General performance of *Eucalyptus* L'Heritier silviculture in Northeast Brazil

Dráuzio Correia Gama[1] Deise Amaral de Deus[2], Teresa Aparecida Soares de Freitas[1], Thaís Santana Botelho[1], Ana Caroline Pereira dos Santos[1] Julio Conceição dos Santos Neto[1], Janisson Batista de Jesus[1]*

[1] Universidade Federal do Recôncavo da Bahia - UFRB
[2] Universidade Federal Rural da Amazônia - UFRA
[3] Universidade Federal do Rio Grande do Sul - UFRGS

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*Corresponding
drauziogama@hotmail.com

RESUMO: The objective of this study was to evaluate the performance of the eucalyptus forestry sector in Northeast Brazil, based on timber production and planting units per state. Biennial data (2021-2022) on timber production by segment and number of eucalyptus planting units were obtained from the electronic platform of the Brazilian Institute of Geography and Statistics (IBGE). The data were analyzed using descriptive statistics, cluster analysis by the Euclidean dissimilarity effect, Kendall's non-parametric correlation test, and an unweighted composite aggregate index (Iȓ), based on the Sauerbeck Index method. Statistical analyses were performed using ActionStat 3.6/R®. It was observed that the charcoal segment, in terms of variation in nominal production and productivity, followed by logs for other purposes, showed the greatest support among the segments. These segments showed a strong positive correlation with each other (τ^2 = 65.2%), although forming distinct subgroups through cluster analysis based on their relative variations. The performance index of the forestry sector was extremely low (Iȓ = 0.026). The dynamics of planted areas and municipalities participating in eucalyptus cultivation in Northeast Brazil were not equitable among the states, both in terms of their direct sizes and the resulting productivity by timber segment. Therefore, the performance of eucalyptus cultivation in Northeast Brazil during the study period showed a productive dynamic more focused on the timber segment, to the detriment of an unbalanced land structure.

Keywords: Planted forest, Index number, Forest development.

Desempenho geral da silvicultura de *Eucalyptus* L'Heritier no Nordeste do Brasil

ABSTRACT: O objetivo deste estudo foi avaliar o desempenho do setor florestal de eucalipto no Nordeste do Brasil, com base em produção madeireira e unidades de plantio por cada estado. Dados bienais (2021-2022) da produção madeireiro por segmento e número de unidades de plantio de eucalipto foram obtidos da plataforma eletrônica do IBGE. Os dados foram analisados por estatística descritiva, análise de agrupamento pelo efeito de dissimilaridade euclidiana, teste de correlação não paramétrico de Kendall e por índice agregada composta não ponderada (Iȓ), com base no método do Índice de Sauerbeck. Empregou-se para as análises estatísticas o Action Stat 3.6/R®. Observou-se que o segmento de carvão vegetal, em termos de variação da produção nominal e produtividade, seguido por toras para outros usos, apresentou o maior suporte entre os segmentos. Apresentaram forte correlação positiva entre si (τ^2 = 65,2%), embora formando subgrupos distintos pela análise de cluster, O índice de desempenho da silvicultura foi extremamente baixo (Iȓ = 0,026). A dinâmica de áreas plantadas e de municípios participantes, não foram equitativos entre os estados, pelas discrepâncias dos tamanhos e da produtividade por segmento madeireiro. Portanto, o desempenho da atividade de cultivo de eucalipto no Nordeste do Brasil, durante o período estudado, apresentou uma dinâmica produtiva mais voltada para o segmento madeireiro em detrimento de uma estrutura fundiária desequilibrada.

Keywords: Floresta plantada, Número índice, Desenvolvimento florestal.

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Introduction

Global planted forest areas comprise 293.895 million hectares, of which South America accounts for 7.0% (Olmos, 2020). These forests, whose areas continue to increase over time, have compensated for the decrease in the supply of timber due to the reduction in natural forest coverage (Payn et al., 2015). In tropical regions, for example, natural forest areas converted for agricultural purposes, have lower native wood stocks, increasing the consumption of plantation-dependent timber (McEwan et al., 2020). In South America, the total plantation area will likely more than double by 2050, growing from 10.7 million to 26.7 million hectares (McEwan et al., 2020). Furthermore, according to Wunder et al., (2021), the costs of fuel and agricultural production subsidized by governments, natural forest remnants tend to be more protected, less managed and therefore, unavailable.

The contribution of the Brazilian forestry sector in wood production to the national Gross Domestic Product (GDP), was of US$ 23.7 billion in 2018, based on the average exchange rate of 1:3.65 in 2018 (ACI, 2022), equivalent to 1.3% of Brazilian GDP and 6.9% of industrial GDP recorded in 2018 (Rabelo et al., 2020). Furthermore, the sector generated more than 2.0 million jobs, of which 533 thousand were classified as direct employment (IBÁ, 2022). Furthermore, planted forests play an important role in compensating for the pressure and negative impacts that natural forests face, including the use of biomass for energy, carbon trading and other products and services (Payn et al., 2015). However, international competition, lack of adequate policies and the instability of legal security make the Brazilian silviculture sector vulnerable to several risks which could render the production chain unviable for the development of the sector (Soares et al., 2010; Soares-Filho et al., 2016), especially for long term investments (Oliveira et al., 2020).

