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## The conditions of urban sprawl in medium-sized cities in the Brazilian semi-arid region: a causal inference approach

*As condicionantes da expansão urbana em cidades médias do semiárido brasileiro: uma abordagem baseada em inferência causal*

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**Abstract:** The promotion of regional development in the Brazilian semi-arid region, such as the inland expansion of industries, services and educational institutions, which began in the 1960s, led to the growth of medium-sized cities and the reversal of an urbanization pattern that concentrated resources solely in Brazil's large coastal metropolises. The medium-sized cities, as they are also known, have gained increasing prominence in the semi-arid region as poles of influence and have received a population and economic growth in recent decades which has been reflected in urban expansion, impacting on nearby small towns. The objective of this paper is to investigate the geographical factors that have conditioned urban expansion in six medium-sized cities in the Brazilian semi-arid region: Campina Grande (PB), Caruaru (PE), Arapiraca (AL), Mossoró (RN), Feira de Santana (BA) and Juazeiro do Norte (CE). The methodology combined a correlation analysis and the construction of a causal model between the variables that describe the pattern of urban growth and the distance from the main centrality of these cities. The results allowed us to conclude that, despite the spatial particularities of the municipalities, there are indicators capable of inferring how urban growth was conducted in the context of the medium-sized cities of the Brazilian semi-arid region.

**Keywords:** urban sprawl, medium-sized cities, semi-arid region.

**Resumo:** Os incentivos ao desenvolvimento regional no semiárido brasileiro, como a interiorização de indústrias, serviços e instituições de ensino, que se deram a partir da década de 1960, ocasionou no crescimento de cidades de médio porte e na inflexão de um padrão de urbanização que concentrava recursos unicamente nas grandes metrópoles litorâneas do Brasil. As cidades médias, como também são chamadas, têm ganhado cada vez mais destaque no semiárido como pólos de influência, e nas últimas décadas, receberam um incremento populacional e econômico que se refletiu na expansão urbana, impactando as cidades de pequeno porte próximas. O objetivo deste artigo é investigar as circunstâncias geográficas que condicionaram a expansão urbana em 6 cidades médias do Semiárido brasileiro: Campina Grande (PB), Caruaru (PE), Arapiraca (AL), Mossoró (RN), Feira de Santana (BA) e Juazeiro do Norte (CE). A metodologia combinou uma análise de correlação e a construção de um modelo causal entre as variáveis que descrevem o padrão do crescimento urbano e a distância da principal centralidade dessas cidades. Os resultados permitiram concluir que, apesar das particularidades espaciais dos municípios, existem indicadores capazes de inferir como o crescimento urbano foi conduzido no contexto das cidades médias do semiárido brasileiro.

**Palavras-chave:** expansão urbana, cidades médias, semiárido.

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## 1. Introduction

Medium-sized cities are surrounded by conceptual discussions regarding the criteria which they are characterized by, these go beyond demographic aspects, as urban functions, regional influence capacity, and infrastructure are also taken into account (LIMA; SILVEIRA, 2017). Despite the imprecision surrounding the topic, due to the lack of consensual agreement that extends beyond the Brazilian context and reaches different regions and countries, it is necessary to agree with Lopes (2024), when he affirms that this debate is not the most essential. However, despite conceptual variations, there is indeed an agreement that medium-sized cities have been important strategic nuclei within the urban network.

In Brazil's case, the relevance of medium-sized cities increased after the 1970s decade. In this period, there were not only the first steps towards the establishment of an urban hierarchy, with the creation of the first metropolitan regions, but also the greater effort in the development of policies aimed at Regional Development (BRANCO, 2006; LOPES, 2024). The secondary poles, as medium-sized cities were also referred to, were the focus of the National Development Plans (PND) during the Military Regime. These plans had strategies aimed at inland expansion and spatial deconcentration of economic activities that, up until then, had been concentrated in the larger cities in the South and Southeast regions (MOTTA; MATA, 2008).

These new strategic policies were the first step, and currently, medium-sized cities are benefiting from them and achieving more national prominence. Motta e Mata (2008), based on the data from the IBGE Census (2002) and subsequent population projections, concluded that cities with over 500 thousand inhabitants – which are classified by the Brazilian Institute of Geography and Statistics (IBGE) as large cities – began to grow in population terms, Gross Domestic Product (GDP) and employment in lower rates than those with populations between 100 and 500 thousand inhabitants. Other studies, such as those conducted between 2000 and 2010 by the Institute for Applied Economic Research (IPEA), were analyzed by Motta e Eglér (2023), who highlighted, during that period, that “for every R\$ 1 increase in Brazil's GDP, R\$ 0.40 were generated in medium-sized cities” (MOTTA; EGLER, 2023, p. 174; IPEA, 2010).

The articulation potential of these cities within the urban network has been emphasized in IBGE studies known as the “Region of Influence of Cities”, conducted since 1972, that contributed by investigating how these medium cities influence and are influenced by both large and small cities (IBGE, 2020). In an attempt to categorize the urban hierarchy, many of these cities were classified as regional capitals that, according to IBGE (2020, p.11), are “the urban centers with a high concentration of management activities, but a more limited reach in matters of region of influence in comparison with metropolises.”

More recent studies analyzed the interval from 2010 to 2022 and identified that the population growth tendency of Brazilian medium-sized cities did continue; in this period, these cities grew in a faster pace than the metropolitan areas, as well as increased their share of the national GDP (MOTTA *et al.* 2024). The same study identified 230 mid-sized cities based on eight analytical vectors<sup>1</sup>. By selecting a subset of 70 cities in this group, Motta *et al.* (2024) found an elevated correlation (0.806) between resident population and urbanized area. Furthermore, the authors found that the greatest increases in urbanized area, considering the period from 2015 to 2019, happened in the Northeast region, a dynamic that requires further investigation considering the still limited amount of studies that focus on this region of the country.

