The Spatial Patterns of Deforestation in Pará, Brazil: From Economic Necessity to Environmental Threat

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Abstract

The emergence of green deforestation demands heightened attention, as it conceals environmental degradation under the guise of sustainability. In this context, the objective of this study is to analyze the deforestation pattern in the state of Pará, assessing whether it exhibits a specific spatial distribution and whether the structural causes of deforestation enable the identification of areas correlated with so-called green deforestation. The research adopts a descriptive and quantitative approach, employing the Moran's I and LISA indices to identify spatial clusters of deforestation. Additionally, the Kruskal-Wallis and Spearman correlation tests were applied to analyze relationships among deforestation, development, and productive activities in 143 municipalities of Pará. The results reveal four distinct territorial patterns (clusters), in which deforestation is strongly associated with livestock farming (ρ = 0.866), followed by agriculture. The High-High cluster is particularly noteworthy for combining high municipal development with elevated deforestation rates, driven by intensive agricultural and livestock expansion. Conversely, the Low-Low cluster demonstrates lower environmental pressure and greater sustainable extraction of non-timber forest products such as açaí and Brazil nuts. The principal conclusion is that deforestation in Pará does not follow a uniform pattern but instead reflects distinct territorial trajectories, which require regionally tailored public policies. Based on these findings, there is a pressing need for greater governmental attention in the planning of public initiatives to promote economic activities and combat deforestation. Such interventions must be implemented in accordance with the specific characteristics of each region.

Keywords: Political planning, Deforestation indicators, Spatial dependence

1. Introduction

The exploitation of natural resources accompanies Brazil's history, but the irrational use of these resources has increased societal concern, academic discussions, and governmental attention due to its contribution to deforestation, biodiversity loss, global warming effects, among others. In this context, (Freitas, Magalhães, Carmona, Arroyo-Rodríguez, Vieira, & Tabarelli, 2021) draw attention to another problem: the replacement of forests with non-timber forest products, especially açaí (Euterpe oleracea), which represents an important economic opportunity for local populations.

This process masks deforestation by replacing native forest with a species that negatively impacts biodiversity and ecosystem services, culminating in so-called "green deforestation"(Freitas et al., 2021). The term "green deforestation" frequently describes various forest management practices involving selective vegetation suppression to promote plant species with greater economic value (Barrozo, De Sousa, Santos, De Almeida, & Weiss, 2019; Neves & Bizawu, 2019).

It involves seeking strategies that reconcile forest conservation with economic and social development. The term may refer to approaches attempting to make deforestation less harmful or policies aimed at mitigating its environmental, social, and economic impacts (Busch & Ferretti-Gallon, 2017). In many cases, green deforestation receives justification based on arguments promoting sustainability through environmentally responsible practices designed to minimize adverse ecosystem impacts (Lopes, Chiavari, & Segovia, 2023; Nishimwe, Hakizimana, Nahayo, Maniragaba, & Nirere, 2021; Young, 2009).

However, critical reflection on these claims remains necessary, as reality often fails to align with these perspectives. While some practices may reduce environmental impacts, others may disregard long-term cumulative effects such as biodiversity loss, soil degradation, and intensification of climate change (Lopes et al., 2023; Prates & Bacha, 2011). Additionally, practices may be implemented with insufficient regulation or oversight, resulting in significant environmental degradation and abuse (Marschner, 2014).

In this context, deforestation creates a false sense of security by encouraging practices that maintain apparent vegetation cover, masking the impoverishment of biodiversity and local ecosystem functioning in favor of economic interests (Freitas et al., 2021; Miyamoto, 2020). Therefore, developing a holistic approach to map and combat practices that compromise forest integrity and generate climatic, economic, and social imbalances becomes necessary.

Understanding the factors driving deforestation in a territory is essential to guide strategic actions. These factors include illegal timber product exploitation, livestock expansion, growing urbanization, poverty, infrastructure expansion, mining, oil extraction, and political influence (Busch & Ferretti-Gallon, 2017; Pastoral Land Commission [CPT], 2017; Hänggli, Armenteras, Bovolo, Brandão, Rueda, & Garrett, 2023; Jakimow, Baumann, Salomão, Bendini, & Hostert, 2023; Miyamoto, 2020). Specifically in Brazil, agricultural frontier expansion plays a predominant role in increasing deforestation.

In Pará state, the problem reaches critical levels. Deforestation in Pará reflects patterns marked by expansion and consolidation of areas designated for agricultural activities, especially bovine production (Carneiro Filho, 2009, p. 163; Herrera & Moreira, 2013; Oliveira Junior, De Souza Filho, Ferreira, & Souza Junior, 2024). Certain administrative periods contributed to this phenomenon (Jakimow et al., 2023). State policies, by encouraging land use changes, favored converting native forest areas into pastures and crops, contributing to significant native forest loss, more than 271,735 km² until 2019 (Coelho & De Toledo, 2024).

Despite efforts to combat deforestation, such as enforcement with fines, collaborative governance, advances in protected area management and land control, and involvement of communities and stakeholders in conservation strategies, results remain below expectations (Aguiar, 2022; Conceição, Chaves, & Mataveli, 2020; Correia-Silva & Rodrigues, 2019). Analyses indicate that deforestation in the territory occurs in different phases and at varying rates, rendering standardized strategies and actions ineffective. Therefore, delineating spatial patterns revealing correlations between factors underlying forest loss becomes fundamental to inform more effective public policies that minimize deforestation problems, especially green deforestation.

This study aims to analyze Pará's deforestation pattern, whether it presents a specific spatial distribution, and whether structural causes of deforestation allow identification of areas correlated with "green deforestation." Although traditional deforestation, related to agricultural expansion and timber product exploitation, receives extensive study, more subtle practices such as green deforestation may gain ground and configure a new challenge for conservation policies, especially linked to non-timber products with high economic value.

Therefore, understanding deforestation's spatial distribution and structural correlations becomes essential to identify areas with greater potential for different deforestation types, especially green deforestation. Such understanding can inform more specific, effective, and territorially adjusted public policies, overcoming standardized deforestation confrontation models that often ignore local and regional dynamics.

Moreover, by integrating spatial and causal analysis, this study contributes to the debate on limits and contradictions of practices considered sustainable, promoting a more critical approach to territorial development in the Amazon. In doing so, it aims to contribute to a deeper understanding of the complexities involved in the interaction between economic development and environmental conservation in the state.

