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Impact of organic fertilization on establishing an agroforestry system in a semi-arid Brazilian region

Impacto da adubação orgânica no estabelecimento de um sistema agroflorestal em região semiárida brasileira

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Highlights

Sheep manure enhances soil fertility in semi-arid agroforestry systems.
Native tree growth is unaffected by organic fertilization in these systems.
Organic fertilization boosts crop grain yields in semi-arid agroforestry settings.

Abstract

Improving soil fertility with organic sources is crucial, particularly in degraded regions. Organic fertilizers, when integrated into systems, provide cost-effective solutions. This study aimed to assess the impact of various organic fertilizers on the establishment of an agroforestry system in Planosol in a semi-arid region of Ceará State, Brazil. We used a randomized block design arranged in split plots. Four organic fertilizer sources (sheep manure, cattle manure, carnauba palm straw, and control) were assigned to the main plots. Evaluation years for annual crops (2015, 2017, and 2019) and for trees (2015 through 2017, and 2019) were allocated to subplots, with three replicates. All organic fertilization sources received an annual rate of 10 t ha^{-1}, broadcasted uniformly. Experimental plots, spanning 18 x 7 m, were intercropped with maize and cowpea between rows of trees (*Mimosa caesalpiniifolia* and *Spondias mombin*). We examined soil fertility, tree growth, and crop grain yield. Soil chemistry, notably P and K, showed marked improvement with sheep manure. Organic fertilization did not enhance tree growth in the newly

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established agroforestry system. However, organic fertilization elevated maize and cowpea grain yields by over 60% and 90%, respectively, compared to the control. In conclusion, the use of sheep manure, cattle manure, and carnauba palm straw can significantly boost maize and cowpea grain yields in an agroforestry system found in the semi-arid region of Ceará, Brazil.

Key words: *Zea mays.* Vigna unguiculata. Integrated production systems.

Resumo

Melhorar a fertilidade do solo com fontes orgânicas é crucial, especialmente em regiões degradadas. Os fertilizantes orgânicos, quando integrados em sistemas, proporcionam soluções económicas. Este estudo teve como objetivo avaliar o impacto de diversos fertilizantes orgânicos no estabelecimento de um sistema agroflorestal em Planossolo, no semiárido do Estado do Ceará, Brasil. Utilizou-se delineamento em blocos casualizados dispostos em parcelas subdivididas. Quatro fontes de fertilizantes orgânicos (esterco ovino, esterco bovino, palha de carnaúba e controle) foram atribuídas às parcelas principais. Os anos de avaliação para culturas anuais (2015, 2017 e 2019) e para árvores (2015 a 2017 e 2019) foram alocados em subparcelas, com três repetições. Todas as fontes de adubação orgânica receberam uma taxa anual de 10 t ha^{-1}, distribuída uniformemente. Parcelas experimentais, medindo 18 x 7 m, foram consorciadas com milho e feijão-caupi entre fileiras de árvores (*Mimosa caesalpiniifolia* e *Spondias mombin*). Examinamos a fertilidade do solo, o crescimento das árvores e o rendimento dos grãos. A química do solo, especialmente P e K, mostrou melhoria acentuada com esterco de ovelha. A fertilização orgânica não melhorou o crescimento das árvores no sistema agroflorestal recentemente estabelecido. No entanto, a fertilização orgânica elevou a produtividade de grãos de milho e feijão-caupi em mais de 60% e 90%, respectivamente, em comparação com o controle. Concluindo, o uso de esterco ovino, esterco bovino e palha de carnaúba pode aumentar significativamente a produtividade de grãos de milho e feijão-caupi em um sistema agroflorestal encontrado na região semiárida do Ceará, Brasil.

Palavras-chave: *Zea mays. Vigna unguiculata.* Sistemas integrados de produção.

Introduction

Agriculture is still a primary contributor to global land degradation. Intensive farming practices, especially monocultures, worsen this degradation due to overgrazing and unchecked use of fire. Such degradation impoverishes ecosystems and can lead to desertification, especially in arid, semi-arid, and dry sub-humid regions.

Organic fertilizers not only enhance yield but also elevate the quality of agricultural products. They achieve this by improving the soil's physical, chemical, and biological properties (Pal et al., 2018; Eckhardt et al., 2018). Derived from varied sources such as minerals, animals, sewage sludge, and plants organic fertilizers boost soil organic matter content. Compared to soluble fertilizers, they are cost-effective, enhance soil structure and texture, augment aeration, increase water retention, and foster healthy root development (Assefa & Tadesse, 2019).

Sheep and cattle manure, rich in N, P, and K, emerge as promising alternative nutrient sources. Their value lies in fostering soil fertility, attributable to their slow nutrient-release properties through the mineralization of soil organic matter (Souza et al., 2021). Nunes et al. (2022) also highlighted the positive environmental impact of organic fertilizers, noting increased soil fauna diversity in a study on carnauba palm straw.

