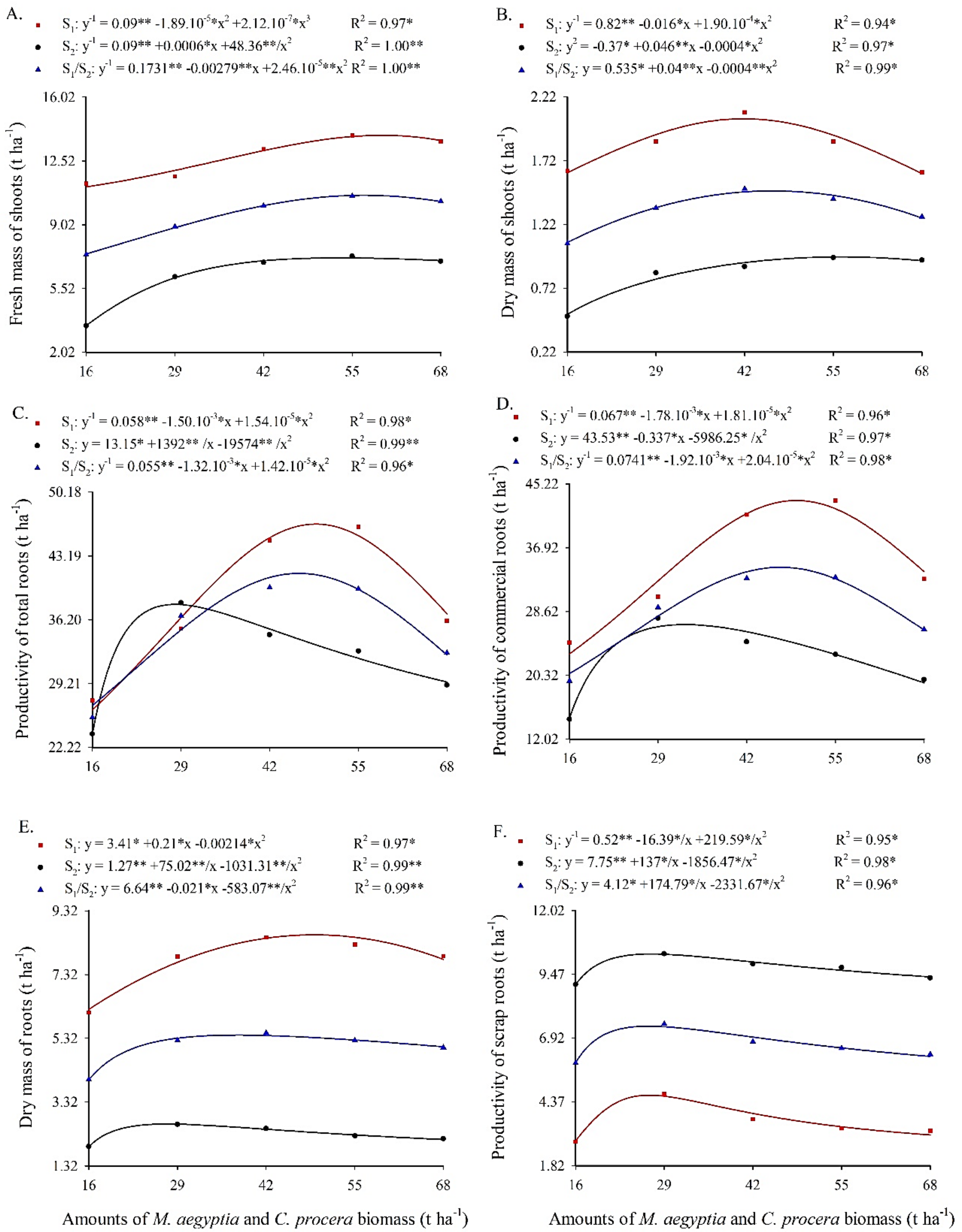

Figure 3. Shoot fresh and dry mass, total and commercial yields, root dry mass, and productivity of scrap roots of sweet potato according to the equal amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil in the 2021 and 2022 cropping seasons.