In terms of wood consumption only, it is expected that the demand for wood logs by 2050 will be around six billion m3 (McEwan et al., 2020). However, the yearly rates between 2010 and 2015 show a 1.2% drop in global forest plantations (Payn et al., 2015). However, to meet future global timber and fiber demands and to offset the impacts of native forests deforestation, there needs to be 2.4% increase in the forest planting rate (Payn et al., 2015). In this context, planted forests assume a strategic role in the supply of forest raw materials, with almost all planted forests are privately owned (95.0%) and provide 91.0% of all the wood used for industrial purposes, the majority of which (72.0%) are comprised of different *Eucalyptus* L'Heritier species (Chudy & Hagler, 2020). These plantations originates clonal material with a high technological level, from improved and highly productive varieties (Xavier & Silva, 2010; Castro et al., 2016; Masiero et al., 2022).

In Brazil, the total forests plantations area in 2022 covered 9,472,157.00 hectares, according to data from the Brazilian Institute of Geography and Statistics (IBGE) This is equivalent to a little over 1.1% of the country's territorial extension (Brasil, 2023). Of this total planted area, 77.3% (7,317,653.0 ha) represents eucalyptus plantations (Brasil, 2023). About the forestry market, although eucalyptus logs are not exported, Brazil is the world's largest exporter of short-fiber cellulosic pulp, derived from eucalyptus, and is the second largest exporter of all types of cellulose (Soares et al., 2010).

Regarding geographic distribution, the biggest eucalyptus plantations are in South and Southeast Regions, which stand out as the largest in wood stuffs production, accounting for 90.0% of charcoal (Southeast) and 58.0% of firewood (South), in addition to 45.0% of logs for paper and cellulose (Brasil, 2023). Furthermore, the Southeast accounts for 48.0% of logs production for other purposes, while the South contributes for 43.0% (Brasil, 2023). Northeast Brazil's participation in the national eucalyptus silviculture production, both for total logs (12.7%) and firewood (3.2%), is limited when compared to other Regions. Nonetheless, although the Northeast region only accounts for 5.6% of charcoal production, it still produced more of this product compared to other regions, coming second only to the Southeast (Brasil, 2023).

Therefore, given the forecasts and projections in the market for timber products, this is an opportunity for the forestry sector in Northeast Brazil to increase its participation in this scenario, especially through efficient production performance.

The performance of the structural efficiency of the forestry sector in Northeast Brazil, based on land and production factors (timber segments), can be analyzed simply through indicators on time intervals (Silva et al., 2005; Hosokawa et al., 2013), for example, relative values (index number). An index number is a quotient that expresses the relative variation between the values of any measurement (Farias, 2015), such as variations observed in a specific variable over time.

For complex quantities (multiple items or variables), this is defined as a composite (or synthetic) index. This allows for complex comparisons between a set of values that do not have a common physical measure, such as a quantitative expression of individual measurements (Farias, 2015). The use of an index number is therefore essential to clarify and facilitate understanding when the variation may represent a different path and may even be expressed as a percentage variation (Vasconcelos & Furletti, 2009). And as a statistical measure to compare groups of related variables and to obtain a simple and summarized overview of significant changes in related areas (Fonseca et al., 1988).

Among the indices, there is the Sauerbeck method which, although more commonly used in economics as a statistical technique, has been employed in forestry science as a tool for synthesizing structural data, aggregating relative indices of various variables (such as volume, basal area or diameter) to monitor the combined growth of different parameters in forest inventories, evaluating the overall performance or growth of a stand by summing the individual indices and dividing them by the total number of variables analyzed

(MacGregor, 1953; Pastorella & Paletto, 2013). Therefore, the variation in wood production by segment and the dynamics of the number of municipalities and the size of planted areas in the forestry sector of Northeast Brazil can be analyzed using indices that can guide more precise decisions in light of market perspectives and trends. Especially in unstable and critical market periods, such as was in the recent case of the Covid-19 pandemic (Kyfyak et al., 2022). Thus, the objective of this study was to evaluate the performance of eucalyptus forest planting in Northeast Brazil between 2021 and 2022, based on the production volume of wood segments and the distribution pattern of planted areas.

Material and Methods

Study area description

The Brazilian Northeast Region covers 1,552,175.48 km² (Brasil, 2022a), comprising nine federal states (Alagoas-AL, Bahia-BA, Ceará-CE, Maranhão-MA, Paraíba-PB, Pernambuco-PE, Piauí-PI, Rio Grande do Norte-RN and Sergipe-SE). It houses an estimated population of 54.1 million in habitants, equivalent to ~26.9% of Brazil's population (Brasil, 2022b).