In Brazil's semi-arid regions, typified by erratic rainfall and frequent droughts, farmers often apply minimal inputs. This restrained use results in yields that fall below national averages. In the country, common practices involve using native vegetation as livestock feed without proper stocking rate management, indiscriminate use of fire for land clearing, and neglecting nutrient management. Such practices erode soil fertility and undermine production stability (Araújo & Silva, 2015; Sousa et al., 2012). In the Sertão dos Inhamuns, Ceará, a soil fertility survey revealed that half of the examined areas had low phosphorus levels, and 90% were deficient in organic matter (Souza et al., 2015). To counter this, experts recommend the application of organic fertilizers combined with leguminous plant matter and abstaining from burning as cost-effective conservation measures for local farmers.

Integrated systems, like agroforestry, which combine crop, livestock, and forestry productions, emerge as both sustainable and technologically advanced farming methods (Borges, 2018; Leite-Moraes et al., 2023). Research in semi-arid areas supports the efficacy of these systems in enhancing organic matter content, soil fertility, and farming stability (Aguiar et al., 2014; Fialho et al., 2013; Tonucci et al., 2023).

Organically-fertilized agroforestry systems present a practical strategy for smallholders, enabling them to provide essential nutrients to both crops and trees, thus enhancing production stability. Our hypothesis suggests that using organic fertilizers in integrated systems, specifically those featuring woody and fruit tree species intercropped with maize and cowpea can be an economical approach for growers seeking to rehabilitate degraded lands and enhance soil quality. This study aimed to assess the impact of organic fertilizers on the soil fertility and yield of an agroforestry system in which maize and cowpea are intercropped with sabiá (*Mimosa caesalpiniifolia*) and yellow mombin (*Spondias mombin*) in the semi-arid region of Ceará State, Brazil.

Material and Methods

Location and background

The study took place from June 2014 to June 2019 at Fazenda Triunfo, situated in Ibaretama, Ceará State, Brazil. The land features haplic Planosol soil (Albaquults/Planossolo) (Santos et al., 2018). Soil tests, conducted at two depths (0.0-0.2 m and 0.2-0.4 m), revealed low levels of P, K, Ca, Mg, and OM, and a high pH (Table 1), based on Fernandes (1993) classification for Ceará. To improve soil pH and neutralize Al, 2.4 t ha^{-1} of limestone and 600 kg ha^{-1} of gypsum were applied before the trial initiation. Climate data for the years 2015, 2017, and 2019 are presented in Figure 1.

Table 1
Chemical, physical and texture attributes of the soil on the experimental area (Planosol)

Layer	pH	OM	P	K	Ca	Mg	Al	H+Al	SB	CEC	BS	m
M	H_2O	g kg^{-1}	mg dm^{-3}		------------- $cmol_c$ dm^{-3} --------------						--- % ---	
0-0.2	5.0	4.7	1.8	0.09	0.70	0.16	0.25	1.60	1.00	2.60	38	20
0.2-0.4	5.2	4.1	2.6	0.06	0.70	0.16	0.20	1.80	1.00	2.80	36	17
	Na	Cu	Fe	Mn	Zn	Sand	Silt	Clay	BD	PD	TP	EC
		-------- mg dm^{-3} --------				---- g kg^{-1} ----			kg dm^{-3}		%	mS cm^{-1}
0-0.2	11.5	0.11	36	12	0.22	827	147	26	1.55	2.57	40	0.20
0.2-0.4	16.1	0.17	61	11	0.29	826	140	34	1.52	2.60	41	0.13

Note: OM - Organic matter; SB - Sum of bases; CEC - Cation exchange capacity; BS - Base saturation; m - Aluminum saturation; BD - Bulk density; PD - Particle density; TP - Total porosity; EC- Electric conductivity.

In 2015, an agroforestry system was introduced. Two tree species were planted, setting them 3.5 m apart in rows and 3.0 m apart within the rows. The rows contained a combination of a woody species, sabiá (*Mimosa caesalpiniifolia*), and a fruit tree, namely a cashew tree (*Anacardium occidentale*). However, due to a staggering 98% mortality rate in cashew seedlings over two years (2015-2016) owing to severe drought, they were replaced with yellow mombin (*Spondia mombin*) in 2017. This local species proves more resilient to the soil and climatic challenges. Amidst these trees, maize and cowpea crops were grown. The tree seedlings were planted in 0.4 x 0.4 x 0.4 m holes, enriched with 500 g of superphosphate and 2 L of hydrogel. In the first year, each tree received weekly irrigation of 1.5 L of water.

Treatments and experimental design

The treatments involved three organic fertilizers (sheep manure, cattle manure, and carnauba palm straw) and a control (unfertilized) set within an agroforestry system of crops (maize and cowpea) intercropped with trees (sabiá and yellow mombin). The experimental design used randomized blocks, treating agricultural years as variation sources. Organic fertilizers were assigned to plots and agricultural years to subplots (2015, 2017, and 2019), divided into three blocks (replications).

