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Scientific Article

Productive and economic efficiency of beetroot fertilised with roostertree in a semi-arid environment

Eficiência produtiva e econômica de beterraba adubada com flor-de-seda em ambiente semiárido

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ABSTRACT - The use of spontaneous species from the northeastern semi-arid region can be a viable alternative in the practice of fertilising tuberous vegetables. Therefore, the objective of this work was to evaluate the maximum physical and economic efficiencies of the agroeconomic characteristics of beetroot in monocropping as a function of different biomass amounts of roostertree (*Calotropis procera*) in two cultivations. The experimental design used was randomised blocks with five treatments and five replications. The treatments consisted of the amounts of roostertree biomass incorporated into the soil: 16, 29, 42, 55 and 68 t ha^{-1} on a dry basis. In each block of the experiments, two additional treatments were added, one without fertilisation (control treatment) and the other with mineral fertilisation, for comparison purposes with the treatment of maximum physical or economic efficiency. The beetroot cultivar planted was Early Wonder. The fertilisation of beetroot to obtain the maximum optimised productive efficiency (36.14 t ha^{-1}) was possible with the incorporation of 61.29 t ha^{-1} of dry *C. procera* biomass into the soil. The maximum optimised agroeconomic efficiency (based on a net income of 68,740.15 BRL ha^{-1}) of beetroot cultivation was obtained with an amount of 58.68 t ha^{-1} of dry *C. procera* biomass added to the soil. The rate of return obtained was 2.91 BRL for each real invested, and the profit margin was 74.93%.

Keywords: *Beta vulgaris*. *Calotropis procera*. Monocropping. Green manuring. Agro-economic optimisation.

RESUMO - A utilização de espécies espontâneas do semiárido nordestino pode ser uma alternativa viável na prática da adubação em hortaliças tuberosas. Portanto, o objetivo desse trabalho, foi avaliar as máximas eficiências físicas e econômicas das características agroeconômicas da beterraba em monocultivo, em função de diferentes quantidades de biomassa de flor-de-seda (*C. procera*) em dois cultivos. O delineamento experimental utilizado foi blocos casualizados com cinco tratamentos e cinco repetições. Os tratamentos consistiram das 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 adicionais, um sem adubação (tratamento controle) e outro com adubação mineral, para fins de comparação com o tratamento de máxima eficiência física ou econômica. A cultivar de beterraba plantada foi a Early Wonder. A adubação da beterraba para obtenção da máxima eficiência produtiva otimizada (36,14 t ha^{-1}) foi possível com a incorporação ao solo de 61,29 t ha^{-1} de biomassa seca de *C. procera*. A máxima eficiência agroeconômica otimizada (baseada na renda líquida de 68.740,15 R$ ha^{-1}) do cultivo da beterraba foi obtida com a quantidade de 58,68 t ha^{-1} de biomassa seca de *C. procera* adicionada ao solo. A taxa de retorno obtida foi de R$ 2,91 para cada real investido e a margem de lucro foi de 74,93%.

Palavras-chave: *Beta vulgaris*. *Calotropis procera*. Monocultivo. Adubação verde. Otimização agroeconômica.

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INTRODUCTION

Beetroot (*Beta vulgaris* L.) is a tuberous vegetable belonging to the Amaranthaceae family, with a cycle that varies from 60 to 100 days, and it has a markedly sweet taste (BOVI et al., 2019). It is rich in sugars, vitamins C and B complex (B1, B2 and B5), and nutrients, such as potassium, sodium, iron, copper and zinc (SILVA et al., 2019). It also contains phenolic compounds, flavonoids and anthocyanins, which are important antioxidant compounds capable of fighting oxidative stress, acting directly against oxygen-derived free radicals (RAMOS et al., 2016). In addition to its roots, its leaves can also be consumed.

In the Brazilian Northeast, beetroot production is still not very expressive; that is, there is not enough production to meet the demand of the domestic market throughout the year, hence the need to import from other states (LINO et al., 2021a). This vegetable has been cultivated in a conventional way with the intensive use of mineral fertilisers and pesticides, seeking to increase productivity and quality. However, the intensive use of these products has affected the environment, in addition to making the production system more expensive. A new alternative has emerged with the use of spontaneous species from the Caatinga biome as green manure in the production of tuberous crops, thus improving crop quality and production (SILVA et al., 2017; LINO et al., 2021b). Among them is the roostertree (*Calotropis procera* (Ait.) R.Br.), popularly known in the Brazilian Northeast, with several names according to the regions of Brazil, including silk cotton, beach cotton, milkmaid, silkworm, old man's bag, milkman, burner, balloon foot, janaúba and jealousy.

This plant species is of shrub or subshrub size, reaching 3.5 m in height, erect and perennial with few branches. It is a fast-growing species that requires only 90 days after germination to reach a height greater than 50 cm and to produce its first flowers (RANGEL; NASCIMENTO, 2011). This plant, in addition to being very prolific, has the capacity to supply phytomass throughout the year, even in times of drought, giving it a prominent position in relation to several native and naturalised species of the Caatinga. Its tissues have high concentrations of N, P and K, reaching values around 15.1, 3.0 and 24.8 g kg^{-1}, respectively (FERREIRA et al., 2022). Its first tests on some tuberoses and hardwoods have shown promising results as green manure (OLIVEIRA et al., 2015; SILVA et al., 2017; SILVA et al., 2018).

One of the great challenges in the production of tuberous vegetables is defining an optimised quantity that provides a high productive yield with the economic efficiency of the production system. Faced with the lack of results in the cultivation of beetroot fertilised with roostertree in a semi-arid environment, the present work aimed to evaluate and estimate the maximum physical and economic efficiencies of the production of beetroot in monocropping and of its components as a function of different amounts of roostertree biomass in the two cultivations.

MATERIAL AND METHODS

Field experiments were carried out from October to December 2021 and from September to November 2022 at the Experimental Farm ‘Rafael Fernandes’, belonging to the Universidade Federal Rural do Semi-Árido (UFERSA), located in the district of Lagoinha, 20 km from the municipality of Mossoró, RN, at the geographical coordinates of 5° 03’ 37” south latitude, 37° 23’ 50” west longitude, and an approximate altitude of 80 m.

The climate of the region, according to the Köppen classification is ‘BShw’, dry and very hot, with two distinct seasons: a dry season, which usually occurs from June to January, and a rainy season from February to May (BECK et al., 2018). During the period of beetroot development and growth, the average meteorological data recorded are presented in Table 1 (LABIMC, 2022).

The average temperature and average daily air relative humidity data after beetroot sowing during the two cultivations are shown in Figure 1.