Tropical climate types As (summer dry), Aw (winter dry) and BS (semi-arid) predominate in the north-south, north-west and central regions of Northeast Brazil, respectively (Alvares et al., 2013). The average rainfall is 1,053.2 (±236.9) mm year^{-1}, with Maranhão accounting for the maximum rainfall (1,632 mm year^{-1}) and Rio Grande do Norte representing the minimum (817 mm year^{-1}) (Silva et al. 2011). The average temperature is 23.7 (±0.56) ºC based on the types of climates that predominate in the region (Alvares et al., 2013).

The original vegetation cover in Northeast Brazil is comprised of several forest typologies largely distributed throughout the central region of the Phytogeographic Dominions of the Caatinga, Cerrado (western region), Atlantic Forest (east coast) and the Amazon in the extreme northwest region of Northeast Brazil. Predominant soil classes include Oxisols (29.5%), Neosols (24.0%) and Acrisols (16.7%), which together cover 70.2% of the Region's territorial extension (Marques et al., 2014).

Data acquisition and analysis

To evaluate the performance of eucalyptus cultivation in Northeast Brazil based on the analyzed indices, data on volume (m^3) and megagrams (Mg) of timber production by segment (charcoal, pulp, and logs) were used; as well as data on the numerical quantity of municipalities and size of areas with forest plantations in the region. The data were obtained from the electronic platform of Plant and Forest Extractive Production, available at the Brazilian Institute of Geography and Statistics - IBGE (Brazil, 2023), referring to the biennial activity (2021-2022) of this forestry sector (Brazil, 2023). The dataset was organized, tabulated, and used to calculate the indicators. Descriptive statistics were also performed, obtaining measures of position and dispersion for the analyzed variables: number of municipalities, number of areas with eucalyptus plantations, production and productivity of charcoal, firewood, and logs (for pulp and paper and other purposes) by state. Productivity was estimated from the direct ratio of production (by timber segment) to the planted area.

Based on the Sauerbeck index method (Balk, 2012), the relative quantity (q_r) and the aggregate unweighted arithmetic mean index (I_r) were calculated as indicators of changes in the analyzed variables between the base period (2021) and the current period (2022), according to Equations (1), (2), and (3).

$$q_{r(0,t)} = \frac{q_t}{q_0} \quad (1)$$

$$\Delta = q_{r(0,t)} - 1 \quad (2)$$

$$\bar{I}_r = \frac{1}{n}\sum_{i=1}^{n} q_{r\,(0,t)}, \quad (3)$$

where: q_r = relative quantity; q_t = quantity of the variable during the current period: q_0 = quantity of the variable during the base period; Δ (%) = percentage variation; $\bar{I}_r$ = unweighted composite aggregate arithmetic mean index; n = number of variables, varying from 1 to n federal states.

Was evaluated the relative variables and the cluster analysis was performed using Euclidean dissimilarity effect. For this, Kendall's non-parametric rank test was used, considering non-linear relationships and measurements with non-normally distributed data (Puth et al., 2015). And the Kendall's rank correlation ($p < 0.05$). In order to understand the relationship between the variables, a cluster analysis was performed based on the level of dissimilarity according to Kendall's classification correlation matrix ($p < 0.05$). Statistical analyses were performed using Action Stat 3.6 ® (Action P, 2016).

Vector cartographic data [SHP] obtained for the year 2018 (most recent data), were used for representative purposes regarding eucalyptus plantations in the Northeast Region of Brazil, from the database available on the Global Forest Watch platform of the World Resources Institute (WRI/GFW). With this data, was possible to generate a thematic map of the distribution of eucalyptus plantations in Northeast Brazil using Qgis 3.26.3 ® software.

Results

Forest plantation distribution

The spatial distribution of *Eucalyptus* L'Heritier plantations in the states of Northeast Brazil showed a concentration in a few states, with forest density restricted to a few locations. The state of Bahia stands out with 64.0% of the areas and 37.0% of the municipalities with eucalyptus plantations, followed by Maranhão (28.0% and 18.0%, respectively). The state of Alagoas, despite representing only 2.0% of the areas with plantations in the Northeast, concentrated 18.0% of the municipalities with plantations in the Northeast region (Figure 1).

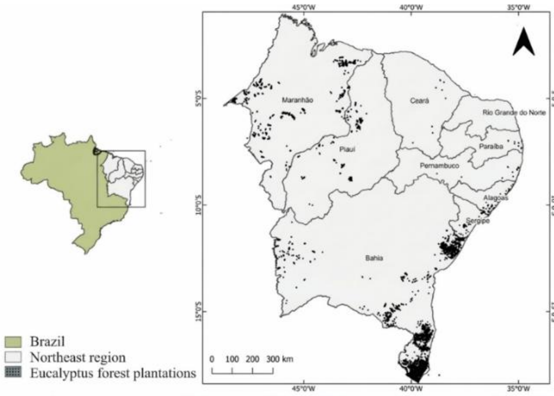

Figure 1. Distribution of *Eucalyptus* L'Héritier plantations across Northeast Brazil (WRI/GFW, 2019).