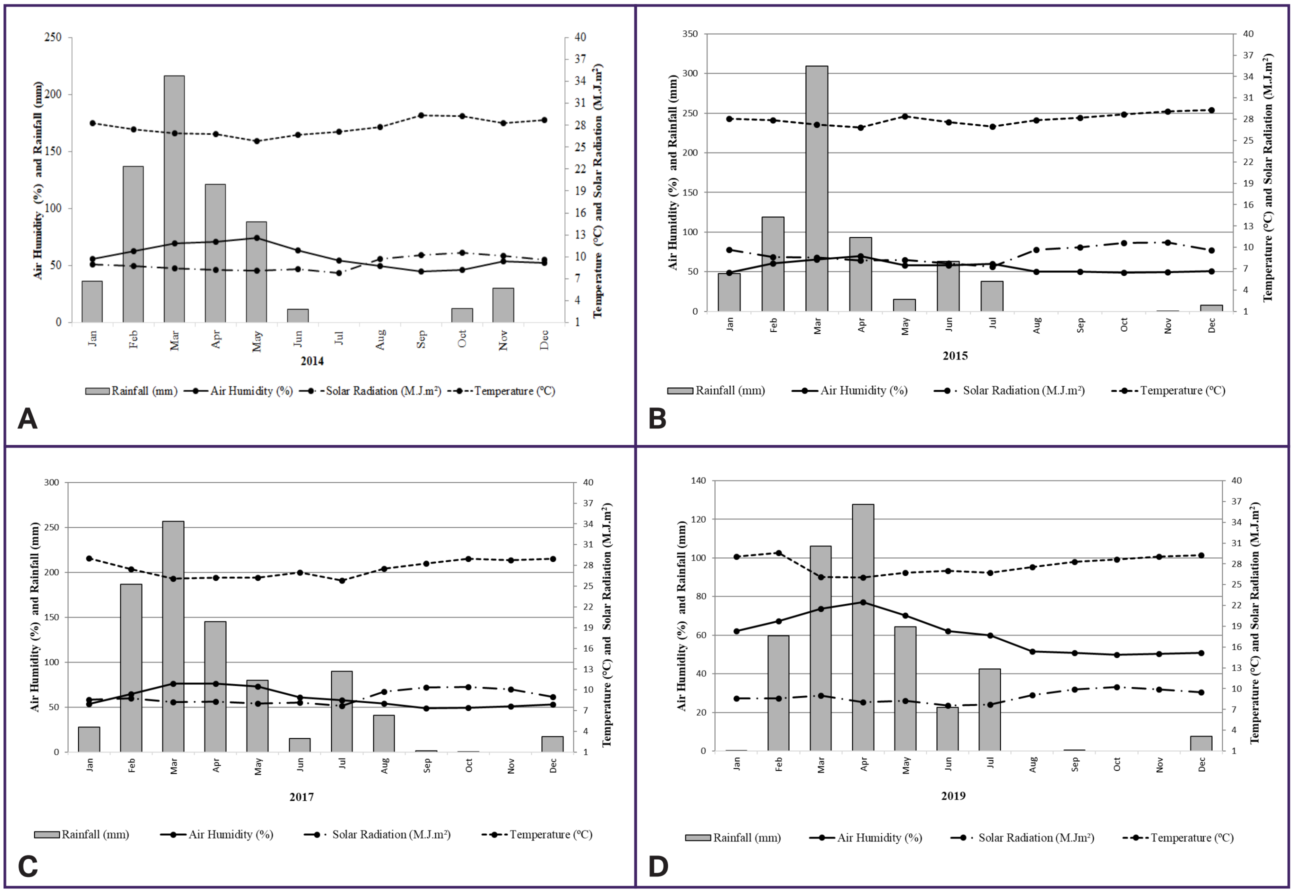

Figure 1. Rainfall, air humidity, solar radiation and air temperature in the experimental area in the period of 2014 (A), 2015 (B), 2017 (C) and 2019 (D). Ibaretama, Ceará, Brazil. Source: Triunfo Farm.

Crop management

Annually, a single application of each organic fertilizer at a rate of 10 t ha^{-1} was broadcast across the entire plot area, specifically at the onset of the rainy season, between February and March. The chosen application rate aligns with the findings of Ribeiro et al. (1999). The first fertilizer application occurred in 2014. Table 2 highlights the chemical composition of these organic fertilizers, all sourced from the farm where the study was undertaken.