Pereira e Valença (2024) analyzed the drivers behind the growth of medium-sized cities in the Brazilian Northeast and highlight the following: the commercial and service sectors (influenced by globalization); higher education institutions (resulting from national policies aimed at the decentralization of education); and modern commercial forms (such as shopping malls), all contributing to a spatial restructuring of these cities. According to Sposito (2010), some of these cities, due to their distance from metropolitan regions, end up exercising an interurban centrality among several nearby small cities.

Considering Brazilian medium-sized cities within the context of the Brazilian semi-arid region, which is the focus of this paper, it is important to highlight the following aspects: they experienced a more delayed urbanization process compared to medium-sized cities in the South and Southeast, due to unequal economic production relations; they are located within the Brazilian semi-arid region, which constitutes a major poverty cluster in the country; and they are shaped by the Caatinga biome, characterized by low rainfall levels. In this context, the region has historically benefited more from public policies aimed at the universalization of health and education services, income transfer programs, credit for small

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<sup>1</sup> Dynamics in urban hierarchy and region of influence, demographic and economic dynamism, regional flows and infrastructure, and centrality in business management, public administration, health, and education (MOTTA; EGLER, 2023)

rural producers, and government infrastructure projects, which have enhanced regional resilience and enabled urban development (CARVALHO *et al.*, 2018).

Based on the context of medium-sized cities in the Brazilian semi-arid, as well as the factors that have driven their population growth in recent decades, this paper aims to investigate the spatial particularities that have conditioned the expansion of the urban areas. To this end, six medium-sized cities located in the Brazilian semi-arid region, the main biome of the region, were selected. By correlating four spatial indicators, this study seeks to identify which variables have the greatest potential to explain how the expansion of the urban footprint was experienced in each of the selected cities, thereby contributing to the understanding of the particularities of their urbanized areas.

## 2. Methodology

The methodology of this study is composed of the following steps: selection of study objects; definition of the center and study variables; definition of quadrants and neighborhood levels; and correlation analysis and causal graph.

### *Selection of study objects*

The first methodological step consisted in the process of selecting the study objects. The objective was to select medium-sized cities with a population of 100,000 to 750,000 inhabitants, with similar population sizes, and located in the Brazilian semi-arid region, with sharing similarities in terms of urban hierarchy, that is, in the relationship they maintain with smaller cities (IBGE, 2018). Additionally, isolated cities were selected, meaning those not included in the Metropolitan Region of the state capital and not conurbated with it, but that perform the role of regional centers from economic, social, cultural or political perspectives.

This process came about to six cities in total, which social, spatial and economic characteristics are summarized in Table 1. Despite the similarities between these cities, Pereira *et al.* (2022) questioned these similarities after analyzing them through various socio-spatial patterns using satellite imagery and finding that they exhibited morphological particularities that made methodologies based on generalization unfeasibility.

*Table 1 – Socio-spatial indicators of medium-sized cities in the semi-arid region.*

Cities	Population (2022)	Territorial Area (km <sup>2</sup> )	Population Density (inhab/km <sup>2</sup> )	Urban Hierarchy (2018)	GDP per Capita (2021) (US\$) <sup>2</sup>
Campina Grande (PB)	419,379	591	708.8	Regional Capital C	4,641
Caruaru (PE)	378,048	919	409.5	Regional Capital B	4,343
Arapiraca (AL)	234,696	345	678.9	Regional Capital C	4,675
Mossoró (RN)	264,577	2.099	126	Regional Capital C	4,920
Feira de Santana (BA)	616,272	1.304	472	Regional Capital B	5,127
Juazeiro do Norte (CE)	286,120	258	1,105	Regional Capital B	3,403

*Source: Authors (2025).*

### *Definition of the center and study variables*

The second methodological step consisted of defining a center with common characteristics across the six cities. Considering that these cities already present multiple centralities, it was established that this center would be the “Primal Core” (or primary nucleus), where the urban occupation initially began. In this context, a reference point within the Primal

<sup>2</sup> The values were converted considering a mean real (R\$) value (5.40/sale) of the American currency in 2021, according to IBGE.

Core was defined: the cathedral, a landmark historically present in the centers of Latin American cities until the 20<sup>th</sup> century and still present today (SOARES, 2014).

After defining the center, the indicators used to investigate the occupation patterns of the urban footprint were established, as described in Table 2.

*Table 2 – Variables used.*

<b>Indicators</b>	<b>Describes</b>	<b>Data Source</b>	<b>Relevancy</b>
Address density	Housing density	Obtained from the National Register of Addresses for Statistical Purposes (CNEFE) - IBGE (2022).	Allows flexibility for the density calculation, based on number of addresses across different spatial units (IBGE, 2024).
Slope	Topography	Obtained from the Copernicus 30 Digital Elevation Model (DEM)	Geographic obstacle that limits urban expansion (PANERAI, 2006).
Lacunarity	Distribution of open spaces	Obtained through the use of the LACUNAE software prototype, developed by the research team	Lacunarity is effective in distinguishing urban texture patterns, differentiating areas with varying densities (BARROS FILHO, 2006).
Normalized Difference Vegetation Index (NDVI)	Distribution of green areas	Calculated through Google Earth Engine (GEE), using 2024 imagery from the Planet NICFI sensor.	NDVI has already been associated with texture data to distinguish urban occupation patterns (KIT <i>et al.</i> 2013); may also act as a geographic constraint to growth. (PANERAI, 2006).

*Source: Authors (2025).*

#### *Definition of quadrants and neighborhood levels*

The third methodological step consisted of defining quadrants and rings around the Primal Core established in the previous step. Quadrants are used to analyze the direction in which the urban expansion in each city happened, while rings are used to analyze which indicators best explain morphological differences as the distance from the Primal Core increases. This approach is based on the assumption that significant changes in occupation occur as one moves away from the urban center towards rural areas (FARR, 2013). The representation of rings and quadrants is shown in Figure 1. Each ring is spaced 500 meters from the primal core, totaling 12 rings for each city. These values take into account the extent of urban areas and are therefore relative to the studied objects.