Variation in planted area and municipality number

The dynamics observed in eucalyptus plantations in Northeast Brazil during the study period suggest that there may have been a reduction in area variations (-8.2%) and an increase in the number of municipalities (1.0%), with a more centralized distribution of the highest densities of plantations and industries in the sector. The states of Ceará (3144.2%) and Alagoas (15.7%) represented the largest areas with plantations. Paraíba (-13.3%), Piauí (-8.2%) and Maranhão (-7.4%) showed the smallest reductions. Regarding the number of municipalities, the states of Ceará (100.0%) and Alagoas (1.9%) showed the largest positive variations, while the state of Bahia showed a negative variation of 1.8% (Table 1).

Table 1. *Eucalyptus* L'Heritier plantation area, municipality count, and relative changes (2021–2022) in Northeast Brazil.

States	Area (ha)			Municipalities		
	2021	2022	Δ-%	2021	2022	Δ-%
BA	572,928	564,456	-1.5	112.0	110.0	-1.8
MA	272,157	252,105	-7.4	57.0	57.0	0
AL	20,989	24,277	15.7	53.0	54.0	1.9
PI	27,427	25,182	-8.2	28.0	28.0	0
SE	6,161	6,171	0.2	22.0	22.0	0
PB	1,192	1,033	-13.3	10.0	10.0	0
PE	1,109	1,142	3.0	9.0	10.0	0.1
CE	52.0	1,687	3,144.2	3.0	6.0	98.0
RN	0	0	0	0	0	0
Overall	953,963	876,053	-8.2	294.0	297.0	1.0

Where: BA= Bahia; MA= Maranhão; PI= Piauí; AL= Alagoas; SE= Sergipe; CE= Ceará; PB= Paraíba; PE= Pernambuco; RN= Rio Grande do Norte; (Δ-%) = rate of change (variation).

Variation in production by timber segments

In 2022, eucalyptus cultivation developed in the Northeast region of Brazil produced 111,015,298.0 m^3 of lignocellulosic phytomass (firewood, logs for paper and pulp, and logs for other purposes) and 395,423.0 Mg of charcoal (Table 2), varying positively compared to the previous year by 55.4% in charcoal production and 5.4% in logs - other purposes. However, during the same period, it varied negatively in the production of logs - paper and cellulose (-41.4%) and in the production of firewood (-1.9%). Maranhão showed the largest variations in firewood and charcoal production, respectively 134.5% and 224.8% during the study period. Piauí showed the largest variation in logs for other purposes (665.2%). No state showed a positive variation in logs for cellulose. The state of Alagoas, with little tradition in the sector, showed the second largest variation in charcoal (190.0%).

Table 2. Production of firewood, charcoal, and logs for paper, cellulose, and other purposes, and relative changes (2021–2022) in *Eucalyptus* L'Héritier silviculture in Northeast Brazil, according to IBGE (Brazil, 2023).

States	Firewood (m^3)			Charcoal (Mg)			Logs – paper and cellulose (m^3)			Logs – other purposes (m^3)		
	2021	2022	Δ-%	2021	2022	Δ-%	2021	2022	Δ-%	2021	2022	Δ-%
BA	1,091,843	1,147,142	5.1	161,606	157,848	-2.3	11,315,265	5,416,651	-52.1	23,504	73,376	212.2
MA	23,628	55,415	134.5	65,235	211,849	224.8	4,176,738	3,660,292	-12.4	0	0	0
AL	34,66	26,255	-24.3	30.0	87.0	190.0	0	0	0	414,403	378,37	-8.7
PI	223,626	99,3	-55.6	27,63	25,618	-7.3	0	0	0	1,188	9,091	665.2
SE	120,243	135,802	12.9	3	3	0	0	0	0	3,49	5,453	56.3
PB	200.0	160.0	-20.0	0	0	0	9.8	6.0	-38.8	0	0	0
PE	1,062	1,351	27.2	0	0	0	0	0	0	18.0	40.0	122.2
CE	260.0	265.0	1.9	0	18	0	0	0	0	320.0	335.0	4.7
RN	0	0	0	0	0	0	0	0	0	0	0	0
Overall	1,495,522	1,465,690	-1.9	254,504	395,423	55.4	15,501,803	9,082,943	-41.4	442,923	466,665	5.4

Where: BA= Bahia; MA= Maranhão; PI= Piauí; AL= Alagoas; SE= Sergipe; CE= Ceará; PB= Paraíba; PE= Pernambuco; RN= Rio Grande do Norte; (Δ-%) = rate of change (variation); (Mg) = megagrams.

Variation in timber productivity per unit area

The general average productivity of eucalyptus production among Northeast states varied from a decline (-44.3%) in the log for paper and cellulose sector and logs for other purposes (-35.6%) to a significant increase in the charcoal sector (40.5%) (Table 3). Among the states, Maranhão had the highest productivity (144.4%) of firewood and charcoal (250.0%). And Piauí (800.0%) and Bahia (over 220.0%) with a growing variation in the sector of logs for other purposes.