Data collection for the annual crops was restricted to the years 2015, 2017, and 2019. In 2016 and 2018, setbacks in the planting phase prevented the crops from completing their growth cycle, attributed to intense droughts. For the sabiá trees, evaluations spanned from 2016 to 2019, while the yellow mombin, due to its protracted growth, was assessed solely in 2019. The plots treated with organic fertilizers were 18 x 7 m in dimension, totaling an area of 126 m^2. Interspersed between the tree rows were four

6-m-long maize rows with a spacing of 0.8 m between rows and three plants per meter. Similarly, six 6-m-long cowpea rows with a 0.5 m spacing and a density of four plants per meter. Data collection for both crops was limited to the central rows, specifically four rows for maize and two for cowpea, excluding 0.5 m from either end. Each plot was home to five tree specimens, with evaluations focusing on the three central trees.

Table 2
Chemical analysis of the organic fertilizers used in the experiment, Ibaretama, Ceará, Brazil

Fertilizers	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Lignin
	----------------- g kg^{-1} ------------------						------------ mg kg^{-1} -----------					%
Carnauba palm straw	20.1	0.8	9.0	3.5	2.6	2.5	5	840	20	80	20	40
Cattle manure	14.1	1.4	8.1	12.3	7.0	1.3	17	4480	59	314	23	16
Sheep manure	13.1	1.6	14.7	17.4	8.1	1.9	16	3620	58	230	28	13

Note: Analysis - after nitroperchloric digestion; P was determined by colorimetry; K by flame photometry; S by turbidimetry; Ca, Mg, Cu, Fe, Mn, and Zn by atomic absorption spectrophotometry; nitrogen by the Kjeldahl method; and boron by calcination (Abreu et al., 2006). Lignin - extraction via sulfuric acid (72%).

Within the plots, the cultivation alternated annually between maize (of the AL Piratininga variety) and cowpea (of the BRS Xiquexique cultivar). Conventional cultural practices, encompassing pest, disease, and weed management, were performed, adhering to guidelines set for maize-cowpea systems. The plants relied exclusively on organic fertilizers for nourishment, with the application rates corresponding to the fertilizer types in use.

Analyzed attributes

Soil samples were randomly collected from the 0.0-0.2 m layer in each experimental plot (Figure 2). For a comprehensive analysis, every six individual samples made up a composite sample. Sampling was conducted in the years when grain yields were measured. These samples underwent a series of analyses based on the method proposed by P. C. Teixeira et al. (2017). The pH (in H_2O) was assessed in a 1:2.5 soil-to-solution ratio. The Walkley-Black method was employed to determine organic matter. Key minerals such as P, K, Na, Cu, Fe, Mn, and Zn were extracted using the Mehlich-1 method, while Ca, Mg, and Al were isolated with KCl. H+Al was extracted using calcium acetate, while B was extracted via hot water and S through a reaction with barium chloride. The critical soil parameters sum of bases (SB), cation exchange capacity (CEC), and base saturation (BS) were calculated using the following equations: SB = Ca + Mg + Na + K, CEC = SB + H+Al, and BS = SB / CEC*100.

Grain yields for maize and cowpea were quantified in the field during the 2015, 2017, and 2019 seasons by harvesting a 5-meter section from each plot. Accumulated grain yield was determined by summing the outputs from these three years. For tree metrics, height, stem diameter, and diameter at breast height were measured. Sabiá was evaluated from 2016 to 2019, while the yellow mombin was assessed only in 2019 due to its more gradual growth.

Statistical analysis

The experimental data were subjected to an analysis of variance (F-test) at a 5% significance level. If an interaction between fertilization sources and years was significant at the 5% level, it was further explored. To assess the individual effects of sources and years, mean values were compared using the Tukey test at a 5% significance level. All statistical analyses were conducted using the R software for statistical computing (R Core Team [R], 2017).

Results and Discussion

Regarding soil fertility analysis, there was an interaction effect (sources x years) on K content. Independently, sources influenced P, K, and SB. Animal waste-based fertilizers (cattle and sheep manure) presented higher P concentrations than carnauba palm straw and the control. Sheep manure improved SB compared to the control but was like carnauba palm straw and cattle manure (Table 3).

Table 3

Mean values, F test and coefficient of variation for fertility analysis of Planosol (0-0.2 m) in an agroforestry area as a function of organic fertilizers and years of evaluation. Ibaretama, Ceará, Brazil