This study encompasses not only the aforementioned introduction but also a section dedicated to materials and methods, followed by results and discussions exploring the implications of findings, and finally, concluding considerations summarizing key discoveries with possible implications for public policy formulation and decision-making.

2. Method

The study adopts a descriptive character. This research type focuses on the accurate description and characterization of phenomena, events, people, clusters, objects, or processes, serving as a fundamental basis for the development of a solid information framework that can act as a starting point for more in-depth investigations (Creswell, 2010). In many research endeavors, descriptive studies constitute the initial phase of a broader research process, as they allow researchers to explore a topic or problem, identify relevant variables, and formulate hypotheses for future inquiry.

The field of study encompassed the state of Pará. This state covers an extensive area of 1,245,870.798 km² and exhibits considerable territorial disparity, with municipal areas ranging from 103.21 km² to 1,595.331 km² (Brazilian Institute of Geography and Statistics

[IBGE], 2021a). The state comprises 144 municipalities; however, one was excluded from the analysis due to the unavailability of data. The municipal development index also reveals heterogeneity, ranging from 0.19 to 0.61, with a mean value of 0.36 and a standard deviation of 0.09, indicating significant challenges and disparities in regional development (IFDM) (Federation of Industries of Rio de Janeiro [FIRJAN], 2018).

To achieve the research objective, deforestation data provided by the Amazon Foundation for Support of Studies and Research (FAPESPA, 2021) were employed to calculate the Moran's I index, in order to identify the presence of spatial autocorrelation within the state of Pará. The data used correspond to the year 2021. Based on the variable, the Global Moran's I index was computed to evaluate spatial autocorrelation, indicating whether a given spatial pattern is random, dispersed, or clustered.

In this regard, the studied object may exhibit diverse spatial effects depending on its relationship with geographic location (Bonat, Paiva, & Sliwiany, 2010; Câmara, Carvalho, Cruz, & Correa, 2002). Accordingly, the index allows for the identification of four spatial association patterns or clusters (Bonat et al., 2010; Câmara et al., 2002): High-High, where areas with high values are concentrated; Low-Low, where regions with low values are grouped; and High-Low and Low-High, which represent spatial outliers with contrasting values relative to adjacent areas (Bonat et al., 2010; Câmara et al., 2002).

Subsequently, the Local Indicators of Spatial Association (LISA) were applied to identify, with greater statistical significance, the areas with the highest explanatory potential regarding deforestation patterns. Additionally, data on municipal territorial extension, municipal development indicators (as measured by the IFDM Index, developed by the Federation of Industries of the State of Rio de Janeiro), the number of permanent and temporary crop areas, livestock information, as well as various timber and non-timber forest products, were collected for detailed analysis (FIRJAN., 2018; IBGE, 2021b). The annual variation of these variables was calculated to determine whether they exhibit trends of growth or decline.

Finally, following the spatial analysis, the Kruskal-Wallis test was employed to assess whether the studied variables displayed similar mean values across the identified municipal clusters. Furthermore, the Spearman correlation test was applied to analyze the degree of correlation among these variables within the identified clusters.

3. Results

Pará possesses a diversified economy driven by mineral extraction (iron and bauxite). Agriculture (soybeans, fruits) and livestock production (Cattle and Buffalo) also maintain significant relevance. Industry and tourism complement the economic landscape, demonstrating a state with multiple productive sectors. Specifically, plant extraction of products such as Brazil nuts, açaí, latex, as well as timber and other forest resources generates income for traditional and indigenous communities, contributing to the regional economy and biodiversity preservation.

In this context, deforestation generates environmental and economic impacts for numerous communities. Total deforestation presents an average of 1,969.48 km², with peaks reaching

20,471.50 km², while annual variation exhibits an average of 36.01 km² with significant oscillations, as observed in Table 1.

Table 1. Municipal indicators

Descriptive Statistics	Minimum	Maximum	Mean	Standard Deviation
Municipality area in KM²	103,21	159533,31	8677,50	19582,89
Municipal Development Index	0,19	0,61	0,36	0,09
Total Deforestation	0,00	20471,50	1969,48	2637,23
Deforestation Variation	0,00	777,50	36,01	100,15
Cattle (heads)	15,00	2468764,00	167156,09	301917,03
Variation Cattle (heads)	-17518,00	208750,00	10390,41	24014,07
Permanent crops (hectares)	0,00	61530,00	3019,74	8563,02
Change Permanent crops (hectares)	-7370,00	4004,00	-52,41	907,50
Temporary crops (hectares)	0,00	196941,00	9920,72	26071,05
Change Temporary crops (hectares)	-23648,00	34230,00	863,56	4715,39
General Plant Extraction	0,00	542512,00	40598,59	88465,52
Variation in General Plant Extraction	-107125,00	110714,00	2573,87	21308,27

Cattle ranching reaches an average of 167,156 head, with notable extremes. Permanent and temporary crops also demonstrate expressive dispersion in their cultivated areas. General plant extraction reaches an average of 40,598.52 tons, with considerable annual variations. These data point to the heterogeneity of activities and environmental changes in the state, demanding more in-depth analyses for effective territorial development strategies.

In view of this, Spearman analysis revealed important associations for understanding deforestation in Pará. There exists a significant positive correlation with cattle quantity (ρ = 0.866), indicating a vector of forest suppression, reinforcing a historically verified pattern in agricultural expansion zones where conversion of forest areas into pastures constitutes a recurrent practice. This pattern typically occurs in agricultural frontier regions where forests are converted to pastures (Carneiro Filho, 2009; Herrera & Moreira, 2013; Oliveira Junior et al., 2024).

Another significant correlation was found with agriculture. Agriculture also contributes to deforestation, as evidenced by positive correlations with temporary crops (ρ = 0.646) and, to a lesser degree, permanent crops (ρ = 0.294). However, its impact remains relatively inferior to that of livestock production. Generally, these correlations demonstrate that the predominant economic logic is oriented toward productive land valorization, often to the detriment of environmental conservation.

This economic logic gains reinforcement through deforestation correlation with total municipal area (ρ = 0.679) and municipal development indicators (ρ = 0.281). The correlation with territory area reveals that larger municipalities concentrate extensive agricultural activities, which requires territorialized attention in environmental governance strategies. Conversely, the development index indicates that local socioeconomic advancement occurs at the expense of environmental degradation, revealing a trade-off between growth and sustainability (Marschner, 2014). Reinforcing these findings, the negative correlation between the development index and plant extraction ($\rho = -0.291$) indicates that this activity has reduced economic weight in more developed municipalities.