The green fertilizer amounts in each cropping season (S) increased the gross and net incomes, rate of return, and profit margin in the first (S1) and second (S2) seasons, according to the increasing equal amounts of *M. aegyptia* and C. *procera* biomass incorporated into the soil in a polynomial model (Figure 4).

The highest values were BRL 95,271.28 (S1) and BRL 59,223.97 ha^{-1} (S2) for gross income, BRL 66,126.75 (S1) and BRL 33,666.90 ha^{-1} (S2) for net income, BRL 3.04 (S1) and 2.50 (S2) for each Brazilian Real (BRL) invested for the rate of return, and 67.33 (S1) and 58.17% (S2) for the profit margin with 49.28 (S1) and 32.89 (S2), 48.57 (S1) and 29.14 (S2), 44.63 (S1) and 24.56 (S2), and 43.73 (S1) and 27.47 t ha^{-1} (S2) of green fertilizer biomass, respectively. The values decreased until the last incorporated amount (Figures 4A, 4B, 4C, and 4D).

Table 4. Mean values of the control treatment (Twf), maximum economic efficiency treatment (MEE), fertilized treatments (Tf) with green manure, and the mineral treatment (Tmf) with chemical fertilizer, in the gross income, net income, the rate of return, and the profitability index of sweet potato, in two growing seasons - 2021 (S1) and 2022 (S2). Mossoró, RN, Brazil, 2022.

Comparison between treatments	Gross income (BRL ha^{-1})			Net income (BRL ha^{-1})		
	2021	2022	2021-2022	2021	2022	2021-2022
	(S1)	(S2)	(S1/S2 mean)	(S1)	(S2)	(S1/S2 mean)
Control (without fertilization. T_{wf})	19,714.00^{cA}	19,465.00^{bA}	19,589.00	4,348.00^{cA}	4,099.00^{cA}	4,224.00
MEE Treatment	95,271.28^{aA}	59,223.97^{aB}	75,542.52^{+}	66,126.75^{aA}	33,666.90^{aB}	44,352.89^{+}
Fertilized treatments (T_f)	75,826.35^{aA}	48,316.45^{aB}	62,071.40^{+}	46,695.97^{aA}	19,186.07^{bB}	32,941.00^{+}
Mineral treatment (T_{mf})	38,821.00^{bA}	22,020.00^{bB}	30,420.00^{+}	19,177.00^{bA}	2,376.00^{cB}	10,776.00^{+}
CV (%)	9.22	12.18	10.41	15.69	33.67	20.88
Standard deviatio	5,761.88	4,925.02	5,359.81	5,761.88	4,925.01	5,359.81
	Rate of return			Profit margin (%)		
Control (without fertilization. T_{wf})	1.28^{cA}	1.27^{cA}	1.27	20.85^{cA}	20.44^{cA}	20.65
MEE Treatment	3.04^{aA}	2.50^{aB}	2.60^{+}	67.33^{aA}	58.17^{aB}	59.67^{+}
Fertilized treatments (T_f)	2.64^{bA}	1.71^{bB}	2.17^{+}	60.82^{aA}	37.14^{bB}	48.98^{+}
Mineral treatment (T_{mf})	1.97^{cA}	1.12^{cB}	1.55^{+}	49.19^{bA}	9.23^{dB}	29.21^{+}
CV (%)	9.48	12.18	10.59	9.76	28.46	17.10
Standard deviatio	0.22	0.20	0.21	5.20	8.76	7.20

*Means followed by the same lowercase letter in the column and capital letter in the row do not differ by the F test at $p<0.05$. $^{+}$Significant difference between fertilized and control (T_{wf}) treatments.