Organic Fertilizers	pH	OM	P	K	Ca	Mg	H+Al	SB	CEC	BS
	H_2O	g dm^{-3}	-- mg dm^{-3} --		---------------		$cmol_c$ dm^{-3}		--------------	%
Carnauba palm straw	6.32	6.33	7.5b1	59.4bc	1.67	1.08	1.25	4.69ab	5.94	79
cattle manure	6.44	6.77	23.6a	69.3ab	1.36	0.89	1.07	4.51ab	5.58	80
Sheep manure	6.48	7.44	27.8a	83.2a	1.76	0.98	1.02	5.20a	6.22	82
Control	6.25	6.33	7.6b	45.1c	1.36	0.83	1.72	3.73b	5.45	68
Test F	Ns	ns	**	**	ns	ns	ns	*	ns	ns
CV_1 (%)	4.0	30.3	31.4	14.1	32.9	25.1	54.7	15.9	18.1	12.2
Years										
2015	5.81b	6.16	16.8	36.1b	1.10b	0.57b	1.85a	3.09b	4.90b	62b
2017	6.58a	7.66	17.5	75.1a	1.80a	1.09a	1.14b	5.09a	6.29a	82a
2019	6.73a	6.33	15.6	81.6a	1.76a	1.18a	0.81b	5.32a	6.21a	87a
Test F	**	ns	ns	**	**	**	**	**	*	**
CV_2 (%)	4.1	32.9	37.9	15.7	26.4	27.2	36.00	15.6	16.3	7.9
Sources x Years	Ns	ns	ns	**	ns	ns	ns	ns	ns	ns

ns, * and ** - Nonsignificant, significant at 5 and 1% probability. 1 Means followed by the same letter in the column do not differ by Tukey 's test (5% probability). CV1 and CV2 – Coefficient of variation of plot and subplot, respectively.

For the factor 'years', multiple attributes such as pH, Ca, Mg, SB, CEC, and BS showed an increase from 2017 but stabilized in 2019. In contrast, potential acidity (H+Al) decreased over the years.

Table 4 details the significant interaction between sources and years for K concentration. Within each year, organic fertilizers showed no differences in 2015. Yet, in 2017 and 2019, sheep manure resulted in a higher soil K concentration than the unfertilized control. Evaluating each source yearly, soil K concentration increased due to each organic fertilizer and the control in 2017, paralleling the 2019 results.

There were interactions between the source and years for $S\text{-}SO_4^{2-}$, Na, and B soil concentrations. Other soil attributes shifted annually, with Cu concentration rising from 2015 to 2019 but mirroring 2017. The peak Fe values appeared in 2019. Concentrations of Mn in 2017 and 2019 exceeded those in 2015, while Zn concentrations increased in 2017 compared to 2015 (Table 5).

Sulfur showed no difference between sources in 2017 and 2019. In 2015, sheep manure fertilization resulted in the lowest S concentrations. Evaluating sources across the years, only carnauba palm straw differed in sulfur content, peaking in 2015 (Table 4).

Table 4
Concentrations of potassium, sulfur, sodium, and boron on Planosol (0-0.2 m) in an agroforestry area as a function of organic fertilizers and years of evaluation. Ibaretama, Ceará, Brazil

K ($cmol_c$ dm^{-3})	2015	2017	2019	$S\text{-}SO_4^{2-}$ (mg dm^{-3})	2015	2017	2019
Carnauba palm straw	33.8bA1	70.2aAB	74.1 aBC	Carnauba palm straw	16.0aA	5.0bA	6.0bA
Cattle manure	49.4bA	74.1aAB	84.5aB	Cattle manure	13.6aA	8.0aA	7.3aA
Sheep manure	35.1bA	97.5aA	117.0aA	Sheep manure	3.0aB	6.0aA	6.0aA
Control	26.0bA	54.6aB	54.6 aC	Control	12.0aA	5.0aA	9.3aA
Na (mg dm^{-3})	2015	2017	2019	B (mg dm-3)	2015	2017	2019
Carnauba palm straw	15.6aA	6.0bA	6.6bB	Carnauba palm straw	0.34aAB	0.18bA	030abAB
Cattle manure	10.7aAB	9.2aA	12.8aA	Cattle manure	0.32aB	0.27aA	0.36aA
Sheep manure	8.5aB	7.0aA	6.2aB	Sheep manure	0.48aA	0.22bA	0.26bB
Control	11.2aAB	7.3aA	7.7a AB	Control	0.18aB	0.18aA	0.18aB

[1]Means of the same lowercase letter in the row and uppercase letter in the column do not differ from each other according to Tukey's test (5% probability).

Table 5
Mean values, F test and coefficient of variation for the analysis of sulfur, sodium and micronutrients on Planosol (0-0.2 m) in an agroforestry area as a function of organic fertilizers and years of evaluation. Ibaretama, Ceará, Brazil

Sources	$S\text{-}SO_4^{2-}$	Na	B	Cu	Fe	Mn	Zn
	-------------------------------------			mg dm^{-3}			-------------------------------------
Carnauba palm straw	9.0	9.4	0.27ab [1]	0.21	29	9.6	0.51
Cattle manure	5.0	10.9	0.32a	0.18	31	6.6	0.65
Sheep manure	9.7	7.3	0.33a	0.23	29	10.7	0.69
Control	8.8	8.7	0.18b	0.21	30	6.6	0.30
Test F	ns	Ns	**	ns	ns	ns	ns
CV1 (%)	44.7	37.6	20.4	22.6	26.8	49	62.5
Years							
2015	11.2a	11.5a	0.33a	0.16b	22b	6.0b	0.29b
2017	6.0b	7.4b	0.21b	0.22ab	26b	10.7a	0.64a
2019	7.2b	8.4a	0.28ab	0.25a	40a	8.4ab	0.70a
Test F	**	**	**	*	**	**	**
CV2 (%)	42.6	37.6	25.8	37.9	28.3	32.7	48.3
Sources x Years	*	*	*	ns	ns	ns	ns

ns, * and ** - Nonsignificant, significant at 5 and 1% probability. 1Means followed by the same letter in the column do not differ by Tukey 's test (5% probability). CV1 and CV2 – Coefficient of variation of plot and sub-plot, respectively.