Table 3. Productivity of firewood, charcoal, and logs for paper, cellulose, and other purposes, and relative changes (2021–2022) in *Eucalyptus* L'Héritier silviculture in Northeast Brazil, according to IBGE (Brazil, 2023).

States	Firewood ($m^3.ha.year^{-1}$)			Charcoal ($Mg.ha.year^{-1}$)			Logs for paper and cellulose ($m^3.ha.year^{-1}$)			Logs for other purposes ($m^3.ha.year^{-1}$)		
	2021	2022	Δ-%	2021	2022	Δ-%	2021	2022	Δ-%	2021	2022	Δ-%
BA	1.91	0.49	-74.2	0.28	0.28	-0.9	19.75	9.60	-51.4	0.04	0.13	225.0
MA	0.09	0.22	144.4	0.24	0.84	250.0	15.35	14.52	-5.4	0	0	0
AL	1.65	0.92	-44.0	0	0	150.7	0	0	0	19.74	15.59	-21.0
PI	8.15	0.25	-96.9	1.01	1.02	1.0	0	0	0	0.04	0.36	800.0
SE	19.52.0	22.01.0	12.8	0	0	0	0	0	0	0.57	0.88	54.4
PB	0.17	1.03	5.9	0	0	0	8.22	0.01	-99.9	0	0	0
PE	0.96	1.18	22.9	0	0	0	0	0	0	0.02	0.03	50.0
CE	5.00	11.59	31.8	0	0.01	0	0	0	0	6.15	0.11	-98.2
RN	0	0	0	0	0	0	0	0	0	0	0	0
Overall	37.45	37.69	0.6	1.53	2.15	40.5	43.32	24.13	-44.3	26.56	17.1	-35.6

Where: BA=Bahia; MA=Maranhão; PI=Piauí; AL=Alagoas; SE=Sergipe; CE=Ceará; PB=Paraíba; PE=Pernambuco; RN=Rio Grande do Norte; (Δ)= rate of change (variation in productivity).

Kendall's correlation analysis

Using Kendall's non-parametric rank test with a significance of 5 %, for the variation rates (2021 to 2022) of the analyzed variables, a significant correlation was observed (p < 0.05) only between charcoal and Logs for other purposes (p = 0.015), with a weak to moderate association, explained in 65.2% (Table 4, Figure 2).

Table 4. Kendall's rank correlations (p < 0.05) among 2021–2022 changes in eucalyptus plantation area, municipalities, logs (paper and cellulose - pc; other purposes - op), firewood, and charcoal in Northeast Brazil, according to IBGE (Brazil, 2023).

Variables	Municipality	Firewood	Charcoal	Logs (pc)	Logs (op)
Area	*p* (0.104) τ (0.46) τ^2(18.9%)	*p* (0.484) τ (0.20) τ^2(4.0%)	*p* (0.631) τ (0.43) τ^2(18.6%)	*p* (0.154) τ (0.38) τ^2(14.5%)	*p* (0.717) τ (-0.09) τ^2(0.8%)
Municipality		*p* (0.416) τ (-0.22) τ^2(4.7%)	*p* (0.128) τ (0.43) τ^2(18.6%)	*p* (0.300) τ (0.30) τ^2(9.0%)	*p* (0.149) τ (-0.39) τ^2(15.5%)
Firewood			*p* (0.631) τ (0.13) τ^2(1.6%)	*p* (0.684) τ (-0.11) τ^2(11.9%)	*p* (0.586) τ (0.14) τ^2(1.9%)
Charcoal				*p* (0.83) τ (-0.06) τ^2(0.4%)	*p* (**0.015**)* τ (-0.65) τ^2(65.2%)
Logs (pc)					*p* (0.757) τ (-0.09) τ^2(0.7%)

Where: *p* = significance value of the alpha error; τ = coefficient of Kendall's rank correlation matrix; τ^2 = coefficient of determination of the effect size correlation; (*) = Kendall's rank correlation significant at 5%.

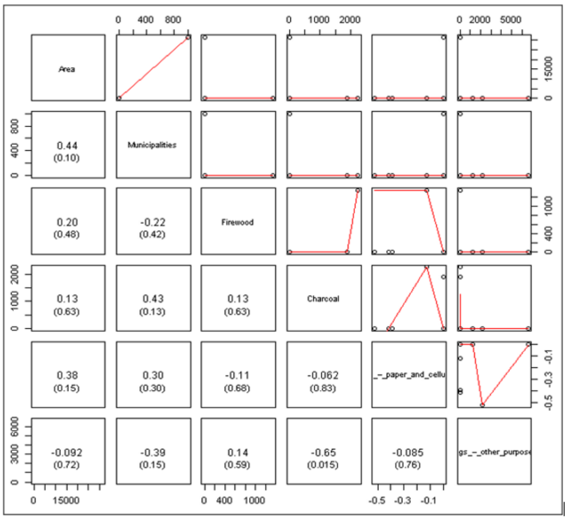

Figure 2. Kendall's rank correlation scatterplot (p < 0.05) of 2021–2022 changes in eucalyptus silviculture variables in Northeast Brazil, according to IBGE (Brazil, 2023).