The estimation of maximum economic efficiencies (MEE) of these indicators over the cropping seasons also showed a polynomial behavior according to green fertilizer amounts (Figure 4). The maximum values were BRL 75,542.52 and 44,352.89 ha^{-1} for gross and net income, respectively, and 2.60 and 59.67% for the rate of return and profit margin with 46.97, 41.55, 36.61, and 35.63 t ha^{-1} of green fertilizer biomass, respectively, later decreasing up to the highest amount of the tested fertilizers (Figures 4A, 4B, 4C, and 4D). These results partially agree with Silva et al. (2021), who fertilized a carrot tuberous crop with different doses of *C. procera* green fertilizers, obtaining economic efficiency indicators of BRL 62,704.94 and 33,744.07 ha^{-1} for gross and net incomes, and 2.27 and 56.63% for the rate of return and profit margin, respectively, with 47.60, 42.81, 31.69, and 31.85 t ha^{-1} of biomass from these fertilizers. Such findings show the economic efficiency of green fertilizers on the performance and development of tuberous crops such as carrot.

4. Discussion

Agronomic and production characteristics of sweet potato

The difference between cropping seasons within each amount of green fertilizers in the treatments tested for agronomic and productive characteristics of sweet potato is due to the improved soil and climate conditions of the first season compared to the second one. Climate conditions, such as higher temperatures, combined with lower rainfall in the last half of the first cycle and better soil nutrition in S1, were probably decisive for the better performance of the evaluated characteristics of sweet potato cultivation. However, the results of mean values of green fertilizers treatments (Tf) over the cropping seasons show the potential of green manuring, when correctly performed, to increase production and agronomic characteristics of sweet potatoes.

The optimized results of sweet potato agronomic and production characteristics, in the form of a polynomial model, can be attributed to the law of maximum, where the excess of a nutrient in the soil provided by the equitable amounts of *M. aegyptia* and *C. procera* may have had a toxic effect and/or reduced the effectiveness of other elements, resulting in the reduction of these characteristics under analysis after the maximum point (Almeida et al. 2015). However, it is known that larger fertilizer applications do not necessarily produce higher yields because excess tends to reduce the effectiveness of other elements and the plants' ability to grow and mature. Furthermore, the behavior of these characteristics may be related to the behavior of the tuberous crop, of the adequate synchrony between the decomposition and mineralization of the mixture of the green manures added to the soil and the time of greatest nutritional demand of the crop (Fontanétti et al. 2006).