Distinct Na concentrations arose from each organic fertilizer source in 2015 and 2019. In 2015, carnauba palm straw yielded the highest values, while cattle manure led in 2019. For animal waste-based fertilizers (cattle and sheep manures) and control, no yearly difference appeared. Yet, carnauba palm straw displayed lower Na concentrations in 2017 and 2019 (Table 4).

Boron concentration in 2017 remained consistent across sources. In 2015, sheep manure application produced a greater B concentration than the control, equating to other sources. In 2019, cattle manure surpassed other sources and the control in B concentration. For cattle manure and control, yearly B concentrations remained steady. However, carnauba palm straw showed a decline in 2017 from 2015, comparable to 2019. Sheep manure provided higher B concentrations in 2015 compared to 2017 and 2019 (Table 4).

Although no interaction existed between sources and years, individual effects from both parameters affected maize and cowpea yields (Table 6). Maize grain yield excelled with sheep manure compared to other fertilizer sources and the control. Carnauba palm straw enhanced yields compared to the control but paralleled cattle manure. For cowpeas, animal waste-based fertilizers surpassed the control in yields, while yields from carnauba palm straw-fertilized plants matched those of the control.

Table 6
Mean values, F test and coefficient of variation for maize and cowpea yield data in an agroforestry area as a function of organic fertilizers and years of evaluation. Ibaretama, Ceará, Brazil

Fertilizer source	Maize yield	Cowpea yield
	kg ha^{-1}	kg ha^{-1}
Carnauba palm straw	1,138b[1]	823ab
Cattle manure	1,045bc	915a
Sheep manure	1,683a	1,029a
Control	653c	479b
Test F	**	**
CV_1 (%)	23.8	28.3
Years		
2015	1,355a	1,478a
2017	817b	536b
2019	1,218a	421b
Test F	**	**
CV_2 (%)	27.8	42.6
Fertilizer x Years	ns	ns

ns, * and ** - Nonsignificant, significant at 5 and 1% probability. [1] Means followed by the same letter in the column do not differ by Tukey 's test (5% probability). CV_1 and CV_2 – Coefficient of variation of plot and subplot, respectively.

The effect of years on cowpea yield revealed that the highest yields appeared in 2015 compared to 2017 and 2019. For maize, the highest yield appeared in 2015 and 2019 (Table 6). The highest accumulated yield, reflecting maize and cowpea yields from 2015, 2017, and 2019, was achieved using sheep manure. Still, carnauba palm straw and cattle manure outperformed the control (Figure 2).

Regarding sabiá tree development, no interaction between sources and evaluation years emerged. Yet, cattle manure notably influenced stem diameter, matching the control's results. Annually, differences were observed across three variables: tree height and stem diameter showed a linear pattern, while stem diameter at breast height followed an exponential trend (Table 7).

For yellow mombin evaluations in 2018, fertilizers exerted no influence on height (avg. = 1.23 m), stem diameter (avg. = 42 mm), or breast height diameter (avg. = 65 mm).

Chemical analysis of organic fertilizers (Table 2) revealed animal waste-based fertilizers, like sheep and cattle manure, have superior concentrations of P, K, Ca, Mg, B, Cu, Fe, Mn, and Zn. In contrast, carnauba palm straw displayed elevated levels of N, S, and lignin. Even though carnauba palm straw has more N, its higher lignin/N ratio diminishes nutrient availability due to slower microbial mineralization rates (V. B. D. Silva et al., 2014).

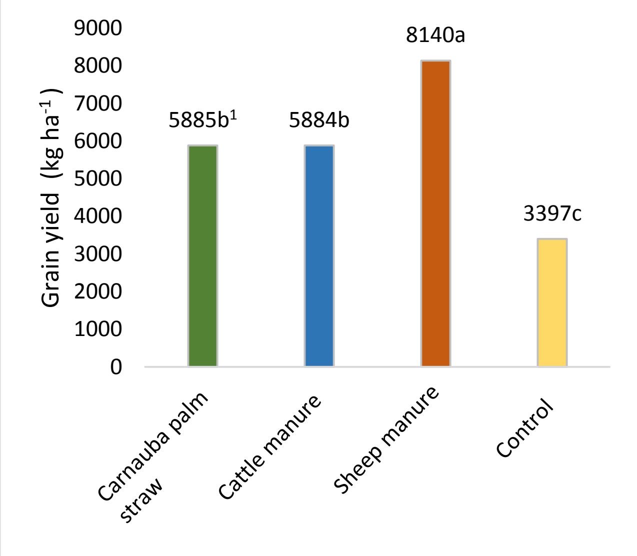

Figure 2. Accumulated grain yield of maize and cowpea for the years 2015, 2017 and 2019 in an agroforestry area as a function of organic fertilizers. Ibaretama, Ceará, Brazil. [1]Means followed by the same letter in the column do not differ by Tukey's test (5% probability).