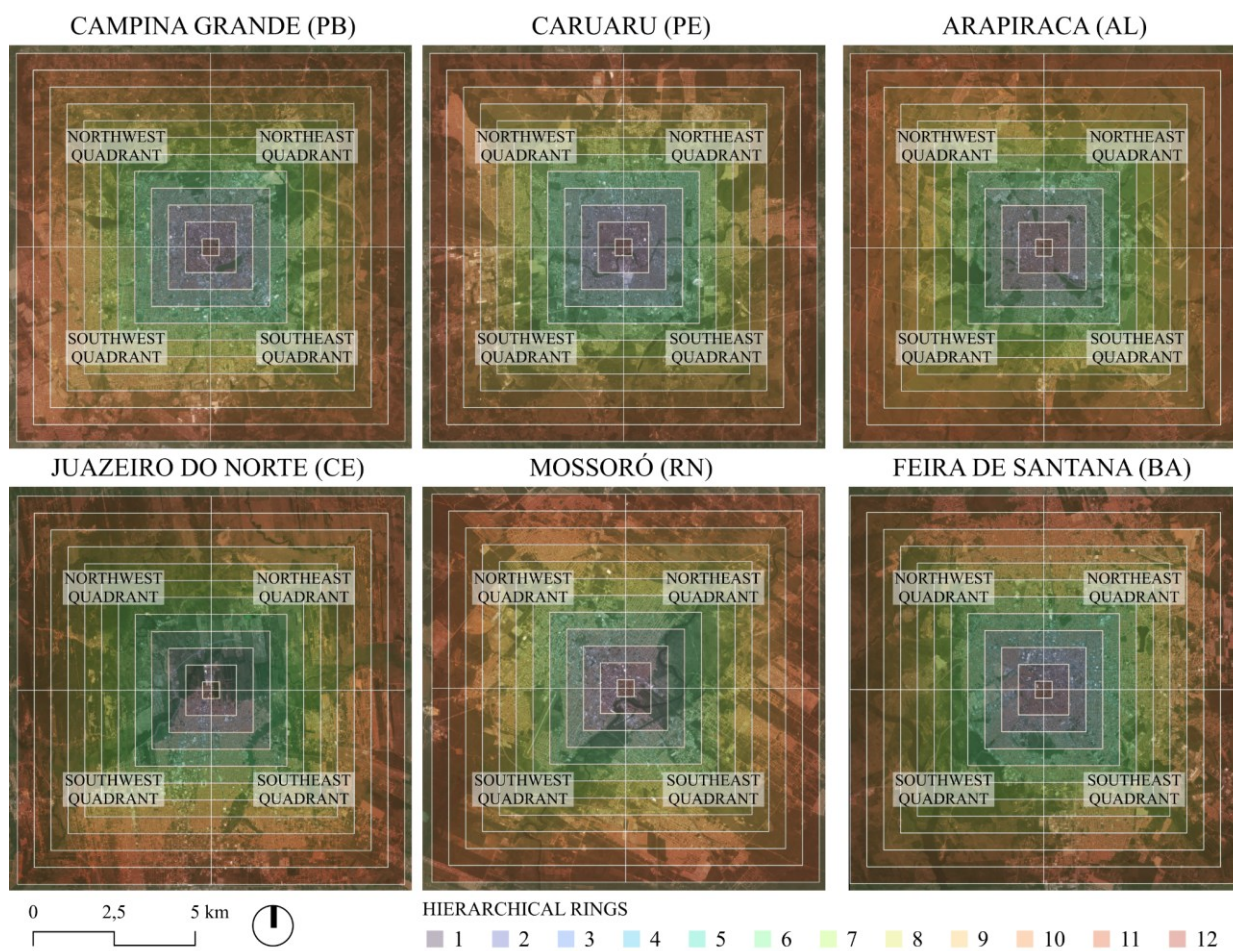


Figure 1 – Divisions of rings and quadrants in the six cities. Source: Authors (2025).

Finally, geoprocessing tools were used to associate the indicators to each ring. For all indicators, the mean value was used as the primary metric. However, for address points, which represent housing density, was necessary to consider density (number of points per area), since outer rings have larger areas, which directly influences the number of points.

### Correlation analysis and causal graph

The final methodological step consisted of calculating the correlation of each indicator with the hierarchical rings, that is, analyzing how each indicator behaves as the distance from the city center increases. There are two main correlation coefficients: Pearson and Spearman. These coefficients range from -1 to 1, and measure the statistical dependence between two variables. Pearson correlation is applied when data follows a normal distribution, while Spearman is used for non-normal distributions. A normal distribution occurs when data is symmetrically distributed around the mean, with most values concentrated near it, forming a bell-shaped curve. A non-normal distribution is characterized by asymmetry, where deviations from the mean result in varied curve shapes and differences between mean, median and mode.

Normality tests are typically conducted prior to correlation analysis, such as the Shapiro-Wilk test, applying the appropriate method for each data distribution. Several studies have demonstrated the effectiveness of these approaches (WINTER *et al.* 2016). In this study, causal assumptions were established regarding how variables behave as the distance from the Primal Core increases across the six analyzed cities; therefore, the Pearson coefficient was prioritized. Selecting the coefficient solely based on p-values from significance tests may introduce a bias disconnected from the established assumptions. It is also important to emphasize that identifying a correlation (positive or negative) does not reduce the indicators to a cause-effect relationship.

This research applied the causal inference approach<sup>3</sup> due to the limitation from the correlation method to analyze the causal relationships between urban growth and the five analyzed indicators. The causal inference framework proposed by Pearl (2009), known as Do-Calculus, was employed. In this theory, a causal model is represented using a Directed Acyclic Graph (DAG); event associated probabilities; and a set of rules for exchange, removal and insertion of observational and interventional information. Table 3 represents the Pearson correlations among the variables used to construct the causal graph. Although correlation does not imply causation, analyzing Pearson correlation is important to identify potential associations between variables, such as collinearity, when there is a significant correlation between variables, as well as to detect irrelevant variables and test causal assumptions. To evaluate these values allows for adjustments to be made to the model, reducing bias in the results.