The correlations reveal a development pattern in which deforestation strongly associates with livestock expansion and, to a lesser degree, agricultural expansion. Economic development positively associates with deforestation but negatively associates with plant extraction. These relationships demonstrate the existence of an economic development model based on converting forest areas for agricultural use, with possible implications for sustainable development policies and environmental conservation in the analyzed region.

In this scenario, the Moran Index calculation revealed significant spatial autocorrelation for deforestation, with a value of 0.39 at the 0.01 significance level. This clustered spatial distribution pattern indicates that deforestation does not occur in isolated or random form but rather in interconnected territorial blocks where occurrence in one municipality influences surrounding reality. In other words, deforestation occurrence in one municipality positively associates with the occurrence of the same phenomenon in neighboring municipalities.

Cluster formation and identification of "spatial contagion effects" confirm the necessity for "intermunicipal public policies" and "integrated environmental control strategies." Therefore, more efficient deforestation control policies must be planned on a regional rather than global scale (Bonat et al., 2010; Dittmar & Mrozinski, 2022).

This finding reinforces and qualifies the identified correlations. Spatial autocorrelation shows that such relationships are not merely local but part of a broader territorial process in which economic dynamics and land use patterns replicate on a regional scale. Thus, the association between deforestation and livestock production, as well as with agriculture, combined with spatial autocorrelation, points to territorialized expansion circuits.

Similarly, the correlation between municipal area and deforestation, within a spatial dependence context, indicates that larger territorial extensions not only concentrate agricultural activities but also disseminate their effects on neighboring municipalities. In view of this, spatial autocorrelation not only validates bivariate correlations but also requires that deforestation control policies be planned on a regional rather than merely local scale (Bonat et al., 2010; Dittmar & Mrozinski, 2022; Santos et al., 2023), considering the interdependent nature of territories.

Under these circumstances, the Moran Index, by identifying positive spatial autocorrelation and forming clusters, allows delimitation of critical zones, evidencing spatial contagion effects and supporting intermunicipal public policies. These clusters indicate that predatory practices in one territory propagate to neighboring areas, requiring integrated environmental control strategies. Thus, the index not only confirms territorial interdependence but also guides efficient resource allocation and planning of coordinated environmental management and conservation actions on a regional scale, figure 1.

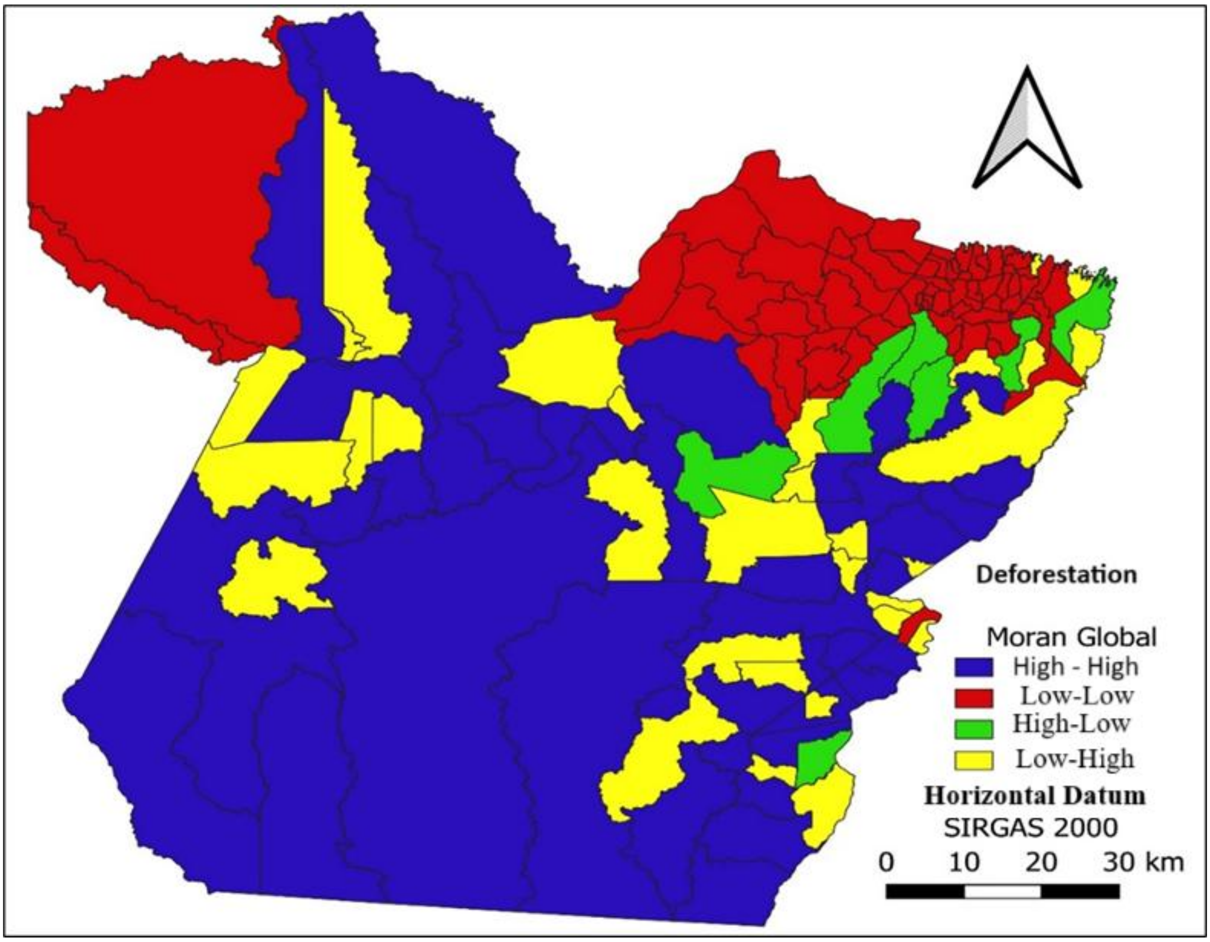

Figure 1. Spatial dispersion of deforestation in the territory of Pará

The predominance of municipalities classified as High-High (dark blue) evidences critical zones. The cluster comprising 41 municipalities characterizes itself by the coexistence of municipal development (average of 0.3947) and deforestation (average of 4,290.62 km², with variation of 97.19 km²). They present territorial area (average of 18,761.09 km²) and the largest cattle herd (average of 407,808 head, with growth of 25,510), indicating strong agricultural activity. The expansion of temporary crops (average of 20,769.44 ha and variation of 2,018.07 ha) and permanent crops (variation of 94.73 ha) reinforces the economic dynamics associated with primary production, reflecting a correlation between development and pressure on forest cover.