Table 7
Mean values, F test and coefficient of variation for sabiá trees in an agroforestry area as a function of organic fertilizers and years of evaluation. Ibaretama, Ceará, Brazil

Sources	Height	Stem Diameter	DBH
	M	---------------- mm -----------------	
Carnauba palm straw	3.1	36c[1]	13.8
Cattle manure	3.3	42a	14.1
Sheep manure	3.2	39bc	15.1
Control	3.3	40ab	13.2
Test F	Ns	**	ns
CV_1 (%)	6.3	5.5	12
Years			
2 (2016)	2.7	25	1.5
3 (2017)	3.1	37	2.4
4 (2018)	3.3	38	25.0
5 (2019)	3.8	58	27.1
Test F	**	**	**
Equation	y = 2.0 + 0.35x R^2 = 0.97	y = 4.5 + 10x R^2 = 0.89	y = e (0.681x) R^2 =0.76
CV_2 (%)	5.6	6.8	11.7
Sources x Years	Ns	Ns	ns

ns, * and ** - Nonsignificant, significant at 5 and 1% probability. 1Means followed by the same letter in the column do not differ by Tukey 's test (5% probability). CV1 and CV2 – Coefficient of variation of plot and subplot, respectively. DBH = Diameter at breast height.

With a consistent organic fertilizer rate (10 t ha^{-1}) across sources, nutrient contents and mineralization rate of each fertilizer potentially influenced outcomes. Manure applications, notably from sheep and cattle, led to the highest soil P concentrations, which were deemed adequate after manure use (Souza et al., 2014). This outcome might arise from the lower C:P ratio of manures compared to carnauba palm straw, facilitating a more substantial P release to the soil (Pal et al., 2018).

Differences in soil K levels were observed among various sources. Remarkably, sheep manure showed a pronounced increase in K concentration in 2017. Even the unfertilized control demonstrated a progressive increase in K over the years, likely due to the liming conducted in the area. Compared to the control, the application of organic fertilizers resulted in notable K content boosts: 28% (2017) and 36% (2019) for carnauba palm straw, 36% (2017) and 55% (2019) for cattle manure, and a substantial 78% (2017) and 114% (2019) for sheep manure. Based on first soil test results, current soil K concentrations are categorized as high (Fernandes, 1993; Souza et al., 2014).

The elevated K content in sheep manure accounts for the increased soil K levels. The liming conducted in the area made potassium more accessible, preventing K from depletion in the soil solution (Eckhardt et al., 2018). Similar findings of enhanced soil K levels have been reported in other studies when using sheep manure (Souza et al., 2021). Liming neutralized differences in pH, Ca, Mg, H+Al, and BS across all organic fertilizers and the control. Nonetheless, sheep manure application elevated the sum of bases, attributable to its higher K content. The sum of bases combines the soil concentrations of K, Ca, and Mg.

In comparison to the critical levels suggested by Souza et al. (2014) for the semi-arid region of Ceará State, Brazil, certain soil attributes present noteworthy findings. For instance, pH and Mg values approached the critical levels irrespective of the fertilizer used. While Ca concentrations lie below these critical levels, the application of sheep manure resulted in OM values surpassing them. Additionally, all organic fertilizers, including sheep and cattle manure as well as carnauba palm straw, showed BS values exceeding the critical threshold. It is also pertinent to highlight the impact of liming. From 2017 onward, liming enhanced pH, exchangeable cations (K, Ca, and Mg), SB, CEC, and BS while reducing H+Al across all treatments. This undoubtedly signifies a boost in soil fertility.

Over time, carnauba palm straw led to a decrease in S concentration in the soil. This trend is attributable to the straw's high lignin content, reducing the mineralization rate of nutrients, particularly C, N, P, and S. This effect aligns with the high C/N ratio, lignin, and polyphenol contents observed (Maluf et al., 2015). Additionally, applying carnauba palm straw annually, at a rate of 10 t ha^{-1}, might hinder nutrient release, given its rich lignin composition.

Similarly, the use of carnauba palm straw also reduced Na and B concentrations in the soil over the years. The declining Na concentration is particularly significant, considering its effect on soil physical attributes like clay dispersion. This decline underscores the benefits of employing this organic fertilizer in semi-arid regions. While no studies have reported a rise in Na concentrations due to carnauba palm straw usage (Oliveira et al., 2018), the decrease in B concentrations mirrors the trend seen with S. Additionally, the low B concentration inherent to this organic fertilizer could further elucidate this observation.