Table 1. Average meteorological data during the development and growth periods of beetroot in the 2021 and 2022 cultivations.

Cultivation	Temperature (°C)			Relative humidity (%)	Solar radiation (MJ m^{-2})	Wind speed (m s^{-1})
	Minimum	Mean	Maximum			
2021	23.32	29.90	36.48	67.60	274.80	2.80
2022	22.53	29.38	36.23	62.87	256.41	1.71

Fonte: LABIMC (2022).

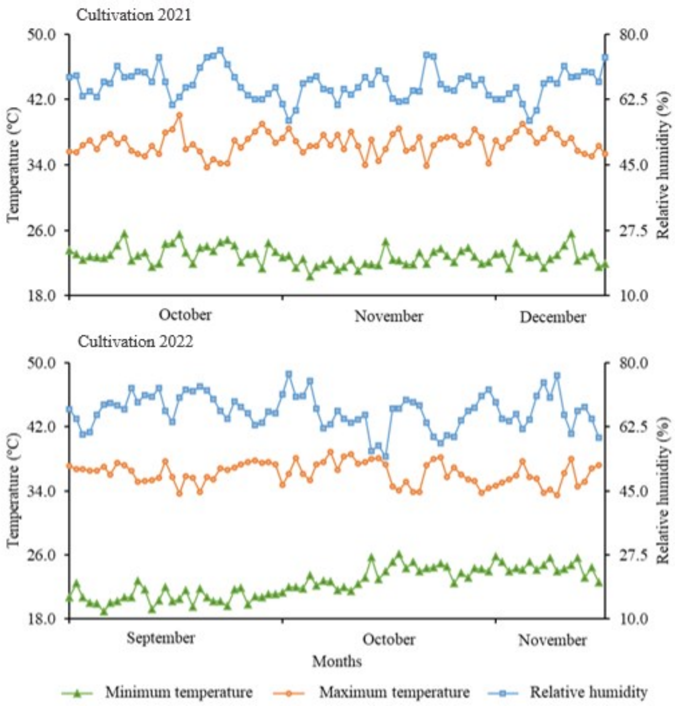

Figure 1. Data on daily averages of temperatures and air relative humidity during beetroot cultivation in 2021 (S1) and 2022 (S2).

The soils of the experimental areas are classified as dystrophic Red-yellow Argisol with a sandy loam texture (SANTOS et al., 2018). In each experimental area, simple soil samples from the 0-20 cm surface layer were collected and homogenised to obtain a composite sample representative of the area. 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, whose analysis results are shown in Table 2.

Table 2. Chemical analyses of the soils of the experimental areas before incorporation of green manure in the first and second cultivations.

Cultivation	C	OM	pH	CE	P	K^+	Ca^{2+}	Mg^{2+}	Na^+	Cu	Fe	Mn	Zn	B
	------ $g\ kg^{-1}$ ------		(H_2O)	$dS\ m^{-1}$	$mg\ dm^{-3}$	------------------------------- $mmol_c\ dm^{-3}$ -------------------------------								
2021	7.92	12.97	6.60	0.56	32.00	2.59	23.70	6.50	2.30	0.30	4.80	6.10	2.70	0.50
2022	7.20	12.41	7.10	0.19	7.00	1.16	20.10	6.10	0.43	0.20	6.80	12.70	1.70	0.48

C: Carbon; OM: Organic matter; pH: Hydrogenionic potential; EC: Electrical conductivity; P: Phosphorus; K^+: Potassium; Ca2+: Calcium; Mg2+: Magnesium; Na^+: Sodium; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc; B: Boron.

For soil preparation, the area was mechanically cleaned with the aid of a tractor with a coupled plough, followed by harrowing and mechanised lifting of the beds. Subsequently, pre-planting solarisation was carried out with transparent plastic Vulca type Bril Flex gloss of 30 microns for 30 days following the methodology recommended by Pereira et al. (2016) to combat nematodes and phytoparasites in the 0-20 cm layer of the soil, which could impair crop productivity.

The experimental design used in the research was randomised complete blocks, with five treatments and five replications. The treatments consisted of amounts of roostertree (*Calotropis procera*) biomass at doses of 16, 29, 42, 55 and 68 t ha^{-1}, on a dry basis. In each experiment, two additional treatments were used, one without fertiliser (absolute control) and the other fertilised with mineral fertiliser, for the purpose of comparison with the treatment of maximum physical and economic efficiency.

The treatment with mineral fertilisation in the foundation consisted of the application of 32, 190 and 64 kg ha^{-1} N, P_2O_5 and K_2O, respectively, in topdressing after 20 days of foundation fertilisation with 32 kg ha^{-1} of N and 64 kg ha^{-1} of K_2O, and in topdressing after 40 days of foundation fertilisation with 32 kg ha^{-1} of N (HOLANDA et al., 2017). The following commercial fertilisers were used: urea: 45% N; monoammonium phosphate (MAP): 54% P_2O_5 and 12% N; and potassium chloride (KCl): 60% K_2O.

The experimental plot area was 1.20 m × 1.20 m = 1.44 m^2, with a harvest area of 0.80 m × 1.00 m = 0.80 m^2. Each experimental plot consisted of six rows of beetroot with 12 plants per row. The harvest area consisted of four central rows of plants, excluding an external row on each side and the last plants of each row, used as borders, containing a total of 40 plants per plot (Figure 2).