*Table 3. Correlation of Pearson between variables.*

	<b>Distance from center</b>	<b>Quadrants</b>	<b>Empty spaces</b>	<b>Green Areas</b>	<b>Housing density</b>	<b>Topography</b>
<b>Distance from center</b>	1.00	8.49e-17	0.38	0.66	0.70	0.17
<b>Quadrants</b>	8.49e-17	1.00	-0.08	0.02	-0.00	-0.15
<b>Empty spaces</b>	3.88e-01	-8.73e-02	1.00	0.38	-0.33	0.30
<b>Green Areas</b>	6.68e-01	2.33e-02	0.38	1.00	-0.79	0.33
<b>Housing density</b>	-7.07e-01	-3.33e-03	-0.33	-0.79	1.00	-0.13
<b>Topography</b>	1.74e-01	-1.56e-01	0.30	0.33	-0.13	1.00

*Source: Authors (2025).*

The set of rules used to perform the inference is known as Do-Calculus. The causal graph was constructed based on expert evaluation of whether the edges and causal directions were consistent with the current state of the art. Table 4 presents the causal questions that guided the probabilistic analysis.

*Table 4 – Causal questions based over the variables used in the probabilistic model.*

<b>Question 1</b>	What is the causal effect of topographic slope on housing density?
<b>Question 2</b>	What is the causal effect of housing density on distance from the center?
<b>Question 3</b>	What is the causal effect of housing density on quadrants?
<b>Question 4</b>	What is the causal effect of housing density on the distribution of open spaces?
<b>Question 5</b>	What is the causal effect of open spaces on the distribution of green areas?

*Source: Authors (2025).*

### 3. Results and discussion

The four indicators for the six cities analyzed are presented in Figure 2. From the housing density analysis, diversity in the urban footprint of the six cities can be observed in the urban area from the housing density analysis, and the defined center does not necessarily coincide with the center of mass of urban occupation. An example is Juazeiro do Norte (CE) which expanded predominantly toward the south (SOARES, 2014). Feira de Santana (BA) on the other hand, shows a pattern predominantly oriented toward the northeast relative to the defined center. Mossoró (RN) presents an urban footprint divided between the northwest and southeast quadrants. Campina Grande (PB) shows greater occupation toward the southwest, while Caruaru (PE) expands northeast and northwest. Arapiraca (AL) is the only city where the Primal Core is close to the center of mass, likely due to geomorphological factors. However, it presents a discontinuous growth

<sup>3</sup> The causal inference was generated through a Python script, which used the following libraries: Numpy, Pandas, Graphviz, Networkx and Dowhy, generating the graph (Figure 3) and the Box-plot (Figure 4).

pattern. These observations are directly perceptible through housing density data (measured by address density) and lacunarity, both being capable of describing occupation through the distribution of open spaces (Figure 2).

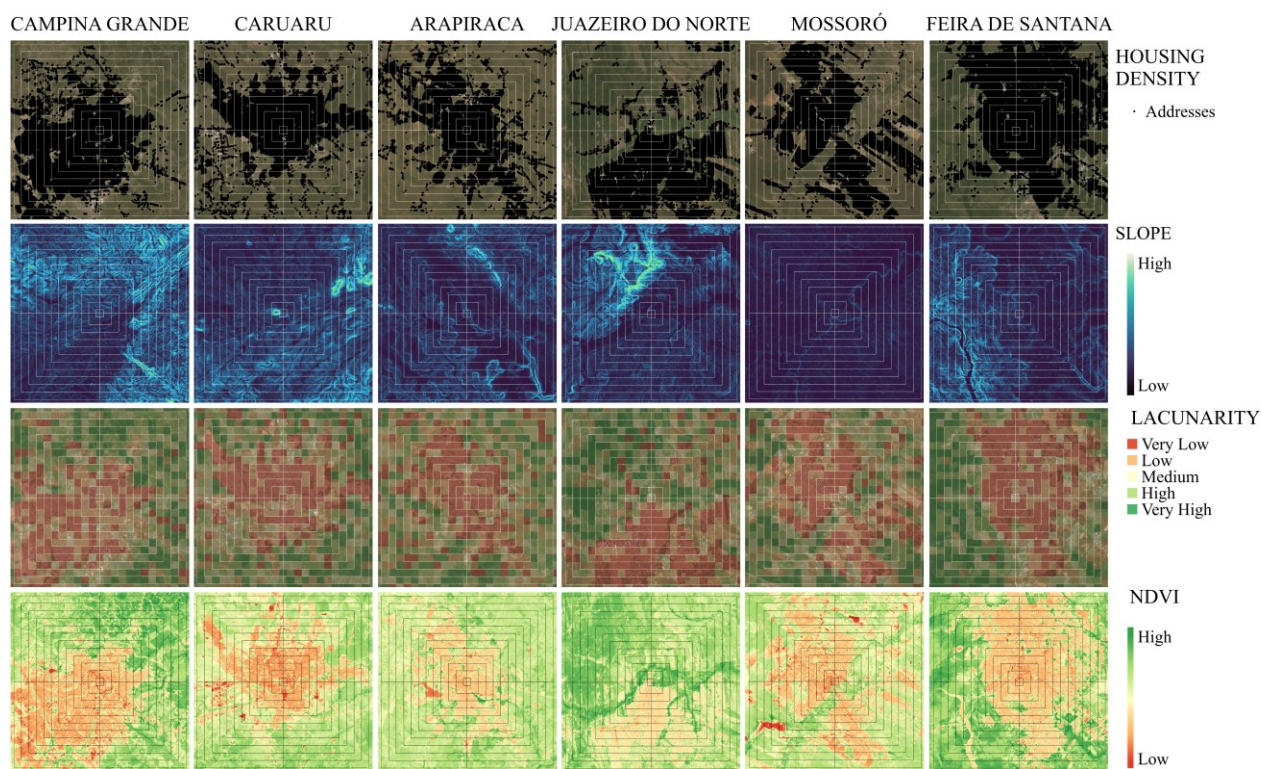


Figure 2 – Results of indicators used for each city. Source: Authors (2025).