The Low-Low cluster, comprising 66 municipalities, characterizes itself by the lowest municipal development index (0.3450) and the smallest average territorial area (3,661.53 km²). It presents the lowest deforestation indicators (460.23 km²) and deforestation growth (1.48 km²), as well as the smallest cattle herd (18,837.33 head) and the smallest area designated for temporary crops (2,235.30 ha). Positive variation in permanent crops (+24.55 ha) and temporary crops (+15.41 ha) remains modest. This scenario describes smaller-scale municipalities with limited agricultural activity and, consequently, reduced pressure on forest resources, reflecting their low level of municipal development.

The High-Low cluster, comprising seven municipalities, characterizes itself by high deforestation index (3,546.70 km²) associated with low municipal development (average IFDM of 0.3456). Despite the considerable area designated for permanent crops (15,849.57 ha), a reduction in this category (-1,829.43 ha) is observed. Simultaneously, an increase in temporary crops (446.86 ha) and cattle herd (14,472.43 head) is recorded. This dynamic characterizes an agricultural and livestock frontier expansion area that does not translate into improvements in social development indicators, indicating a territorial exploitation model with limited sustainability.

The Low-High cluster, comprising 29 municipalities, presents a low deforestation index (1,742.04 km²) in relation to its territorial area (6,492.49 km²), associated with a relatively higher level of municipal development (0.3654). The variation in deforestation (24.37 km²) and cattle herd (10,043.34 head) indicates moderate growth of these activities. Additionally, there exists a discrete reduction in permanent crops (-6.66 ha) and expansion in temporary crops (1,262.17 ha), characterizing a territorial dynamic where development coexists with lower environmental pressure, albeit with gradual agricultural expansion.

In this context, it becomes evident that variation in deforestation indicators exists among clusters, table 2, revealing distinct territorial dynamics.

Table 2. Characterization of the internal dynamics of the clusters

Variables	High-High	Low-Low	High-Low	Low-High
No. of municipalities	41	66	7	29
Municipal development	0,3947	0,3450	0,3456	0,3654
Territorial area km²	18761,09	3661,53	5962,06	6492,49
Deforestation (Km²)	4290,62	460,23	3546,70	1742,04
Variation Deforestation (Km²)	97,19	1,48	51,54	24,37
Cattle (heads)	407808,15	18837,33	199110,00	156763,90
Variation Cattle (heads)	25510,49	717,20	14472,43	10043,34
Permanent crops (hectares)	5167,93	1181,95	15849,57	1068,34
Change Permanent crops (hectares)	94,73	24,55	-1829,43	-6,66
Temporary crops (hectares)	20769,44	2235,30	9654,43	12138,10
Change Temporary crops (hectares)	2018,07	15,41	446,86	1262,17

When applying the Kruskal-Wallis test to compare means among clusters, results indicated statistically significant differences in various variables. Among them, municipal development levels, total municipal area, deforested area and its increment over time, herd size and its variation, as well as areas designated for permanent and temporary crops stand out. These findings demonstrate relevant distinctions among the analyzed clusters, contributing to a better understanding of factors associated with deforestation.

In the High-High cluster, statistically higher values are observed for municipal development, total area, deforestation, deforestation increment, cattle number, and temporary crop area. This set of indicators reflects a concentration of greater economic dynamism but also intense pressure on forest cover.

In contrast, the Low-Low and High-Low clusters generally present lower values in most analyzed variables, reflecting lower intensity in both productive aspects and environmental impacts. The exception is permanent crop area, in which the High-Low cluster distinguishes itself by presenting the highest average among clusters, indicating a differentiated agricultural vocation with potential relation to more stable land use practices.

The Low-High cluster generally presents statistically intermediate values in variables related to deforestation and livestock, positioning itself above the Low-Low and High-Low clusters but below the High-High cluster. This configuration evidences expressive territorial heterogeneity in Pará state. The High-High cluster distinguishes itself by presenting the highest indices of both development and deforestation, while the Low-Low and High-Low clusters reflect realities with lower intensity in these aspects. The Low-High cluster occupies an intermediate position, reflecting a combination of distinct socioenvironmental characteristics.

In this context, when analyzing timber product extraction in the four clusters (High-High, Low-Low, High-Low, and Low-High), critical patterns for understanding deforestation drivers in Pará are observed, given the central role that firewood, charcoal, and roundwood play in forest degradation. For example, in the High-High cluster, intensive and continuous logging is observed. High averages of roundwood extraction (53,218.07 m³) and firewood (10,337.83 m³) are observed, accompanied by considerable production of charcoal (1,030.93 t), reflecting the reality of development in agricultural frontier regions (Carneiro Filho, 2009; Herrera & Moreira, 2013; Oliveira Junior et al., 2024).

Furthermore, the reduction in firewood (-1,284.39 m³) and charcoal (-45.44 t) suggests a possible shift toward direct exploitation of timber with higher commercial value, table 3. This model implies significant impact on forest resources, associated with deforestation for commercial purposes, with potential for lower local value aggregation and accentuation of environmental degradation.

Table 3. Differences in timber product extraction across clusters

Timber Products	High-High	Low-Low	High-Low	Low-High
Charcoal (Tons)	1030,93	55,67	37,57	962,38
Variation Charcoal (tons)	-45,44	0,35	3,43	125,83
Firewood (cubic meters)	10337,83	8249,02	2682,86	19848,31
Variation Firewood (cubic meters)	-1284,39	484,92	-109,43	-172,69
Roundwood (cubic meters)	53218,07	9366,33	14534	32242,48
Variation Wood (cubic meters)	5029,34	1714,09	-2677,86	3045,28

The Low-Low cluster presents reduced volumes of timber (9,366.33 m³), firewood (8,249.02 m³), and charcoal (55.67 t). However, growth is observed across all three categories: timber (+1,714.09 m³), firewood (+484.92 m³), and charcoal (+0.35 t). This dynamic implies intensification of logging activities in territories historically characterized by low environmental pressure. Although current scale remains limited, the growth trend demands attention, indicating possible weaknesses or transformations in local forest governance and potential future environmental pressures.