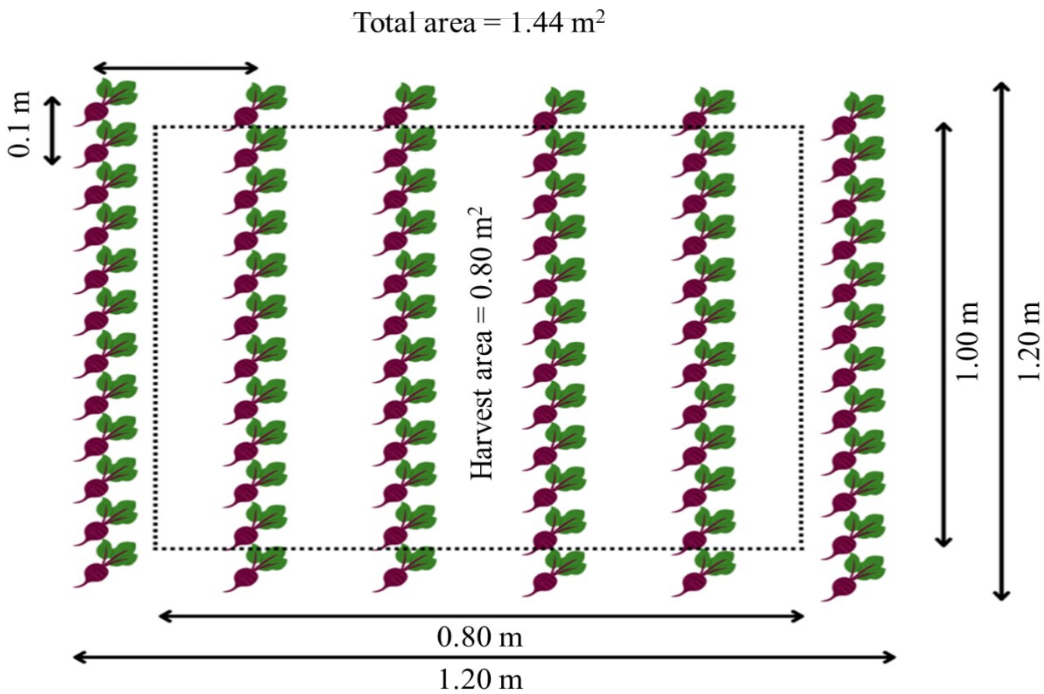

Figure 2. Graphic representation of an experimental plot of beetroot as a monocrop planted at a spacing of 0.20 × 0.10 m.

The roostertree (*Calotropis procera*) used as green manure was collected in the rural area of the municipality of Mossoró, RN, when they were in the flowering period, which coincides with greater accumulation of fresh matter. After collection, the plants were ground in a conventional forage machine, obtaining fragmented particles of around 2.0-3.0 cm, and dehydrated in the sunlight for 4-7 days until reaching a moisture content of 10%. From this material, samples were taken and sent for laboratory analysis. Their chemical composition was as follows: N = 18.40 g kg^{-1}; P = 3.10 g kg^{-1}; K = 24.50 g kg^{-1}; Ca = 16.30 g kg^{-1}; Mg = 13.50 g kg^{-1}; and C:N ratio = 27:1.

The amounts of green roostertree biomass were incorporated into the soil manually with the aid of hoes in the 0-20 cm soil layer in the experimental plots, following the amounts specified in the treatments, in the following proportion: 30% green manure biomass was incorporated 20 days before sowing (DBS) and the remaining 70% was incorporated 20 days after sowing (DAS), as recommended by Bezerra Neto et al. (2019).

The beetroot cultivar planted was ‘Early Wonder’, which is a large foliage plant of 45-65 cm in height, erect, with a smooth, intense red root measuring 6-8 cm in diameter, recommended for the semi-arid conditions of the Brazilian Northeast.

Sowing was carried out in September 2021 in the first cultivation (S1) and in August 2022 in the second cultivation (S2), in holes approximately 3 cm deep, with 3-4 seeds per hole covered with commercial substrate. Thinning was performed 8 days after sowing (DAS) in S1 and S2, leaving one plant per hole. Weeding was performed manually whenever necessary.

Irrigation was carried out using a micro sprinkler system, with a daily irrigation shift divided into two applications (morning and afternoon), providing a water depth of approximately 8 mm per day, according to the recommendations for beetroot (OLIVEIRA NETO et al., 2011), to maintain soil moisture between 50 and 70% of field capacity and meet the need for microorganisms, together with the low C:N ratio of green manure, favouring mineralisation processes of organic matter.

The harvest was carried out in December 2021 at 72 DAS for S1 and in November 2022 at 72 DAS for S2, proceeding with the evaluations in the post-harvest laboratory of vegetables of the plant science department of UFERSA, where the following characteristics of the culture were evaluated: plant height (cm), number of leaves per plant, fresh and dry shoot mass (t ha^{-1}), dry root mass (t ha^{-1}), total and commercial productivity of roots (t ha^{-1}), and classified productivity of roots according to the diameter (DR). DR was classified as follows: extra (DR > 4 and < 5 cm), extra A (DR > 5 and < 6 cm), extra AA (DR > 6 and < 7 cm) and large (DR > 7 cm). Cracked, bruised, bifurcated roots or roots smaller than 4 cm were classified as scraps (SILVA et al., 2019).

The following economic indicators were evaluated: gross income (GI), expressed in BRL ha^{-1} (obtained by multiplying the commercial root productivity of beetroot in each treatment by the value of the product paid to the producer in the region in December 2022, of BRL 2.59 per kilogram); net income (NI), expressed in BRL ha^{-1} (obtained by subtracting treatment production costs from the gross income from inputs and services performed in each treatment); rate of return (RR) per real invested (obtained through the relationship between gross income and production costs of each treatment); and profit margin (PM), obtained from the relationship between net income and gross income, expressed as a percentage.

The production costs calculated in each treatment were obtained based on the cost and service coefficients used in one hectare of beetroot, considering the total expenses made by the producer during the production process per hectare of cultivated area, covering the services provided by stable and circulating capital. The variable costs incurred were with inputs, labour, energy, other expenses, and maintenance and conservation of equipment used. The fixed costs incurred were depreciation, taxes and fees, and fixed labour, and the opportunity costs were land remuneration and fixed capital remuneration (Table 3).

Table 3. Costs of beetroot production at amounts of green manure and in the treatment with mineral fertiliser in the two cultivations.

Treatments (t ha^{-1})	(VC) BRL ha^{-1}					(FC) BRL ha^{-1}			(OC) BRL ha^{-1}		TC (BRL ha^{-1})
	I	L	E	OE	MC	D	TF	FHL	LR	RFC	
0	2520.00	3180.00	29.89	57.30	445.83	1864.73	10.00	1100.00	100.00	896.43	10,204.20
16	2520.00	6610.00	94.41	92.24	544.33	1866.19	10.00	1100.00	100.00	1014.63	13,951.81
29	2520.00	9480.00	151.26	121.51	544.33	1872.97	10.00	1100.00	100.00	1014.63	16,914.70
42	2520.00	12,220.00	208.11	149.48	544.33	1872.97	10.00	1100.00	100.00	1014.63	19,739.51
55	2520.00	15,090.00	264.96	178.75	544.33	1872.97	10.00	1100.00	100.00	1014.63	22,695.63
68	2520.00	17,830.00	321.81	206.72	544.33	1872.97	10.00	1100.00	100.00	1014.63	25,520.45
MF	11,503.32	3180.00	29.89	147.13	445.83	1864.73	10.00	1100.00	100.00	896.43	19,277.35

VC - Variable costs: I – Inputs, L – Labor, E – Energy, OE - Other expenses and MC - Maintenance and conservation; FC - Fixed costs: D – Depreciation, TF - Taxes and fees and FHL - Fixed hand labour; OC - Opportunity costs: LR - Land remuneration and RFC - Remuneration of fixed capital; TC - Total costs and MF – Mineral fertiliser.