The relationship between the variables (timber sectors and production factors) did not show a correlation involving variation between areas and municipalities. Only a positive, albeit weak, correlation was observed between the variation in charcoal production and the production of logs for other purposes, evidencing a direct proportionality.

Dissimilarity-based clustering

Based on the cluster analysis of the distance coefficient for the relativity between the variables (Figure 3), two dissimilar groups were formed. The first group was formed only by the logs for other purposes and firewood sector, while the second group contained the remaining variables, demonstrating lower dissimilarity between municipalities and areas with plantations and logs for paper and cellulose, followed by a lower dissimilarity between charcoal. Notably, two dissimilar subgroups were formed in the second group, the charcoal subgroup and the municipalities, area and paper and cellulose logs subgroup.

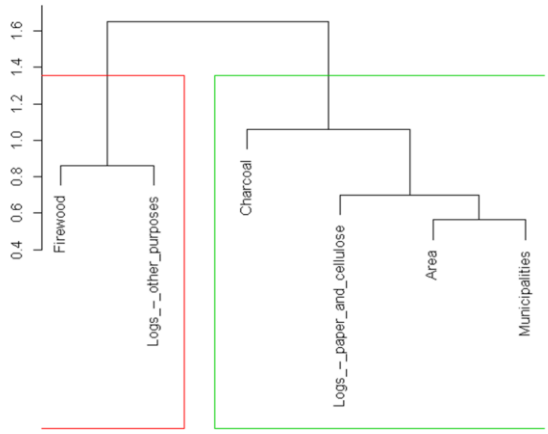

Figure 3. Clustering of eucalyptus silviculture variables based on Kendall's correlations (p < 0.05) and 2021–2022 changes in Northeast Brazil, according to IBGE (Brazil, 2023).

The result of the variables analyzed for the study period showed an extremely low unweighted synthetic aggregate index ($\bar{I}_r$ = 0.026), although the increasing relative indices for charcoal contributed most strongly, followed by logs for other purposes and number of Municipalities with plantations area with plantations, albeit weakly (Table 5).

Table 5. Average index numbers for 2021–2022 changes in eucalyptus silviculture in Northeast Brazil, according to IBGE (Brazil, 2023).

Variables	$q_{r0,t}$
Plantations (ha)	-0.029 (±11.123)
Plantations (nº)	0.010 (±0.331)
Firewood (m^3)	-0.020 (±0.529)
Charcoal (Mg)	0.554 (±0.925)
Logs – pc (m^3)	-0.414 (±0.200)
Logs – op (m^3)	0.054 (±2.188)
$\bar{I}_r$	0.026 (±0.282)

Discussion

Forest plantation distribution

The concentration of *Eucalyptus* L'Heritier silviculture plantations in a few states of Northeast Brazil, especially in Bahia and Maranhão, which together represent over 90.0% of areas and over 50.0% of the number of municipalities with planted forests, is influenced by the major players of the silviculture sector located in these states. Such players, for example the companies Bracell and Veracel in Bahia and Suzano in Maranhão, acquire areas and stimulate activities ranging from intensive silviculture to the large-scale cellulose productive chain (Martin, 2014; ABAF, 2019), adopting high quality and high productivity clonal varieties, acquired mainly through genetic modification (Xavier & Silva, 2010; Castro et al*.,* 2016).

This becomes more evident when observing that 71.5% (180,211.0 hectares) of the planted areas in Maranhão are concentrated in 17.5% (n=10) of the 57 municipalities with plantations in this state. Similarly, in Bahia the 10 (9.1%) largest municipalities in terms of land planted with eucalyptus silviculture, concentrate 62.7% (353,798.0 ha) of the total area with plantations in the state (Gama et al. 2025). Therefore, plantations closer to large industrial centers and associated with land value and logistical costs of production, are more competitive, compared to more distant plantations (Teixeira et al., 2018). Most wood inventories near industrial parks are composed of plantations on leased or company-owned land, to reduce additional costs associated with harvesting and transportation (Barua et al., 2014; Keefe et al., 2014; Teixeira et al., 2018). Using the promotion of silviculture as an essential tool for competitive production (Fischer, 2009).

On the other hand, low density forest formations, distributed further away from the major centers, are mostly comprised of plantations located on small rural properties (Peña-Cortés et al. 2021; Tesfaw et al., 2023).

Generally speaking, the large variation in plantation area, between denser and more dispersed, is likely related to economic and technological factors, expressed based on the type of silviculture adopted (intensive or extensive) and on environmental factors (topographic, climatic and soil limitations) (Rubilar et al., 2018; McEwan et al., 2020; Tomé et al., 2021).