Analysis of the High-Low cluster reveals a retraction in forest resource extraction, with modest volumes of timber (14,534 m^3), firewood (2,682.86 m^3), and charcoal (37.57 t). A significant decrease in timber (-2,677.86 m^3) and firewood (-109.43 m^3) exploitation is observed, contrasting with a discrete increase in charcoal production (+3.43 t). This scenario describes a land use transition process or implementation of restrictive environmental policies, implying resource exhaustion or greater rigor in timber oversight, with potential effect on deforestation mitigation.

Analysis of the Low-High Cluster reveals a critical scenario for territorial sustainability. Characterized by elevated forest resource extraction, firewood (19,848.31 m^3), timber (32,242.48 m^3), and charcoal (962.38 t), the cluster further demonstrates significant increases in charcoal production (+125.83 t) and timber (+3,045.28 m^3), contrasting with a slight retraction in firewood exploitation (-172.69 m^3). This combination of high exploitation volumes and growth in sectors with greater environmental impact signals elevated deforestation risk.

When observing charcoal and timber extraction, intensive exploitation of forest formations and practices with limited local socioeconomic value generation substantially contributes to vegetation cover loss. Generally, this reality tends to reflect biodiversity loss and ecosystem degradation (Esteves & Cruz, 2022).

Utilizing the Kruskal-Wallis test, it was possible to identify statistically significant differences only in the variables "charcoal variation" and "roundwood variation" among the four clusters. The greater variability and presence of more extreme outliers in the High-High cluster demonstrate that, statistically, greater differences in terms of increment (both positive and negative) of charcoal occur in this cluster type.

Regarding roundwood extraction, the mean is statistically more accentuated in the Low-High cluster. Although the High-High cluster presents areas with significant extraction, the central tendency is inferior. This distribution characterizes distinct territorial dynamics in logging exploitation, with the Low-High cluster having indicators expressing greater pressure on forest resources for this specific activity.

This extractivist dynamic centered on timber products negatively impacts non-timber extraction, harming communities dependent on it for subsistence and income (Carneiro Filho, 2009; CPT, 2017; Giatti et al., 2021). This scenario reinforces a process of forest conversion into activities with greater area demand, such as livestock and agriculture, as detailed in table 4. This forest substitution implies challenges for sociobiodiversity maintenance and for traditional populations' economies, table 4.

Table 4. Average extraction of non-timber forest products in the clusters

Non-Timber Products	High-High	Low-Low	High-Low	Low-High
Food (Tons)	167,34	2240,06	306,14	330,76
Variation Food (Tons)	-33,49	-8,94	32,43	121
Açaí fruit (Tons)	85,61	2134,92	188,86	299,93
Variation açaí (Tons)	-10,02	18,98	22,71	129,83
Amazon nuts (Tons)	73,83	30,03	59,71	16,79
Variation Chestnut (Tons)	-24,05	-20,44	-1,71	-12,97
Palm heart (Tons)	0,22	53,26	0,29	2,86
Variation Palm hearts (Tons)	0	-0,02	0	-0,03
Rubber (Tons)	0,71	0,09	0	0
Variation Rubber (Tons)	-0,15	0,02	0	0
Hervea coagulated latex (Tons)	0,71	0,09	0	0
Variation Hervea (Tons)	-0,15	0,02	0	0
Fibers (Tons)	0	4,2	0	0
Variation Fibers (Tons)	0	0,02	0	0
Buriti (Tons)	0	4,12	0	0
Variation Buruti (Tons)	0	0,02	0	0
Oilseeds (Tons)	8,05	1,18	1	2,45
Variation Oilseeds (Tons)	-0,68	0	-0,14	0,48
Babassu kernels (Tons)	0,15	0,03	0	0,17
Variation Babassu (Tons)	0,02	0	0	0
Copaíba oil (Tons)	0,1	0,14	0	0
Variation Copaíba (Tons)	0	0,02	0	0
Cumaru kernel (Tons)	0,37	0,2	0,86	1,55
Variation Cumaru (Tons)	-0,12	0,02	0	-0,14
Pequi kernel (Tons)	7,32	0,3	0	0
Variation Pequi (Tons)	-0,61	-0,02	0	0

The analysis of the High-High cluster reveals a widespread decline in non-timber extraction activities. The average production of Brazil nuts (73.83 tons) and Açaí (85.61 tons) experienced significant reductions (-24.05 tons and -10.02 tons, respectively). A decrease was also observed in the extraction of food products in general (-33.49 tons), Pequi (-0.61 tons), oilseeds (-0.68 tons), and cumaru (-0.12 tons), with near-zero extraction of heart of palm, fibers, and Buriti.

This cluster exhibits a systematic reduction in plant extractivism, possibly due to its replacement by more environmentally aggressive activities, such as extensive cattle ranching or temporary crops. These findings reinforce the indication that the prevailing territorial model in these municipalities is based on forest conversion to unsustainable uses, leading to a decline in the economic relevance of non-timber forest products.

In contrast, the Low-Low cluster, despite its substantial extractive production, particularly of açaí (2,134.92 tons) and heart of palm (53.26 tons), demonstrates low productive dynamism. The negative variation in the volume of food products (-8.94 tons) and Brazil nuts (-20.44 tons) suggests stagnation or decline in extractive capacity. The presence of fibers, buriti, copaiba, cumaru, and babassu, in smaller quantities, does not offset this downturn. It is interpreted that the apparent exhaustion of extractive capacity may be associated with pressures on natural resources or the incipience of investment in value chains. The decline in Brazil nut and food product extraction indicates either overexploitation or the loss of relevant forested areas.

The Low-High cluster, in turn, reveals a territory marked by notable productive dynamism, driven by the substantial growth in açaí production, which reached 299.93 tons, representing the highest increase among the analyzed clusters (+129.83 tons). A significant increase in the extraction of food products in general (+121 tons) was also observed, alongside a modest growth in oilseed production (+0.48 tons) and the presence of cumaru (1.55 tons). In contrast, Brazil nut (-12.97 tons) and cumaru (-0.14 tons) extraction experienced a slight decline.