The remaining indicators (slope and NDVI) provide additional insights into the possible causes that, throughout the urban growth process, have shaped the current spatial configuration of these municipalities. In general, the unoccupied areas tend to coincide with those presenting less favorable topographic conditions for construction, a pattern also observed in the correlation values with distance from the center, as shown in Table 5. Analyzing the intensity of correlations by quadrant, as the distance from the Primal Core increases (Table 5) is a useful approach for identifying which indicators best explain the configuration of the urban footprint. For example, in the case of Campina Grande (PB), the northeast (NE) and northwest (NW) quadrants present positive correlation values, indicating that slope increases with distance from the center, which helps explain the historical tendency to avoid urban expansion in these directions.

Observations of this type, as discussed in the previous paragraph, can be inferred from correlation analysis. Green areas represent a relevant indicator in this context. However, unlike slope, vegetation can be removed in the absence of effective environmental protection policies. Topography may constrain urban form, shaping buildings and street layouts according to contour lines. Dense vegetation, on the other hand, can only exist in spaces free from built structures. In general, the amount of green areas tends to increase with distance from the center. However, this does not imply that population density decreases at the same rate. An example of this is the city of Juazeiro do Norte (CE), where the quadrants with the highest housing density are the northeast (NE) and southeast (SE), in which, the occupation decreases at a slower rate. Despite this gradual decrease, these same quadrants show a more significant increase in green areas, due to the presence of dispersed urban-rural nuclei even in the outermost rings. These nuclei present lower density and coexist with extensive green areas. This allows for the understanding that population density, as distance from the center increases, may decrease at different rates, with abrupt declines at the edge of the main urban footprint, followed by lower and more stable values representing other types of occupation with urban-rural characteristics.

Together with Mossoró (RN), these cities present quadrants with more significant differences in the correlation of green area distribution, suggesting the existence of discontinuous urban centralities beyond the main urban footprint. Table 5

presents the correlation coefficients for the analyzed indicators, whose values are spatially organized according to the four quadrants (NW, NE, SW, SE). Subsequently, Figure 3 illustrates the causal graph representing the relationships among the indicators. The justification for this structure of causal relationships, derived from the covariance matrices described in Table 3, is based on five assumptions represented by the letters a,b,c,d and e in Figure 3.

From the general data analysis presented in Table 5, it is possible to affirm that, for most of the cities analyzed, housing density decreases as the distance from the primal core increases. In a similar manner, for most of the cities analyzed, there is an increase in green areas with the distance from the center. Lacunarity shows a positive correlation with green areas (Table 3), since vegetation requires spaces free of built structures; however, not all open spaces contain vegetation, which explains the moderate correlation value (0.38). The only exception is Juazeiro do Norte (CE), whose distinct behavior may be explained by the location of its Primal Core, at the northern edge of the city. As a result, even the outer rings in the southwest and southeast quadrants exhibit dense urban occupation. The variable that shows the least consistent trend with increasing distance from the center is topography, as correlation values vary more significantly across cities.

Table 5 – Correlation of indicators with distance from the center of the six municipalities. The blue colors show positive values, as the red colors show negative values.

Quadrants		Indicators							
NO	NE	Housing density (CNEFE)		Topography (Slope)		Open spaces distribution (Lacunarity)		Green areas distribution (NDVI)	
SO	SE								
Campina Grande (PB)		-0.93	-0.89	0.85	0.88	0.81	0.89	0.96	0.95
Caruaru (PE)		-0.83	-0.90	-0.81	0.86	0.58	0.76	0.84	0.97
Arapiraca (AL)		-0.99	-0.95	-0.88	0.83	0.75	0.84	0.88	0.99
		-0.91	-0.89	0.04	0.61	0.92	0.86	0.98	0.95
Juazeiro do Norte (CE)		-0.93	-0.87	0.08	0.73	0.81	0.60	0.97	0.92
		-0.93	-0.98	0.62	0.31	0.99	0.95	0.97	0.97
Mossoró (RN)		-0.67	-0.10	0.20	0.71	0.79	0.54	0.66	-0.47
		-0.90	-0.53	0.80	0.59	0.44	-0.13	0.85	-0.02
Feira de Santana (BA)		-0.79	-0.99	-0.53	-0.46	0.66	0.95	0.97	0.83
		-0.96	-0.69	-0.96	-0.76	0.88	0.69	0.91	0.42
Feira de Santana (BA)		-0.85	-0.29	0.56	0.37	0.62	0.75	0.97	0.97
		-0.92	-0.96	0.84	0.37	0.71	0.89	0.93	0.99

Source : Authors (2025).

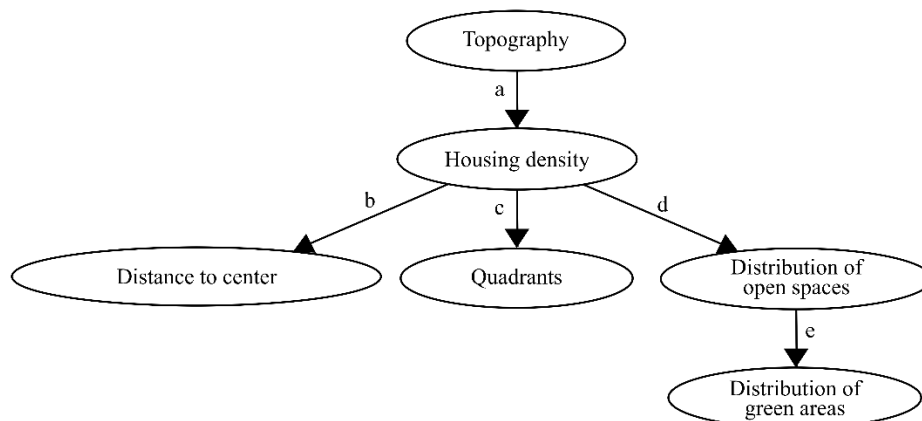


Figure 3 – Causal Graph built from specialized knowledge. Source: Authors (2025).