It is worth mentioning that even though eucalyptus silviculture is present in all Northeast states, except for Rio Grande do Norte (RN), extensive silviculture is not strongly promoted, and is not disseminated beyond the surrounding areas of the major centers. This has been previously observed by authors such as Drumond et al. (2016), who draw attention to the existence of regions that do not traditionally plant forests, and consequently require the development of technologies to obtain good quality, diversified and competitive products. Additionally, in Brazil there are extensive forest resources located at considerable distances from main population concentrations, which consequently discourages consumption due to the high price of the product, mainly due to logistical cost, especially with transportation (Simmons et al., 2002).

Therefore, the expansion of plantations beyond established boundaries would be a decisive factor in balancing production rotation. This would supply and maintain regular wood stocks, during a period when productivity and current stocks are unable to counterbalance supply and demand, especially for less specialized wood forest products such as logs and firewood.

In this way, confirming this trend, the presence of forest incentive programs, including, becomes essentially relevant for the growth prospects of the forestry industry and the formation of commercial forests for medium and large production units, also providing land value to the owners involved and social returns to the related rural communities (Diesel et al. 2006; Basso et al., 2012; Souza et al. 2019)

Production and planted-area dynamics

The sector's dynamics in Northeast states demonstrated a decreasing variation in areas and in the number of municipalities in Bahia and a reduction of areas in Maranhão, highlighting the irregular performance of these two states that contain the two large eucalyptus silviculture centers in the Northeast.

The negative variation in planting areas may be related to the dynamics of cutting and subsequent planting or to changes in land use, which can also be explained for the states of Paraíba and Piauí, although the impacts were smaller in these states.

However, in Ceará we observed positive

variations for the number of municipalities and for the extension of the planted area.

Similarly, the states of Ceará and Alagoas represent the largest positive variation in areas with plantations. Maranhão, Bahia, Pernambuco, Alagoas, and Piauí show positive variations in timber production. Therefore, although eucalyptus silviculture in these states is still incipient in this scenario, these changes demonstrate an optimistic outlook for the behavior of this of the forestry sector, since structuring the sector's production chain in this region could represent a strong long-term trend towards more efficient forestry production in terms of productivity per unit area.

In terms of productivity, Maranhão, Piauí and Paraíba represented the states with the most impactful productivity variations among during the studied period, despite downward variations for both area and number of municipalities. These fluctuations in productivity are likely related to a complex combination of both technical events and market retraction (e.g., the Covid-19 pandemic), which resulted in low demand and consequent depreciation of products (Chudy & Hagler, 2020).

Furthermore, there is a possibility that the forest plots may have been outside the Technical Cutting Age-TCA (cutting cycle) during the analyzed period, since this forest management tool, when not managed correctly, according to Acuna et al. (2017), Lejeune and Kettunen (2017) and Acuña et al. (2018), can interfere with production. In Brazil, the harvest age is generally between 5 and 8 years for cellulose and energy (Ferreira, 1979; Silva et al., 1999; Mafia et al. 2012; Morais et al,. 2017; Coelho et al., 2019; Cunha et al., 2021).

Another point that should be analyzed is that, although the effect of the Covid-19 pandemic was widespread, the export market experienced greater restrictions, affecting the timber production of logs for paper and cellulose more than any other timber sector (Chudy & Hagler, 2020). This can be observed through the decrease in this sector's production, which is mostly comprised of commodity products. Contrarily, the low reduction in logs other purposes and charcoal production, which is a local and regional market sector, maintained a more current and less restrictive availability, with greater stimulus, due to the demand for this national market. Furthermore, while there was low demand for Brazilian agricultural production in the international market, due to the Covid-19 pandemic, in Brazil the circulation of resources made available from government programs, due to the fight against Covid-19 (Cardoso, 2020), contributed to the increase in domestic consumption, which may have favored silviculture, indirectly, through the circulation of capital.

Although the factors (areas and municipalities) point towards increasing variations for eucalyptus plantations in the Northeast, it is still unsafe, especially for non-leased areas or municipalities where this activity is incipient and can fluctuate constantly, support a measure of rapid development of the sector in the region, so much so that stability cannot be guaranteed in the short and medium deadline. It is also worth noting that the production of firewood and charcoal, are products with a relatively low monetary gain value, as they are less specialized and not very aggregative, compared to the logs for paper and cellulose sector. On the other hand, environmental value can be added to these two eucalyptus timber sectors. Since, according to Bichel and Telles (2021), the production of firewood and charcoal from planted forests tends to cause a reduction in the use of forest resources due to extractivism. Therefore, when estimating this sector's performance, each factor and timber sector should be analyzed separately, although inclusively.

Studying the distribution of silviculture in the Northeast, Drummond et al. (2016) observed a similar performance: a positive contribution in Maranhão and a drop in Bahia, despite being the largest in terms of area extension and number of municipalities. The authors further noted positive variations in Piauí, with an increase in areas of just over 10.0% and in the number of municipalities by almost 8.0%. For Alagoas, the authors saw a 12.8% increase in planted areas, while the number of municipalities remained stable.