This scenario suggests a productive transition within the Low-High cluster, with açaí emerging as a key economic driver, potentially exerting pressure on secondary forest areas and inducing a land-use pattern centered on semi-domesticated extractive crops with high commercial value, possibly obscuring the loss of local biodiversity (Miyamoto, 2020). Nevertheless, the implementation of sustainable management practices may enable the reconciliation of economic development and environmental conservation in the region.

Finally, the High-Low cluster presents a territorial dynamic characterized by moderate and diversified extractive expansion. Noteworthy is the production of açaí, with a significant volume of 188.86 tons and an increase of 22.71 tons. Although Brazil nut extraction remains substantial at 59.71 tons, it shows a reduction of 1.71 tons. The presence of cumaru (0.86 tons), oilseeds (1 ton), and heart of palm (0.29 tons) is incipient. Additionally, there is a marked increase in the extraction of food products in general (32.43 tons).

Analysis of the Kruskal-Wallis test results reveals that only certain specific non-timber products (Food Products, Açaí, Brazil Nut, Increase in Brazil Nut Production, and Heart of Palm) exhibit statistically significant differences among clusters. The comparative analysis of non-timber food product extraction averages indicates a consistent pattern, with the Low-Low cluster displaying statistically higher values than the other clusters. This finding suggests a correlation between areas with lower levels of past and recent deforestation and greater intensity in non-timber food product extraction.

This trend is also observed in the specific analysis of açaí extraction, where the Low-Low cluster's average stands out significantly. This observation supports the hypothesis that regions with lower deforestation dynamics may exhibit greater dependence on or potential for the exploitation of this specific resource. Similarly, the average extraction of Brazil nuts is also statistically higher in the Low-Low cluster, indicating that forests with greater integrity (a characteristic of this cluster) may offer more favorable conditions for the production and harvesting of this product.

In contrast, the variation in Brazil nut extraction exhibits a distinct pattern, with mean values near zero across all clusters, despite minimal statistical differences. The statistical significance is attributed to more pronounced outliers in the Low-Low cluster. Finally, heart of palm extraction also displays a higher average in the Low-Low cluster, corroborating the association between reduced deforestation and increased extraction of non-timber forest products. Collectively, these results point to a complex relationship between deforestation levels and the dynamics of non-timber resource extraction in the analyzed region.

The correlation analysis highlights a distinctive territorial dynamic and provides important insights into the region's socioeconomic and environmental profiles. The analysis of the High-High cluster reveals a complex dynamic in which municipal development coexists with intensified exploitation of natural resources. A strong positive correlation (0.782) is evident between the area of municipalities and the increase in deforestation, suggesting that territorial extent within this cluster drives forest loss.

Although municipal development exhibits positive, albeit modest, correlations with deforestation (0.336) and cattle ranching (0.321), it can be inferred that economic development in these municipalities remains intrinsically linked to extensive activities that exert pressure on the environment. The negative correlation between firewood extraction (in cubic meters) and increased deforestation (-0.331) may suggest selective extraction practices or forest management in already established areas.

Additionally, the perfect correlations observed between certain extractive products, such as fibers and charcoal (1.00), indicate a territorial specialization or geographic concentration of these activities. Consequently, the High-High cluster is characterized by a development model that advances in parallel with the intense exploitation of natural resources, showing signs of productive specialization and a possible connection to the expansion of agricultural and extractive frontiers in older colonization areas.

In contrast, the Low-Low cluster reveals a complex scenario in which municipal development is inversely proportional to territorial size, as evidenced by the strong negative correlation between area and the municipal development index. One plausible explanation is the heightened dependence on extractive activities in these municipalities, reflected in moderate positive correlations between area and the extraction of food products, açaí, and heart of palm. Furthermore, the negative correlation between land allocated to permanent crops and timber production points to a potential land-use competition between agricultural and extractive activities.

Conversely, the positive correlation between firewood extraction and its increase suggests an integration of the timber sector, possibly linked to more sustainable management practices. In summary, this cluster represents a diversified economy in which extractivism plays a supporting role in less developed areas, suggesting a more traditional land-use model with reduced deforestation pressure, potentially influenced by the presence of extractive communities and family farming.

The High-Low cluster presents a distinct context of municipalities marked by higher levels of socioeconomic development, paradoxically accompanied by intense exploitation of preexisting natural resources. The near-perfect correlation (0.964) between municipal area and deforestation increment suggests that, in these municipalities, forest loss is intrinsically tied to territorial extension.

Paradoxically, there is strong competition between agricultural expansion and deforestation, as evidenced by the significant negative correlation (-0.775) between the increase in temporary crops and rising deforestation, indicating that agriculture primarily expands over already converted areas. Additionally, the internal agricultural dynamics demonstrate substitution or competition between land allocated to permanent and temporary crops (correlation of -0.829).

By contrast, the extractive economy displays signs of complementarity, with strong positive correlations between the extraction of food products, particularly açaí (0.811), suggesting integrated production chains. Hence, this cluster may represent municipalities with a relatively more sophisticated economic model, where high development levels continue to exert significant pressure on remaining forest resources, supported by a well-defined agricultural structure and a complementary extractive sector.

Finally, the Low-High cluster reveals a concerning dynamic, characterized by a significant negative correlation (-0.381) between municipal development and deforestation increase, a unique pattern among the clusters analyzed. This finding indicates that, in these municipalities, the expansion of agricultural and timber frontiers, evidenced by the strong positive correlation (0.573) between cattle herd growth and timber extraction, occurs at the expense of socioeconomic development. This reinforces the idea that cattle ranching and timber extraction are primary drivers of deforestation (Oliveira Junior et al., 2024).

The coexistence of positive correlations between the increase of various extractive products, such as food products and açaí (0.521), suggests economic cycles founded on the exploitation of natural resources, with long-term sustainability risks. While some development niches are associated with the specific extraction of products such as heart of palm and rubber (positively correlated with municipal development at 0.419 and 0.393, respectively), the overall interpretation points to a predatory exploitation model in which economic growth does not translate into substantial improvements in population well-being. This raises serious concerns regarding the environmental and socioeconomic sustainability of these localities.

Overall, the cluster analysis reveals distinct models of land use, deforestation, and development stages. The High-High cluster concentrates the highest deforestation levels, with strong presence of extensive cattle ranching and intensive use of temporary crops, indicating a model based on rapid forest conversion with low productivity per area. In contrast, the Low-Low cluster exhibits minimal anthropogenic pressure, with negligible agricultural activity, reflecting more preserved areas.