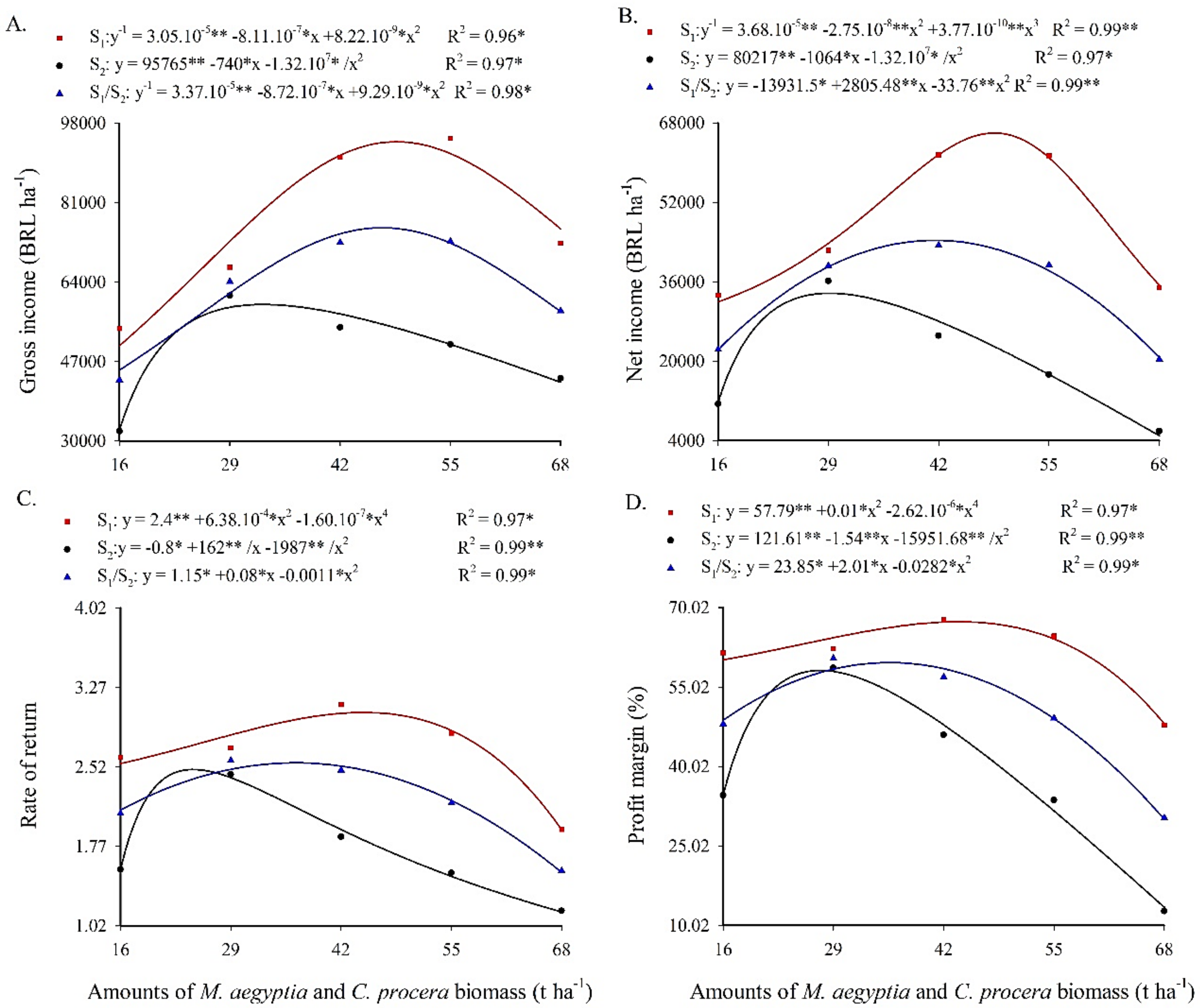

Figure 4. Gross income, net income, rate of return, and profit margin for sweet potato crops according to equal amounts of *M. aegyptia* and *C. procera* biomass incorporated into the soil in the 2021 and 2022 cropping seasons.

According to Fontanetti et al. (2006), the absorption of nutrients from the mineralization of green manure by vegetables depends, to a large extent, on the synchrony between the decomposition and mineralization of plant residues and of the time of greatest demand for the crop. In this way, the slow decomposition of green manure can present synchrony between the availability of nutrients such as phosphorus and nitrogen in sensitive periods for the culture, favoring its satisfactory development.

Economic performance of sweet potato

The rising economic indicators evaluated in sweet potatoes, with a decrease after the maximum point as a polynomial model according to equal amounts of *M. aegyptia* and *C. procera* biomass, are due to the satisfactory response of sweet potatoes to the incorporation of green fertilizers. However, these fertilizers improve fertility, increase soil organic matter content, decrease erosion rates, increase soil water retention, microbial activity, and soil nutrient availability, and reduce the number of invasive plants (Graham and Haynes 2006).

The maximum physical efficiency (MPE) obtained in the productive characteristics of sweet potatoes that received green fertilizers was translated into economic terms in all evaluated indicators, thus providing an optimized economic efficiency over the cropping seasons. These results allow sweet potato producers to choose the optimal green fertilizer amount for incorporation and the economic indicator that best suits them regarding commercial root yield.

Therefore, cultivating sweet potato with a mixture of the green fertilizers hairy woodrose and roostertree provides a financial return compatible with the invested capital, making it a viable alternative, especially for small producers without high investment capital.

5. Conclusions

Sweet potato fertilization aiming at the maximum optimized productive efficiency was possible by incorporating 46.97 t ha^{-1} of *M. aegyptia* and *C. procera* dry biomass into the soil. The maximum optimized agroeconomic efficiency (based on net income) of sweet potato cultivation was obtained by adding 41.55 t ha^{-1} of *M. aegyptia* and *C. procera* dry biomass to the soil. The rate of return and profit margin were BRL 2.60 for each Brazilian Real (BRL) invested, with a 59.67% profit margin. Using the biomass from *M. aegyptia* and *C. procera* green fertilizers is a viable technology for producers who practice sweet potato monocropping in semi-arid environments.

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