Correlation and dissimilarity clustering

When analyzing the relationship between the variables (timber sectors and production factors), no correlation was observed involving the variation in input between areas and municipalities. Only a positive, albeit weak, correlation was observed between the variation in charcoal production and logs for other purposes, evidencing a direct proportionality between them. Therefore, the size of the planted area or the number of municipalities with plantations may not be sufficiently relevant as influencing factors for the preferential increase or decrease of a particular timber production segment.

Based on the results of the cluster analysis, the association of analogous subgroups (charcoal, logs for other purposes, and firewood) occurs, possibly, due to the joint participation of the states in the production of these segments. The results differs from the pulp segment and the areas with plantations, which are practically concentrated in Bahia and Maranhão. Within timber production, although charcoal and logs for other purposes show the best production indicators and index, the grouping of these variables demonstrates greater dissimilarity.

The value of the positive unweighted synthetic aggregate index, in the short study period, implies that there is a regionally competitive forestry sector as a whole. However, observing the decomposition of the causes, the weight of the relative variations of the cellulose and area with forest planting factors more negatively contributed more to a lowering of the index, although remaining positive. This possibly is due to them being less pulverized factors in the forestry sector of the northeast region. However, it is not possible to guarantee the absence of critical and unstable periods in the long term, especially when fluctuating some changes of incipient activities in the forestry sector in some locations in Northeast Brazil. Seen in the cellulose sector, as the most specialized and produced the greatest volume, while providing a less than optimistic performance with an average overall productivity of only 2.7m^3.ha^{-1} and negative variation with relative average index of -0.414.

Relative average performance index analysis

Regarding performance among the states, eucalyptus forestry in Bahia, although dominant in all sectors of timber production in terms of gross value, showed a decline in most sectors, with the exception of log production for other purposes (212.2%) and firewood production (5.1%). In Maranhão, forestry, during this period, showed significant growth (134.5%) in firewood production and charcoal production (224.8%), despite a decrease (-12.4%) in the variation of log production for paper and pulp. The state of Alagoas varied significantly (190%) in charcoal production, even without a productive tradition in the sector or prominence in the extent of plantations. In contrast, Piauí, with a strong tradition in the sector, showed a highly positive variation (665.2%) in log production for other purposes, but had a negative variation (-55.0%) in firewood production and charcoal production (-7.0%). The production of logs for other purposes generated positive variation in Pernambuco (122.2%) and Sergipe (56.3%).

These drastic changes, even for regions traditionally recognized in production, may be a reflection of the economic decline in monetary value in the Brazilian forestry sector, as reported by Oliveira et al. (2023), who found the sector's real GDP in relation to Brazil's real GDP with negative rates, triggered from 2012 onwards. According to the authors, this occurred due to financial crises and market changes that impacted some forest products more intensely than others. Another relevant piece of data in this dynamic is the variation in the size of planted areas, which was reflected in productivity variations in states where production did not keep pace with the increase in planted areas, such as Ceará with a highly positive variation (3144.4%) in planted areas, but which was not reflected in production. Thus, the low productivity under these conditions may be related to the cutting cycle not coinciding with the increase in planted areas or the low technology adopted. This is a characteristic of the forestry sector that needs to be properly managed.

The average relative indices established for most variables, especially charcoal production, show that during the study period there were no demand conflicts between the timber production sectors, with the specific exception of logs for pulp. In this case, higher consumption in one sector leads to increased demand at the expense of the other and vice versa, which can cause economic difficulties in the sector during specific periods.

Regarding the performance index of the forestry sector in Northeast Brazil, which is extremely low ($\bar{I}_r$ = 0.02), it does not accurately represent the phenomenon analyzed, according to authors such as Angilella et al. (2018), Garcia-Bernabeu et al. (2021) and Paula & Fonseca (2025), since more effective performance depends on the balance between variables, which did not occur.

However, in general, as Soares et al. (2010) emphasize, eucalyptus wood production in Brazil, despite the problems, is still economically efficient and capable of overcoming difficulties. However, in the specific case of the Brazilian Northeast, it is necessary for the sector to constantly monitor the growing diversification of the market, demonstrating the ability to adapt to any changes, and continuously improving its strategic planning.

Conclusions

We observed that the performance of *Eucalyptus* L'Heritier silvicultural activity in the forest base formed in Northeast Brazil, during the study period, presents an unbalanced production structure, inclined towards the timber segment to the detriment of the land structure.

The dynamics of planted areas and municipalities participating in eucalyptus cultivation in Northeast Brazil show an inequitable distribution pattern among the states, resulting in discrepant sizes and productivity of the timber segment expressed per unit area.

Due to the highly concentrated distribution of the forestry sector in a few states and the growing demand for wood, it is important that policies for maintaining and expanding eucalyptus silviculture production be directed towards more inland regions of Northeast Brazil and areas distant from traditional centers, in order to avoid restrictions that could limit the performance and productive capacity of the sector in the medium and long term, with the inclusion of new municipalities and larger area extensions.

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