The High-Low cluster represents a more balanced production model, with intermediate deforestation and emphasis on permanent crops, such as Brazil nuts, which help stabilize land use. The Low-High cluster occupies an intermediate position, with mixed land use and signs of transition. These patterns suggest distinct development trajectories: a traditional path (Low-Low → Low-High → High-High) marked by intensification of cattle ranching, and an alternative trajectory (Low-Low → High-Low) centered on sustainable systems.

Likewise, a trajectory of productive diversification (High-High → High-Low) may offer potential for restoring degraded areas. The increasing value of extractive and perennial chains in the Low-Low and High-Low clusters highlights viable pathways for reconciling economic development with environmental conservation.

The relationship between development, economic activities, and deforestation is complex and varies across clusters, with municipal area consistently emerging as a factor associated with increased deforestation. Although agriculture, cattle ranching, and forest product extraction influence deforestation, these patterns are not uniform, emphasizing the need for more in-depth and contextual analyses to understand causal dynamics and practical implications.

These differences underscore that deforestation in Pará does not follow a singular causal model, but rather reflects divergent territorial trajectories influenced by geographic scale, development level, and prevailing productive activities. Larger municipalities tend to experience greater deforestation, but the mechanisms through which this occurs, via cattle ranching, cropping, logging, or extractive activities, depend heavily on regional context. This highlights the necessity for territory-specific public policies capable of promoting sustainable alternatives, such as permanent crops or extractivism, particularly in the High-Low and Low-Low clusters.

The observed pattern suggests a potential sequence of land use: timber extraction followed by agro-pastoral expansion, as noted by Benevides e Almeida, (2015). In general, deforestation in Pará is a multifaceted phenomenon with varying drivers and characteristics across regions. While large-scale conversion to agro-pastoral and logging activities appears to be the dominant form of deforestation in clusters with higher rates, the expansion of crops such as açaí in less deforested areas may signal processes akin to "green deforestation," involving the selective removal of other species to favor this crop's production (Freitas et al., 2021; Neves & Bizawu, 2019).

The relationship between development, economic activities, and deforestation is complex and varies across clusters, with municipal area emerging as a consistent factor linked to increased deforestation. Activities such as agriculture, cattle ranching, and forest product extraction impact deforestation, yet these patterns are not homogeneous across clusters. This suggests the need for more nuanced and contextualized analyses to understand underlying causes and practical implications.

To enhance the likelihood of identifying spatial patterns associated with deforestation, the LISA Map test was employed (Figure 2). The colored areas in this figure more precisely indicate where the explanatory factors for deforestation differences are statistically significant, that is, where confidence is higher that the observed patterns did not occur by chance.

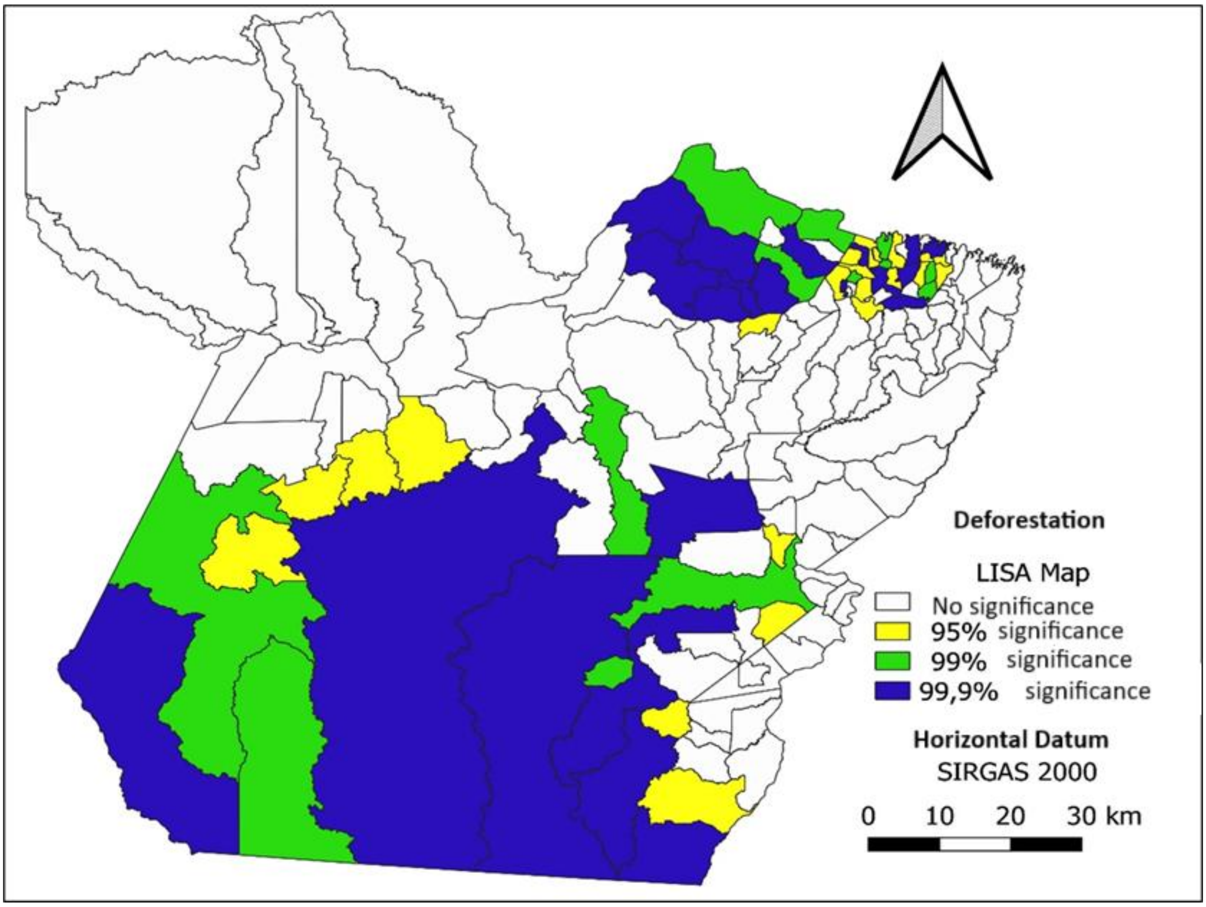

Figure 2. Locations with the highest probability of deforestation occurrence

Figure 1 presents distinct deforestation clusters across the state of Pará, while Figure 2 strengthens the analysis by highlighting the statistical significance of these spatial differentiations. Municipalities such as Altamira, São Félix do Xingu, Ourilândia do Norte, Novo Progresso, and Cumaru do Norte, which belong to the High-High cluster, exhibit high statistical significance (represented in dark and medium blue), indicating a strong influence of consistent spatial factors driving elevated deforestation levels.