Univariate analyses of variance for a complete randomised block design were performed to evaluate the agronomic characteristics and economic indicators of beetroot using SAS software. A joint analysis of these variables was also carried out to determine whether there was an interaction between the treatments tested and the crop cultivations. Subsequently, a regression curve fitting procedure was performed using Table Curve software (SYSTAT SOFTWARE, 2022) to estimate the behaviour of each characteristic or indicator as a function of the amounts of *C. procera* biomass studied, based on the following criteria: in the biological logic (BL) of the variable, that is, when it is found that there is no increase in the variable after a certain fertiliser dose; 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 maximisation of the variable. The F test was used to compare the average values between the cultivations, between the average valuesof maximum agronomic and economic efficiency, between the average value of the treatment fertilised with green manure, and between the average value of the treatment fertilised with mineral fertiliser and the mean value of the control treatment (not fertilised).

RESULTS AND DISCUSSION

Beetroot agronomic characteristics performance

Table 4 describes the analyses of variance of the agronomic characteristics of beetroot: plant height, number of leaves per plant, and shoot and root dry mass. These characteristics showed significant interactions ($p<0.05$) between tested treatment factors: fertilised treatments and cultivations.

Table 4. Mean values of the control treatment (T_c), maximum physical efficiency (MPE), green manure treatments (T_{gm}) and mineral fertiliser (T_{mf}) for plant height, number of leaves per plant, and for mass dry of shoots and roots of beet in the cultivations of 2021 (S1) and 2022 (S2).

Comparison betweenmean values	Cultivation			Cultivation		
	2021 (S1)	2022 (S2)	2021–2022 (S1/S2)	2021 (S1)	2022 (S2)	2021–2022 (S1/S2)
	Plant height (cm)			Number of leaves per plant		
Control treatment mean, T_c	26.08dA	20.67dB	23.37	7.07bA	6.09bB*	6.58
MPE value	39.10aA	40.53aA	39.34+	9.02aA	7.35aB	8.20+
Green manured treatment mean, T_{gm}	37.39bA	34.97bB	36.18+	8.30aA	7.02aB	7.66+
Mineral treatment mean, T_{mf}	30.53cA	26.26cB	28.40+	7.33bA	6.59bB	6.96+
CV (%)	3.62	2.80	3.36	7.78	3.22	6.29
	Dry shoot mass (t ha^{-1})			Dry root mass (t ha^{-1})		
Control treatment mean, T_c	1.11cA	0.77dB	0.94	1.42cA	1.23dA	1.33
MPE value	2.14aB	2.29aA	2.18+	3.85aB	5.21aA	4.52+
Green manured treatment mean, T_{gm}	1.90bA	1.70bB	1.80+	3.11aB	3.96bA	3.54+
Mineral treatment mean, T_{mf}	1.19cB	1.44cA	1.32+	2.43bA	2.28cB	2.36+
CV (%)	7.31	13.67	8.56	16.64	17.06	16.96

*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 green manure treatments, MPE or mineral treatment is significantly different from the control treatment mean by the F-test at the 5% probability level.

S1 differed from S2 in all fertilised treatments in terms of plant height and number of leaves per plant, except for the MPE value for plant height, where the cultivations behaved similarly. For shoot dry mass, S1 also differed from S2 in the control (T_c) and green manure treatments (T_{gm}), while in terms of the maximum physical efficiency (MPE) value and mineral fertiliser treatment (T_{mf}), cultivation S2 outperformed S1. For dry root mass, cultivation S1 surpassed S2 in T_{mf}, while in the value of MPE and in T_{gm}, S2 differed from S1. In T_c, there was no significant difference between the cultivations (Table 4). These differences between cultivations were due to the small differences between the soil fertility levels of the experimental areas (slightly better soil fertility levels from the 2021 cultivation).

The MPE values of T_{gm} and T_{mf} differed significantly from T_c in the following agronomic characteristics: plant height, number of leaves per plant, and dry shoot and root mass (Table 4). The mean values for these characteristics in the two cultivations were 1.7, 1.2, 2.3, and 3.4 times the values of the control treatment. These results suggest the potential of green manuring, when performed correctly, to increase beetroot agronomic characteristics.

Evaluating the green manure amounts within each cultivation (S) for plant height, number of leaves per plant, and dry shoot and root mass, an increasing polynomial behaviour was observed as a result of the increase in the amount of *C. procera* biomass incorporated into the soil, both in S1 and S2, as well as in both cultivations (Figure 3).