Figure 4 presents the box plots of the causal effect analysis for the variables of interest, based on the causal graph shown in Figure 3 and the questions outlined in Table 4. To obtain these box plots, causal effects were computed for 28 pairs of variations for each variable of interest. The analysis of causal effects allows the research questions from Table 4 to be addressed as follows:

- Answer 1. On average, if the topography increases by 100 thousand units, housing density decreases by approximately 40.54% proportionally;
- Answer 2. On average, if housing density increases by one unit, the distance from the center decreases by approximately 4.24% proportionally;
- Answer 3. On average, if housing density increases by one unit, the quadrant variable decreases by approximately 4.24% proportionally;
- Answer 4. On average, if housing density increases by one unit, the distribution of open spaces increases by approximately 3.94% proportionally;
- Answer 5. On average, if housing density increases by one unit, the distribution of green areas increases by approximately 0.16% proportionally.

From the box plot results, shown in Figure 4, it is observed that there are no positive causal effects between topography and housing density. Considering this, along with the average causal effect of  $-0.4054$  between these indicators, there is strong evidence of a significant causal influence of topography on how urban areas are occupied. The data also shows that no significant causal effect was found between housing density and green areas, as indicated by both the low average causal value (0.16%) and the narrow variation range ( $-0.02$  to  $0.02$ ) of the individual values presented in the box plot of Question 5. This suggests that, although an indirect causal relationship exists through the distribution of open spaces by the proposed model, the strength of the causal relationship is more strongly associated with open spaces and green areas. The results for Questions 2 and 3 are noteworthy, as their mean and median values are close to zero, despite a relatively wide range of variation; For Question 2, values range approximately from  $0.25$  to  $-0.55$ , while for Question 3 the range is approximately from  $0.45$  to  $-0.50$ . Only one outlier was identified, corresponding to Question 4, occurring when housing density varied from 24 to 25 units. This may be explained by the presence of large built structures (such as major public or private facilities) or preserved environmental areas surrounded by urban occupation, which affects the texture pattern depending on the scale and spatial extent of the analysis.

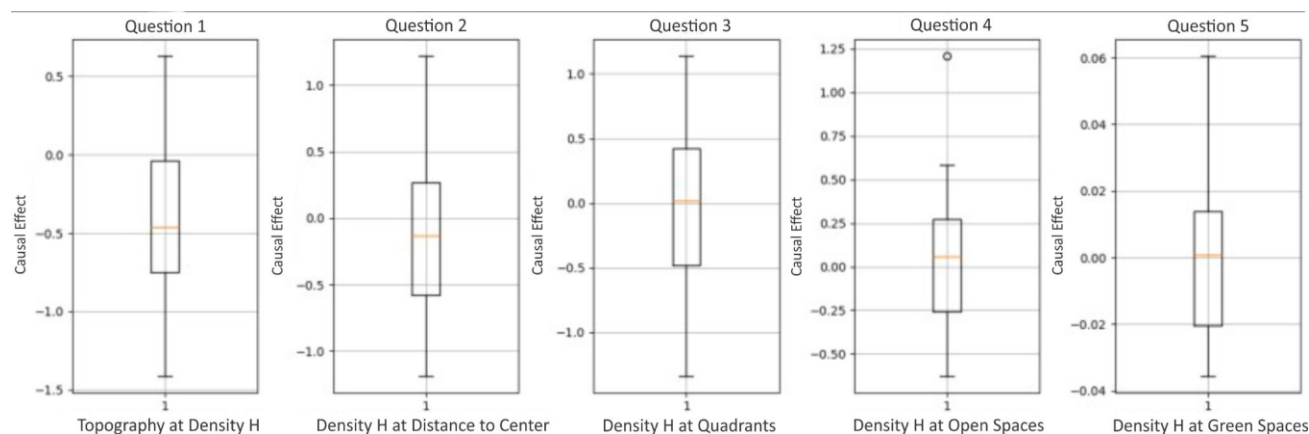


Figure 4. Box plot of the causal effects of changes in the causal variables on the outcome variables of interest, according to the graph in Figure 3. Source: Authors (2025)

Assumption “a” is that housing density is a causal effect of topographic slope, since flatter areas are generally preferred for construction and, consequently, for population densification.

Assumption “b” is that the distance from the center is a causal effect of housing density, as the Primal Core acts as an attractor of flows and permanence due to the concentration of services and infrastructure. Thus, changes in housing density patterns may indicate a displacement of the center of mass relative to the Primal core.

Assumption “c” is that quadrants are a causal effect of housing density. Considering that urban expansion occurs in specific directions from the Primal Core due to various constraints (such as topography, as discussed previously), which

define density patterns rather than being defined by them. Therefore, spatial patterns in quadrants are a consequence, not a cause, of these processes.

Assumption “d” is that the distribution of open spaces is a causal effect of housing density, as the urban footprint grows to occupy determined areas, there is a change in the availability of open spaces, which tends to be reduced. That reduction is not explainable if disconnected from the presence of human beings in the environment, since “open spaces” are defined in relation to the absence of buildings (MAGNOLI, 1982).

Assumption “e” is that the distribution of green areas is a causal effect of the distribution of open spaces, this causal relation can be established since vegetation can only exist in areas free of construction. In this sense, different open space distribution patterns generate different green space patterns. Although not all open spaces are vegetated, greater availability of open spaces increases the likelihood of vegetation presence.