Using sheep manure significantly improved soil attributes, which, in turn, explains the elevated yields for both maize and cowpea. Sheep and goats, being small herbivores with selective grazing patterns, consume a more digestible diet (Lechner-Doll et al., 1995). Paired with a rapid digestion rate (Van Soest, 1994), this results in excrements rich in available nutrients. Maize yields were particularly prominent when fertilized with carnauba palm straw (Table 6). This could be due to the mulching effect of straw, potentially preserving soil moisture (V. B. Silva, 2019). In semi-arid regions, minimizing water evaporation is crucial, and mulching serves as an effective strategy (Almeida et al., 2020). When compared to animal waste-based fertilizers (like cattle and sheep manures), carnauba palm straw, being high in lignin and crushed from carnauba wax, offers an easier distribution across fields.

Considering the accumulated grain yield for both maize and cowpea from 2015 to 2019, the benefits of organic fertilizers are clear. Specifically, sheep manure application led to a yield increase of 139%, while carnauba palm straw and cattle manure each contributed to a 73% rise compared to the control (Figure 3).

Interestingly, the sizes of yellow mombin and sabiá trees showed no significant difference attributed to liming, with an exception observed in the stem diameter of sabiá when treated with cattle manure. It is noteworthy that both sabiá and yellow mombin are indigenous to the region. A concurrent study on the same site revealed that sabiá trees significantly benefit from sheep manure, showing increases in height, stem diameter, and stem diameter at breast height.

The primary sequence of nutrient accumulation is N > Ca > K > Mg > P > S for macronutrients and Fe > Mn > B > Zn > Cu for micronutrients for sabiá (*Mimosa caesalpiniifolia*), (Souza et al., 2021). Notably, sheep manure was the sole nutrient source in this research, with no other soil amendments being applied. Additionally, the yellow mombin tree, in separate research, has demonstrated a positive response to mineral fertilization. Field trials involving P and K fertilizers showed enhanced fruit yields with applications of 30 g of P_2O_5 and 148g of K_2O per plant. Animal waste-based fertilizers, including cattle and sheep manures, are often richer in nutrients than plant-based alternatives. The nutrient profile in these fertilizers originates from animal excretion, which can be substantial, making them valuable nutrient sources (D. S. Teixeira et al., 2019).

Moreover, it has been suggested that growing crops near trees might compromise yields due to competition for essential resources like water and nutrients (Borges et al., 2020, 2021). Moreover, the shading effect from the trees can be a concern. Yet, yields of cowpea and maize in our study surpassed the averages for Ceará State, which in the 2019/2020 season were 380 kg ha^{-1} and 1,232 kg ha^{-1} (Companhia Nacional de Abastecimento [CONAB], 2021). This can be explained by the limited or null use of fertilizers in the semi-arid of Brazil.

In line with our findings, M. D. M. Araújo et al. (2023) postulated that organic compost at rates below 110 kg N-equivalent ha^{-1} might decrease soil fertility and not enhance maize yields in semi-arid settings. Our dose of 10 t ha^{-1} for both animal waste-based fertilizer and carnauba palm straw equates to higher N levels, reaffirming the appropriateness of our chosen dose and efficacy of these organic fertilizers in promoting better yields.

Organic fertilizers impart many benefits to both soil and plants, enhancing plant nutrition (especially nitrogen) and positively impacting plant attributes (e.g., height, stem and root biomasses, and overall yield). Moreover, organic fertilization leads to an increase in soil carbon content (L. J. R. Silva et al., 2022). Soil health also experiences several marked improvements since organic fertilizers help mitigate soil acidity, augment soil nutrient content, and increase organic carbon storage. Lastly, they also have a favorable effect on the soil's microbiome, bolstering its abundance and enhancing its functional role in the ecosystem, such as C and N cycling (Song et al., 2022).

In integrated systems, while potential challenges like competition for water and nutrients, as well as shading, can impede grain crop development, the benefits offered by the altered microclimate and nutrient cycling due to tree litter are substantial and cannot be overlooked. Furthermore, organic fertilizers have emerged as a practical and efficient solution, ensuring nutrient supply, enhancing soil fertility, and facilitating grain production within agroforestry contexts, especially in the semi-arid landscapes of Ceará, Brazil.

Conclusions

In a recently established agroforestry system within the semi-arid region of Ceará State, Brazil, using sheep manure as organic fertilizer enhances the chemical properties of soils, notably increasing concentrations of phosphorus, potassium, and the total sum of bases. Despite this, organic fertilization has no discernible effect on tree growth. Overall, applying sheep manure, cattle manure, and carnauba palm straw enhances grain yields, particularly for maize and cowpea.

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