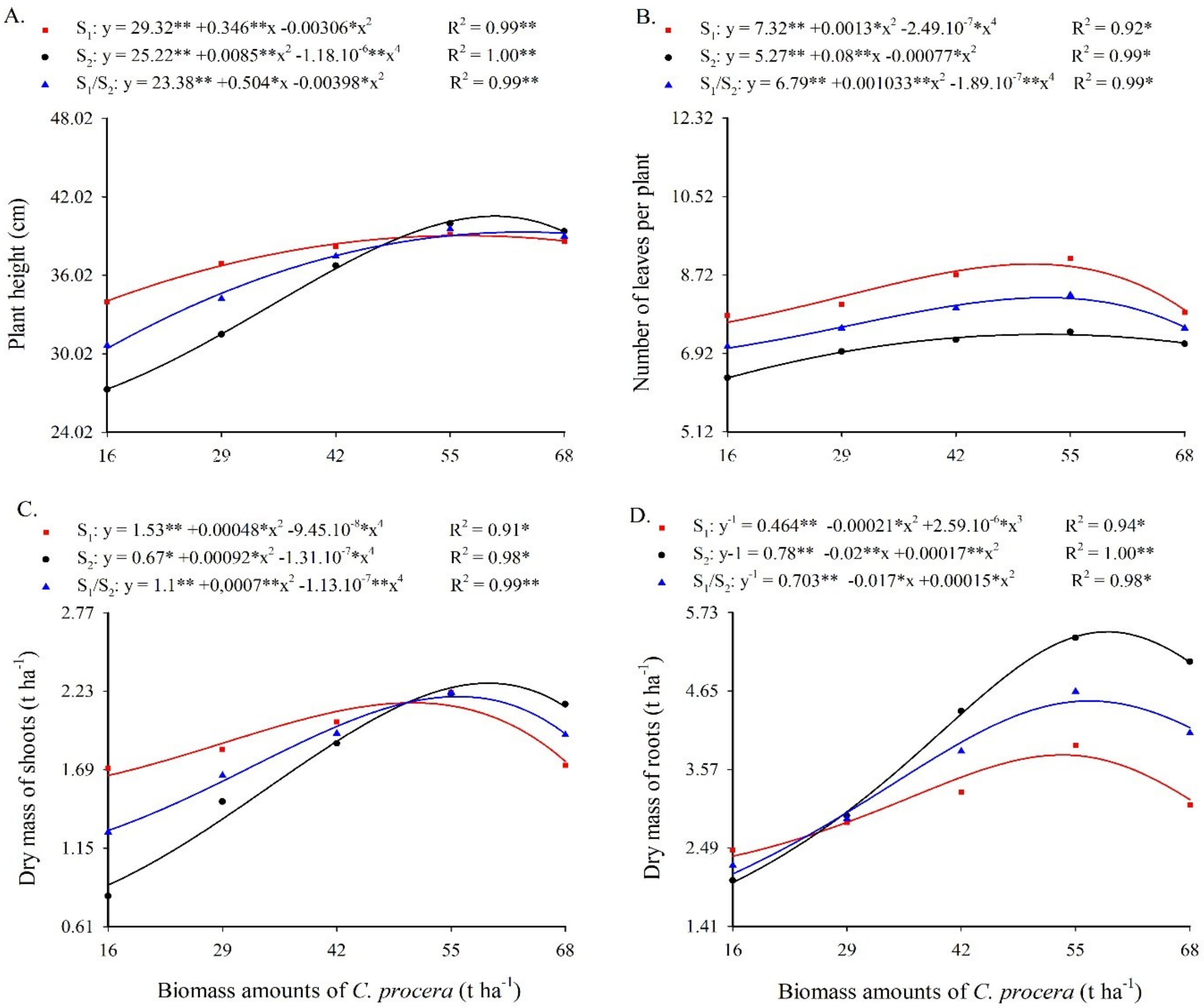

Figure 3. Plant height (A), number of leaves per plant (B), dry shoot mass (C) and dry root mass (D) of beet as a function of increasing amounts of *Calotropis procera* biomass incorporated into the soil in the cultivations in 2021 (S1) and 2022 (S2).

The maximum values of the physical efficiency of these characteristics were 39.10 and 40.53 cm in plant height, 9.02 and 7.35 in the number of leaves per plant, 2.14 and 2.29 t ha^{-1} in the dry shoot mass, and 3.85 and 5.21 t ha^{-1} in the dry root mass for S1 and S2, respectively. For the amounts of *C. procera* biomass, these values were 56.40 and 60.08; 50.69 and 51.99; 50.57 and 59.24; and 53.49 and 58.63 t ha^{-1} for S1 and S2, respectively (Figure 3). However, they decreased until the last biomass amount of the fertiliser incorporated. The maximum physical efficiencies over the two cultivations registered the same increasing polynomial behaviour due to the increase in the amounts of green manure up to the maximum values of 39.34 cm for plant height, 8.20 for the number of leaves per plant, 2.19 for the dry shoot mass, and 4.521 for the dry root mass. For the respective amounts of green manure, these values were 63.30, 52.25, 55.80 and 56.58 t ha^{-1}, decreasing until the last tested green manure dose (Figures 3A, 3B, 3C and 3D).

The optimised results of the agronomic characteristics of beetroot in the form of a polynomial model can be attributed to the maximum law, in which the excess nutrient in the soil provided by amounts of *C. procera* can have a toxic effect and/or reduce the effectiveness of other elements, decreasing these characteristics analysed after the maximum point (ALMEIDA et al., 2015). Higher applications of green fertiliser do not necessarily produce higher agronomic traits because excess fertiliser tends to reduce the effectiveness of other elements and the ability of plants to grow and mature. In addition, the behaviour of these characteristics may be related to the behaviour of the tuberous crop, the appropriate synchronism between the decomposition and mineralisation of the green manure added to the soil, and the moment of greater nutritional demand of the crop (FONTANÉTTI et al., 2006).

Beetroot productive characteristics performance

The analyses of variance of the productive characteristics of beetroot, namely total and commercial productivity of roots, productivity of large + extra AA roots, productivity of extra A roots, productivity of extra roots and productivity of scrap roots, are presented in Table 5. Significant interactions ($p<0.05$) were observed between treatment factors, tested fertilised treatments and cultivations in these characteristics.

Table 5. Mean values of the control treatment (T_c), maximum physical efficiency (MPE), green manure treatments (T_{gm}) and mineral fertiliser (T_{mf}) for the total productivity of roots, commercial productivity of roots, productivity of large + extra AA roots, productivity of extra A roots, productivity of extra roots and productivity of beet scrap roots in the cultivations in 2021 (S1) and 2022 (S2).

Comparison between mean values	Cultivation			Cultivation		
	2021 (S1)	2022 (S2)	2021–2022 (S1/S2)	2021 (S1)	2022 (S2)	2021–2022 (S1/S2)
	Total productivity of roots (t ha^{-1})			Commercial productivity of roots (t ha^{-1})		
Control treatment mean, T_c	10.01dA	9.70dA	9.86	7.58dA	6.12dA	6.85
MPE value	30.62aB	46.84aA	37.38$^+$	29.98aB	44.27aA	36.44$^+$
Green manured treatment mean, T_{gm}	26.43bB	35.48bA	30.96$^+$	25.27bB	31.34bA	28.31$^+$
Mineral treatment mean, T_{mf}	21.19cB	24.09cA	22.64$^+$	19.44cA	20.68cA	20.06$^+$
CV (%)	7.36	5.71	6.33	7.05	4.67	5.68
	Productivity of large + extra AA roots (t ha^{-1})			Productivity of extra A roots (t ha^{-1})		
Control treatment mean, T_c	2.10dA	1.41dA	1.76	2.51bA	1.68cB	2.10
MPE value	22.13aB	35.95aA	28.17$^+$	5.44aA	3.42bB	4.39$^+$
Green manured treatment mean, T_{gm}	17.13bB	24.02bA	20.58$^+$	5.26aA	3.22bB	4.24$^+$
Mineral treatment mean, T_{mf}	7.76cB	10.31cA	9.04$^+$	5.66aA	4.46aB	5.06$^+$
CV (%)	8.53	6.65	6.99	11.25	18.12	13.73
	Productivity of extra roots (t ha^{-1})			Productivity of scrap roots (t ha^{-1})		
Control treatment mean, T_c	2.96bA	3.03cA*	3.00	2.43aB	3.58aA	3.01
MPE value	2.94bB	4.23bA	3.58$^+$	2.00aB	3.74aA	2.88
Green manured treatment mean, T_{gm}	2.88bB	4.09bA	3.49$^+$	1.12aB	3.25bA	2.18$^+$
Mineral treatment mean, T_{mf}	6.02aA	5.91aA	11.93$^+$	1.75aB	3.02bA	2.39$^+$
CV (%)	16.17	15.80	16.06	35.32	20.51	25.35

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

S1 differed from S2 in all treatments tested for the productivity of extra A roots. These differences between cultivations were probably due to the slightly better soil fertility levels in the 2021 cultivation. The opposite behaviour was observed in the productivity of scrap roots. In terms of total and commercial productivity of roots, productivity of large + extra AA roots, and productivity of extra roots, S2 differed from S1, except in T_c, where they were similar (Table 5).