Finally, it is important to highlight additional factors that were initially mentioned, although not directly addressed in this methodology. As these cities expanded over time, infrastructure such as industries, tourism facilities, universities, shopping malls and transportation systems (increasingly more necessary to urban life due to the population densification) were often established in peri-urban areas. Schutzer (2012) argues that this process contributes to the spatial dispersion of Brazilian cities. We reiterate that these elements acted as “motors of growth” of urban growth for the six cities analyzed, particularly in cities with more asymmetric urban footprints relative to the Primal Core. In the case of Campina Grande (PB), public universities and major facilities such as hospitals were established toward the west, where urban expansion is most pronounced. Similar patterns are observed in Caruaru (PE), with textile clusters in the north; in Mossoró (RN), with a shopping mall in the northwest; and Feira de Santana (BA), where the presence of an airport in the northeast quadrant coincides with greater urban expansion in that direction.

The role of the State in promoting this growth must also be considered particularly during the 20<sup>th</sup> century, when there was an intense rural-to-urban migration from the Northeast to the Southeast, Silva and Souza (2025) highlight various public policies and investments in semi-arid cities, such as the São Francisco River Transposition Project, which contributed to increased water security. Since the Brazilian colonial period, drought mitigation policies and infrastructure projects have supported the population’s adaptation to the semi-arid environment (SANTOS *et al.*, 2023).

Considering more recent policies, Silva e Souza (2025) mention that the *Minha Casa Minha Vida* (MCMV) program and the Growth Acceleration Program (PAC), specially the latter, following studies by Amaral Filho *et al.* (2021), have also contributed to the expansion of urban networks in medium-sized cities, both spatially and economically. All cities analyzed in this study have benefited from these programs, suggesting that such factors may also have influenced their patterns of urban growth. The following section presents the conclusions and future research directions.

#### 4. Final Considerations

This study provides methodological contributions that are useful for understanding the factors that have conditioned the urban growth of six medium-sized cities in the Brazilian Semi-Arid region. The experiments allowed the confirmation of theoretical assumptions from urban morphology, particularly that the geographical conditions of the site determine patterns of urban growth, this was observed through the analysis of causal relationships involving housing density, which describes human occupation, and the other indicators, as well as their behavior with increasing distance from the Primal Core of these cities.

Despite the large amount of data currently available for this type of analysis, we observed that data availability decreases at the regional scale when applying the method to multiple municipalities. There is a discrepancy in the institutional capacity of local governments to provide spatial data, and relying on datasets available for the entire region limited the range of variables that could be used across all six cities. As a result, it was necessary to rely on nationally standardized datasets, such as those provided by IBGE, as well as data derived from remote sensing imagery, as in the case of lacunarity, NDVI and slope. Nevertheless, it is still possible to correlate urban growth with both geographic factors and indicators related to human activity in space, a relationship that is fundamental for understanding the conditions that shape the urban occupation patterns of these six municipalities.

There are numerous factors that may explain the growth of urban occupation in these cities, including historical aspects (such as the age of urban structures), commercial areas, and attracting elements such as shopping malls, industrial zones and concentrations of high and low-income areas, among others. The selected indicators explore only some of these dimensions, and the proposed methodology can be adapted to incorporate additional spatial variables. In this sense, future studies should consider a larger number of medium-sized cities, including those outside the Brazilian semi-arid region, in order to investigate whether the characteristics identified in this study are also present in other medium-sized cities in

various contexts. This would allow for a more robust assessment of whether there is, in fact, a typical pattern of urban growth associated with the Brazilian semi-arid region. Furthermore, other types of spatial indicators that correlate positively or negatively with urban growth could be explored, such as water resource availability, distance from medium-sized cities with larger urban centers, and the presence of infrastructure and public policies that may either promote or constrain growth. Due to their more qualitative nature, these indicators were not included in the applied methodology and were instead discussed as secondary aspects.

In addition to analyzing how indicators correlate with increasing distance from the center, it is also possible to examine the relationships among them in order to identify which variables most strongly conditioned urban growth in each city. However, the main conclusion drawn from this study is that there is no single, consistent pattern of urban occupation among medium-sized cities in the Northeastern region of Brazil, as these result from distinct growth processes conditioned by geographical contexts with singular characteristics. Moreover, initially, when quadrants and hierarchical rings were established around the Primal Core of the cities, it was expected that the indicators would have a linear behavior as the distance from the center increased. But the resulting graph pointed that the methodological decisions over the definition of the Primal Core, hierarchical rings and quadrants helped to understand that there is not a urban growth pattern that is continuous and uniform as you move further from the center of the analyzed cities, even if there are high correlation values with the housing density indicator.

## References

- BARROS FILHO, M. N. M. *As múltiplas escalas da diversidade intra-urbana: uma análise de padrões socioespaciais no Recife*. 2006. Tese (Doutorado em Desenvolvimento Urbano). Universidade Federal de Pernambuco, Recife. 2006.
- BRANCO, M. L.C. Cidades Médias no Brasil. In: SPOSITO, E. S., SPOSITO, M. E. B., SOBARZO, O. (org.). *Cidades Médias: produção do espaço urbano e regional*. São Paulo: Expressão Popular. 2006. [ibge](#)
- CARVALHO, C. P. de O. O Novo padrão de crescimento no Nordeste semiárido. *Revista Contexto Geográfico*. Maceió, v.45, n.3, 2016. doi: 10.61673/ren.2014.125
- CARVALHO, C. C. A.; SILVA, M. M. N. da.; ALVES, L. da. S. F.; SOUSA JÚNIOR, A. M. de. As problemáticas urbanas pertinentes às cidades médias do semiárido. In: SILVA, J. B.; ALVES, L. da. S. F.; SILVA, M. M. N. da. *Sustentabilidade, Políticas Públicas e Interdisciplinaridade no Semiárido*. (org.). Natal: CCHLA. 2018.
- FARR, D. *Urbanismo Sustentável: Desenho Urbano com a Natureza*. Porto Alegre: Bookman. 2013.
- IBGE. *Regiões de Influência das Cidades*: 2018. Rio de Janeiro: IBGE. 2020.
- IBGE. *Censo Demográfico de 2022*. Rio de Janeiro: IBGE. 2022.
- IBGE. *Censo Demográfico de 2000*. Rio de Janeiro: IBGE. 2002.
- IBGE. *Censo Demográfico 2022: Coordenadas Geográficas dos Endereços*. Nota Metodológica n. 01. Rio de Janeiro: IBGE. 2024.
- IPEA. Dinamismo das cidades médias do Brasil. In: IPEA: Instituto de Pesquisa Econômica Aplicada (Ed.). *Estrutura produtiva avançada e regionalmente integrada: diagnóstico e políticas de redução das desigualdades regionais*. Brasília: Ipea. 2010.
- KIT, O.; LUDEKE, M. Automated detection of slum area change in Hyderabad, India using multitemporal satellite imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*. v. 83, p. 130-137, 2013. <https://doi.org/10.1016/j.isprsjprs.2013.06.009>
- LIMA, J. G.; SILVEIRA, R. L. L. da. Cidades Médias Brasileiras a Partir de um Novo Olhar Denominal e Conceitual: Cidades de Comando Regional. *Desenvolvimento em Questão*. Ijuí. v.16, n.42, 2017. <http://dx.doi.org/10.21527/2237-6453.2018.42.8-41>