Conversely, municipalities surrounding the Marajó region, the Metropolitan Region, and Northeast Pará, classified within the Low-Low cluster and also represented in dark blue and green, constitute areas of high statistical relevance for further investigation into the underlying causes of the differentiated deforestation patterns observed among the identified clusters.

In this regard, the results obtained thus far provide a clear perspective on the complex interaction between deforestation and the resulting ecological impacts associated with the extraction of non-timber forest products. The findings reveal a direct connection between deforestation expansion in certain clusters and the unsustainable exploitation of natural resources, often justified through the discourse of “green deforestation.” This practice entails the selective removal of plant species deemed undesirable to make way for native or exotic species of economic interest (Giatti et al., 2021).

However, the analysis of the four clusters (High-High, Low-Low, High-Low, and Low-High) underscores significant territorial heterogeneity across Pará, with varying combinations of municipal development, deforestation intensity, economic activities, and forest exploitation patterns. There is no single or linear relationship between development and deforestation; this relationship varies considerably among regions within the state. Such variability reinforces the need to understand local and regional deforestation dynamics (Busch & Ferretti-Gallon, 2017; Freitas et al., 2021; Jakimow et al., 2023; Miyamoto, 2020).

The division into distinct clusters, High-High, Low-Low, High-Low, and Low-High, and their respective characteristics reflect this complexity. The diverse dynamics observed across the four clusters highlight the importance of conducting regional analyses to understand the causes and consequences of deforestation and to develop public policies that are more effective and tailored to local realities.

The relationship between development and deforestation is not uniform. In some areas, the prevailing development model appears to be intrinsically linked to environmental degradation, whereas in others, there are indications of lower deforestation pressure or the potential for more sustainable development pathways. The decline in non-timber product extraction in high-deforestation areas also raises concerns regarding the social and economic impacts on traditional communities.

4. Conclusion

This study investigated the various drivers of deforestation, analyzed its spatial distribution patterns, and identified regions most likely to experience “green deforestation” in the state of Pará. Livestock farming emerged as the most significant vector of deforestation, showing a strong positive correlation with deforested area expansion ($\rho = 0.866$), thereby underscoring the close association between cattle herd growth and pressure on forest cover. Agriculture also played a relevant role in the deforestation process, with positive correlations observed for both temporary crops ($\rho = 0.646$) and permanent crops ($\rho = 0.294$), suggesting that the diversification of agricultural uses constitutes an additional anthropogenic pressure on the territory.

Regarding spatial distribution patterns, the analysis of Moran’s Index revealed significant spatial autocorrelation (value of 0.39, with $p < 0.01$), indicating that deforestation is not randomly distributed but rather concentrated in interdependent territorial clusters. This finding emphasizes the necessity of adopting integrated regional approaches in the formulation of public policies.

The spatial clustering analysis enabled the identification of critical zones, particularly municipalities classified as High-High, where high municipal development indices coexist with elevated deforestation rates. This indicates an environmentally unsustainable development trajectory.

Another relevant finding pertains to the correlation with so-called “green deforestation,” particularly in areas experiencing the expansion of crops such as açaí. In these regions, although native vegetation is not entirely removed, selective species substitution occurs, constituting a type of forest alteration that may not be fully captured by conventional monitoring methods.

Based on these findings, several strategic propositions can be formulated. First, the presence of spatial autocorrelation reinforces the importance of designing deforestation control policies at the regional scale, emphasizing intermunicipal cooperation and integrated territorial management instruments. Second, the heterogeneity of deforestation drivers and land-use patterns calls for territorial development strategies that account for each region's socioeconomic and environmental specificities.

Furthermore, the presence of distinct territorial clusters highlights the need for customized public policies that combine regulatory tools, incentives, and sustainable management practices adapted to local contexts. In regions where extractive activities, such as açaí production, are prominent, the urgent implementation of sustainable management practices that reconcile forest conservation with income generation is paramount.

The study's main conclusions indicate that deforestation in Pará is a complex and multifaceted phenomenon influenced by diverse productive, socioeconomic, and territorial dynamics. The relationship between economic development and deforestation is neither linear nor uniform. In some areas, economic growth is associated with environmental degradation, whereas in others, there is potential for more balanced development trajectories. The spatial pattern of deforestation, marked by statistically significant clustering, reinforces the systemic nature of the issue, necessitating solutions that go beyond isolated or sectoral approaches.

For the academic community, this study makes a significant contribution by deepening the understanding of territorial deforestation dynamics in the Amazon, offering empirical evidence and analytical methodologies that may be replicated in other regions. The robust statistical analysis, combined with the spatial approach, provides a solid foundation for future research, particularly studies concerned with complex territorial processes. For public administration, the results provide concrete input for designing more effective, regionally adapted public policies. The identification of critical clusters, for instance, allows for the prioritization of intervention areas, optimization of resource allocation, and targeting of conservation and development strategies.

Nonetheless, the study presents certain limitations. The emphasis on quantitative and spatial analysis, while essential to the research objectives, limited the depth of inquiry into the social, cultural, and political factors influencing land-use decisions. Moreover, the exploration of “green deforestation” was preliminary and calls for further investigation through case studies. The municipal scale adopted to facilitate analysis may also obscure important internal variations, particularly in large municipalities with considerable socio-environmental diversity.

From these limitations, future research agendas emerge. There is a pressing need for qualitative and multiscale studies on green deforestation, focusing on the socio-environmental impacts of extractivist monoculture expansion. Analyses integrating high-resolution remote sensing data with field-collected information are also recommended, to capture local dynamics that remain invisible at aggregated scales. Additionally, comparative studies across different Amazonian regions may contribute to identifying both patterns and singularities in deforestation processes, thereby expanding the analytical scope of public and academic policy frameworks**.**

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Obtained.

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The Publication Ethics Committee of the Macrothink Institute.

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