The mean values for MPE from T_{gm} and T_{mf} differed significantly from T_c in the productive characteristics of beetroot over cultivations (Table 5). The mean MPE values in the two cultivations were approximately 3.8, 5.3, 16, 2.1, 1.2 and 0.9 times the values of the control treatment for the total productivity of roots, commercial productivity of roots, productivity of large + extra AA roots, productivity of extra A roots, productivity of extra roots and productivity of scrap roots, respectively. These results show the effect of green manuring, when performed correctly, in increasing the agronomic characteristics of beetroot. Green manure has the following effects on soil fertility: increased organic matter content; greater nutrient availability; highest effective cation exchange capacity (t) of the soil; favours organic acid production, which is of fundamental importance for mineral solubilisation; reduction in exchangeable Al levels through its complexation; and an increase in the recycling and mobilisation capacity of leached or poorly soluble nutrients that are in the deeper layers of the profile.

Analysing the behaviour of the green manure amounts applied in each cultivation (S), an increasing polynomial behaviour was observed both in the first (S1) and second (S2) cultivations, up to the maximum values of 30.62 and 46.84 t ha^{-1} in the total root productivity, 29.98 and 44.27 t ha^{-1} in the commercial root productivity, 22.13 and 35.95 t ha^{-1} in the productivity of large + extra AA roots, 5.44 and 3.42 t ha^{-1} in the productivity of extra A roots, 2.94 and 4.23 t ha^{-1} in productivity of extra roots, and 2.00 and 3.74 t ha^{-1} in the productivity of scrap roots. For the respective biomass amounts, these values were 52.60 and 63.40; 53.35 and 63.23; 53.70 and 64.97; 48.78 and 54.89; 44.21 and 50.97; and 16.00 and 16.00 t ha^{-1} of *C. procera*. These values then decreased until the highest dose of green manure was incorporated into the soil (Figures 4A, 4B, 4C, 4D, 4E and 4F).

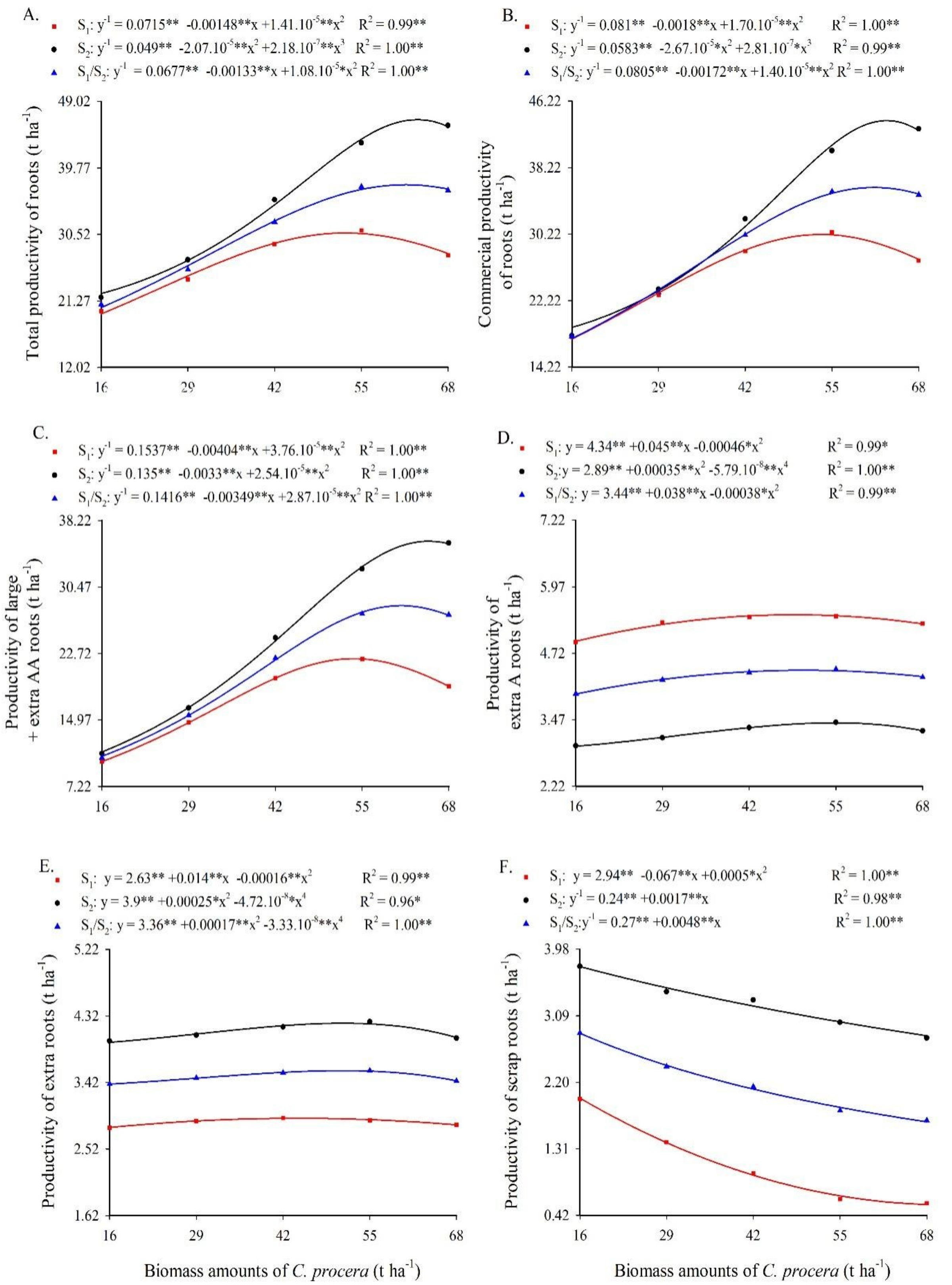

Figure 4. Total productivity of roots (A), commercial productivity of roots (B), productivity of large + extra AA roots (C), productivity of extra A roots (D), productivity of extra roots (E) and productivity of beet scrap roots (F) as a function of increasing amounts of *Calotropis procera* biomass incorporated into the soil in the 2021 (S1) and 2022 (S2) cultivations.