- LOPES, B. de A. Cidades Médias: apontamentos sobre a discussão conceitual. *Geografia (Londrina)*, v. 33, n.1, pp.73-86, 2024. doi: 10.5433/2447-1747.2024v33n1p73.
- MAGNOLI, M. *Espaços livres e urbanização: uma introdução a aspectos da paisagem metropolitana*. 1982. 116 p. Tese (Livre Docência em Arquitetura e Urbanismo) - Faculdade de Arquitetura e Urbanismo, Universidade de São Paulo, São Paulo. 1982.
- MOTTA, D. M. da.; EGLER, C. Rede urbana e cidades médias do Brasil. *Boletim Regional, Urbano e Ambiental*, n. 30, p. 171-179, 2023.
- MOTTA, D. M. da.; MATA, D. da. Crescimento das Cidades Médias. *Boletim Regional, Urbano e Ambiental*, n.1, p. 33-43. 2008.
- MOTTA, D. M. da.; EGLER, C. A. G.; NASCIMENTO, E.; SOBRINHO, F. L. A.; RIBEIRO, M. B.; ARRUDA, R. A. de. Centralidade, competitividade e governança das cidades médias do Brasil. *Boletim Campineiro De Geografia*. v.14, n.2, 2024. <https://doi.org/10.54446/bcg.v14i2.3714>
- NEWBOLD, P. *Statistics for Business & Economics*. 5. ed. New Jersey: Prentice-Hall, 1995.
- PANERAI, P. *Análise Urbana*. Brasília: Editora Universidade de Brasília. 2006.
- PEARL, J. *Causalidade: Modelos, Raciocínio e Inferência: Modelos, Raciocínio e Interferência*. 2a ed. Cambridge University Press. 2009.
- PEREIRA, C. S. S., VALENÇA, M. R. Cidades médias do Nordeste brasileiro no contexto da globalização: uma análise a partir do comércio e serviços. *Ikara. Revista de Geografias Iberoamericanas*. n. 4, 2024. <https://doi.org/10.18239/Ikara.3436>
- PEREIRA, E. T.; BARROS FILHO, M. N. M.; SIMÕES, M. B.; BEZERRA NETO, J. A. Automatic detection of deprived urban areas using Google Earth™ images of cities from the Brazilian semi-arid region. *urbe. Revista Brasileira de Gestão Urbana*, v.14, e20210209. 2022. <https://doi.org/10.1590/2175-3369.014.e20210209>
- SANTOS, K. A. dos.; COLTRI, P. P.; GRECO, R.; JÚNIOR, I. de O.; SÃO JOSÉ, R. V. de. Políticas públicas no semiárido brasileiro: do combate à convivência com a seca. *Geo UERJ*, Rio de Janeiro, n. 42, p. e66666, 2023. DOI: 10.12957/geouerj.2023.66666.
- SCHUTZER, J. G. *Dispersão urbana e apropriação do relevo na macrometrópole de São Paulo*. 2012. 328 f. Tese. Departamento de Geografia da Faculdade de Filosofia, Letras e Ciências Humanas, Universidade de São Paulo, São Paulo. 2012.
- SILVA, R. W. B. F. da; SOUZA, R. C. de. Políticas públicas e financiamentos federais na expansão da rede urbana do semiárido: um estudo revisional. *REVISTA DELOS*, [S. l.], v. 18, n. 66, p. e4633, 2025. DOI: 10.55905/rdelosv18.n66-043.
- SOARES, C. S. De povoado à cidade: a produção do espaço urbano de Juazeiro do Norte/CE (1870-1930). In: XIII SHCU, *Anais (...)*, Brasília. 2014.
- SPOSITO, M. E. B. Novas redes urbanas: Cidades médias e pequenas no processo de globalização. *GEOGRAFIA*, Rio Claro, v.35, n.1, pp. 51-62, 2010.
- SPOSITO, M. E. B. Segregação socioespacial e centralidade urbana. In: VASCONCELOS, P. A.; CORRÊA, R. L.; PINTAUDI, S. M. (Org.). *A cidade contemporânea. Segregação espacial*. São Paulo: Contexto. 2013.
- AMARAL FILHO, J. do., PENNA, C. M. VIEIRA, F. H. Análise do desempenho econômico do Nordeste brasileiro, no período 1985-2014, à luz da história das políticas públicas (Histórias, teorias, instituições, políticas e cálculos). *Série Estudos Econômicos CAEN*, v. 43. 2021.

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WINTER, J.; GOSLING, S.; POTTER, J. Comparing the Pearson and Spearman Correlation Coefficients Across Distributions and Sample Sizes: A Tutorial Using Simulations and Empirical Data. *Psychological Methods*, v. 21, n.3, 2016.