Estimating the values of maximum physical efficiency of these productive characteristics over the cultivations, an increasing polynomial behaviour was observed as a function of the increase in the amount of green manure up to the amounts of 37.38 t ha^{-1} for the total productivity of roots, 36.14 t ha^{-1} for the commercial productivity of roots, 28.17 t ha^{-1} for the productivity of large + extra AA roots, 4.39 t ha^{-1} for the productivity of extra A roots, 3.58 t ha^{-1} for the productivity of extra roots and 2.88 t ha^{-1} for the productivity of scrap roots in the biomass amounts of 61.64, 61.29, 60.82, 50.29, 50.86 and 16.00 t ha^{-1} of *C. procera*, respectively. These values then decreased to the highest amount of fertiliser tested (Figures 4A, 4B, 4C, 4D, 4E and 4F)

The progressive increase and observed optimisation (MPE values) of the agronomic and productive characteristics of beetroot in an increasing polynomial model could be directly linked with the nutritional availability, mainly of N, P and K, released by the *C. procera* biomass, in addition to the improvement of the chemical, physical and biological attributes of the soil (BATISTA et al., 2016). The decomposition and mineralisation of this fertiliser was probably influenced by the C:N ratio, thus promoting a fast mineralisation rate for nutrients, being absorbed by the plant and supplying its nutritional requirements (LINHARES et al., 2022).

The polynomial models tested in the agronomic and productive characteristics of the beetroot plants met the selection criteria and regression adjustment used to express the behaviour of each evaluated characteristic, where the increase in the availability of nutrients was due to the increase in the fertiliser biomass amount added to the soil, resulting in greater plant height, number of leaves per plant, dry root and shoot mass, total and commercial productivity of roots, productivity of large + extra AA roots, productivity of extra A roots and productivity of extra roots up to a maximum value, which then decreased after the last fertiliser application amount.

The significant results of treatments with green manure and mineral fertiliser in relation to the control treatment may be related to the physical, chemical and biological benefits capable of improving the conditions for beetroot growth and development. The MPEs from the green manure treatments (in both cultivations) for the total and commercial productivities of roots were higher than the average productivity in Brazil of 35 t ha^{-1} of beetroots (IBGE, 2017).

The present results denote the efficiency of green manuring in providing sufficient nutrient levels for the demand required by beetroot crops. The nitrogen concentration acts directly on the growth and development of the plant, both in the shoots (increasing the number of leaves) and in the root system (increasing the size of the roots). Potassium acts directly in the regulation of water absorption and translocation of nutrients and photosynthesis, and phosphorus acts in root system development and sugar metabolism (REETZ, 2017).

Beetroot economic performance

The results of the analyses of variance of the beetroot economic indicators, namely gross income, net income, rate of return and profit margin, are presented in Table 6. The production costs of beetroot in each treatment tested at the various stages of the implementation and development of the crop are described in Table 3. This production cost structure considered the actual disbursements made by the producer during the production cycle, including labour expenses work, repairs and maintenance of machines, implements and specific improvements, operations of machines and implements, inputs, and the value of depreciation of machines, implements and specific improvements used in the production process. Significant interactions were detected ($p<0.05$) between treatment factors, fertilised treatments, and cultivations for the evaluated economic indicators (Table 6).

Table 6. Mean values of the control treatment (T_c), maximum economic efficiency (MEE), green manure treatment (T_{gm}) and mineral fertiliser (T_{mf}) for gross income, net income, rate of return and profit margin of beetroot in the cultivations in 2021 (S1) and 2022 (S2).

Comparison between mean values	Cultivation			Cultivation		
	2021 (E1)	2022 (E2)	2021–2022 (E1/E2)	2021 (E1)	2022 (E2)	2021–2022 (E1/E2)
	----------- Gross Income (RS ha^{-1}) -----------			----------- Net Income (RS ha^{-1}) -----------		
Control treatment mean, T_c	19,619.97dA	15,840.44dB*	17,730.00	9415.00dA	5636.00dB	7525.50
MEE value	78,271.77aB	111,343.61aA	92,702.39$^+$	55,561.73aB	86,214.76aA	68740.15$^+$
Green manured treatment mean, T_{gm}	65,457.62bB	81,175.78bA	73,316.70$^+$	45,693.20bB	61,411.36bA	53552.28$^+$
Mineral treatment mean, T_{mf}	50,357.75cA	53,550.84cA	51,954.50$^+$	31,080.00cA	34,273.00cA	32676.5$^+$
CV (%)	5.08	2.37	4.13	7.29	3.27	5.85
	---------------- Rate of return ----------------			---------------- Profit margin (%) ----------------		
Control treatment mean, T_c	1.92dA	1.55dB	1.74	47.92dA	34.97dB	41.45
MEE value	3.65aB	4.57aA	4.04$^+$	72.73aB	78.58aA	74.93$^+$
Green manured treatment mean, T_{gm}	3.35bB	4.02bA	3.68$^+$	69.74bB	74.75bA	72.25$^+$
Mineral treatment mean, T_{mf}	2.61cA	2.78cA	5.39$^+$	61.62cA	63.96cA	62.79$^+$
CV (%)	4.75	3.00	4.09	2.73	2.24	3.62

*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 green manure treatments, MPE or mineral treatment is significantly different from the control treatment mean by the F-test at the 5% probability level.

In relation to each tested treatment, S2 differed from S1 for these indicators, except in the control treatment, where it presented an inverse behaviour, and in the mineral fertiliser, where the cultivations behaved similarly. The means of the maximum economic efficiency (MEE) of the treatments with T_{gm} and T_{mf} differed statistically from T_c in all the evaluated economic indicators of beetroot in the two cultivations (Table 6).

Mean MEE values in the two cultivations for these indicators of gross income, net income, rate of return and profit margin were approximately 5.2, 9.1, 2.3 and 1.8 times the values of the control treatment, respectively (Table 6).

Studying the green manure amounts within each cultivation, an increasing polynomial behaviour was observed in S1 and S2, up to the maximum values of 78.271.77 (S1) and 111.343.61 (S2) BRL ha^{-1} in gross income; 55.561.73 (S1) and 86.214.76 (S2) BRL ha^{-1} in net income; 3.65 (S1) and 4.57 (S2) BRL for each real invested in the rate of return; and 72.73 (S1) and 78.58% (S2) in the profit margin in the biomass amounts from 53.39 and 65.21; 49.63 and 64.35; of 37.27 and 57.93, and 42.95 and 58.36 t ha^{-1} of *C. procera*, respectively. These values decreased until the highest green manure amount incorporated into the soil (Figures 5A, 5B, 5C and 5D).

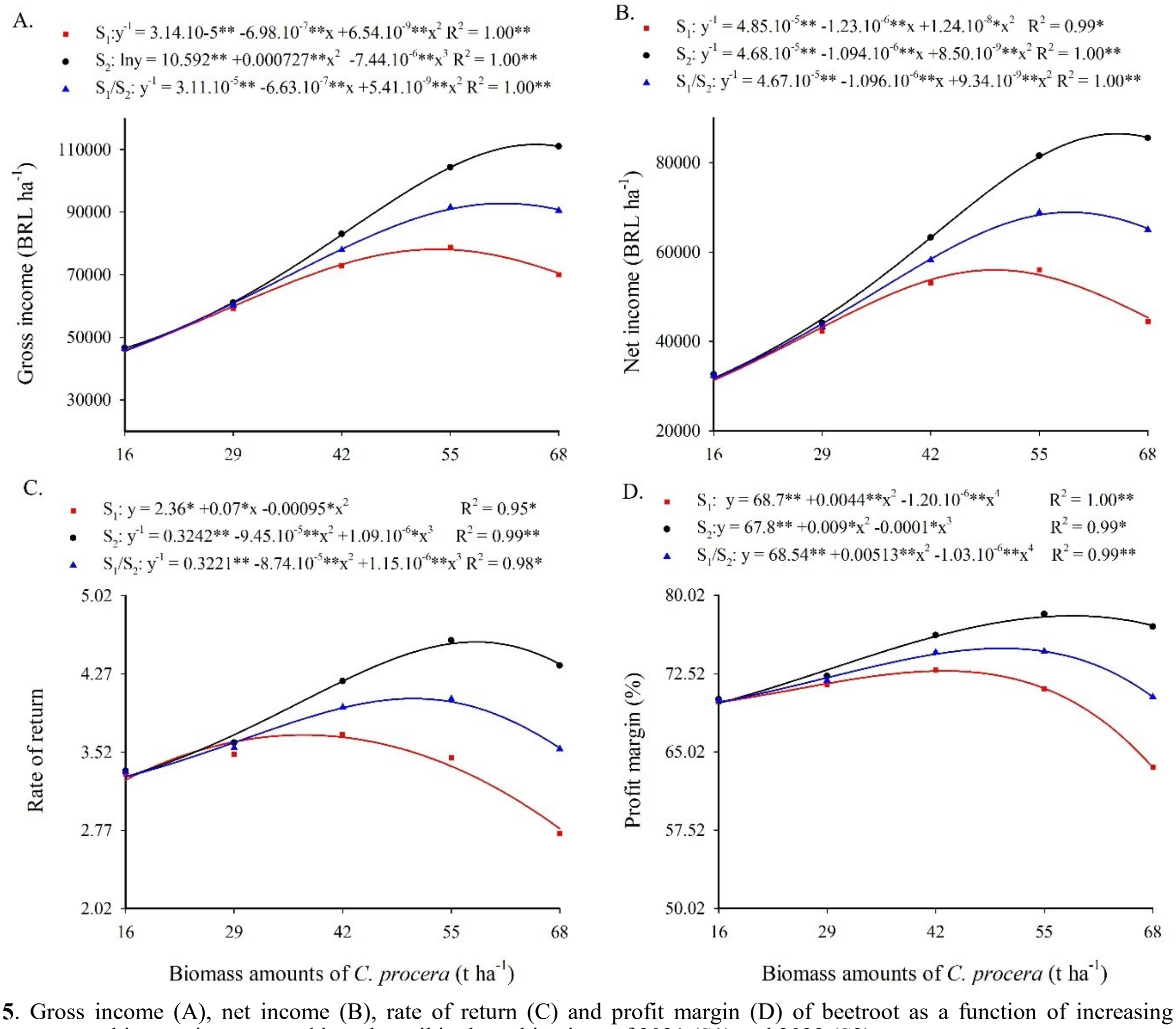

Figure 5. Gross income (A), net income (B), rate of return (C) and profit margin (D) of beetroot as a function of increasing amounts of *Calotropis procera* biomass incorporated into the soil in the cultivations of 2021 (S1) and 2022 (S2).

When estimating the maximum economic efficiencies of these economic indicators over cultivations, an increasing polynomial behaviour was also observed due to the increase in the amount of green manure biomass up to the maximum values of 92.702.39 BRL ha^{-1} for gross income, 68.740.15 BRL ha^{-1} for net income, 4.04% for the rate of return and 74.93% for the profit margin in the green manure amounts of 61.32, 58.68, 50.48 and 49.94 t ha^{-1}, respectively. The values then decreased until the highest amount of fertiliser was tested (Figures 5A, 5B, 5C and 5D). These results partially agree with those obtained by Silva et al. (2021), who fertilised the carrot tuberous crop with different amounts of green fertiliser from *C. procera* and obtained the following economic efficiency indicators: 62.704.94 BRL ha^{-1} for gross income, 33.744.07 BRL ha^{-1} for net income, 2.27 reals for each real invested for the return rate and 56.63% profit margin using green manure biomass amounts of 47.60, 42.81, 31.69 and 31.85 t ha^{-1}, respectively. These results show the economic efficiency of green manuring with roostertree on the performance and development of tuberous crops, such as beetroot.

The increasing values of the economic indicators evaluated in the beetroot culture and the economic optimisations achieved soon after reaching the maximum point in the polynomial model and then decreasing according to the amounts of *C. procera* biomass are related to the great availability of nutrients released after the mineralisation of the green manure being absorbed by the plants without loss by leaching (SANTANA et al., 2021). With the use of this green manure, it is possible to increase the organic matter content, recover soil fertility, improve the cation exchange capacity, make macro- and micronutrients available, and favour conditions for microbial activity, in addition to reducing the rates of erosion and increasing soil water retention (IGUE et al., 1984).

Given the behaviour recorded in these economic indicators, the maximum physical (agronomic) efficiency obtained in the growth and production characteristics of beetroot was translated into economic efficiency, showing that the use of green manure with the spontaneous species *C. procera* provides a financial return compatible with the invested capital. These results allow beetroot producers in a semi-arid environment to choose the ideal amount of green manure for incorporation and the economic indicator that best suits them in relation to the commercial productivity of roots.

CONCLUSIONS

Beetroot fertilisation to obtain the maximum optimised productive efficiency (36.14 t ha^{-1}) was possible with the incorporation of 61.29 t ha^{-1} of dry *C. procera* biomass into the soil. The maximum optimised agroeconomic efficiency based on a net income of 68.740.15 BRL ha^{-1} for beetroot cultivation was obtained with an amount of 58.68 t ha^{-1} of dry *C. procera* biomass added to the soil. The rate of return obtained was 4.04 BRL for each real invested, with a profit margin of 74.93%.

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