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# Environmental inequality and distribution of urban green areas in the Federal District – Brazil

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**A B S T R A C T**

This study explores the spatial distribution and accessibility of urban green areas in Brazil's Federal District, underscoring their pivotal role in enhancing quality of life and advancing environmental sustainability. Through the application of advanced geostatistical methods, notably the Getis-Ord Gi* statistic, the analysis reveals distinct patterns of vegetation concentration and scarcity across census tracts. Central zones, such as Plano Piloto, exhibit abundant green coverage and ease of access—outcomes of deliberate urban design—whereas peripheral areas like Ceilândia and Samambaia show limited vegetation and greater distances to green spaces, reflecting entrenched socio-environmental disparities. These spatial inequities mirror broader socioeconomic divides, with restricted access to green infrastructure adversely impacting the well-being of marginalized populations. The findings highlight the imperative for integrated public policies that promote the expansion and preservation of green areas in underserved regions, thereby improving urban microclimates, public health, and social cohesion. A holistic approach, bridging ecological, social, and urban planning perspectives, is essential to foster a more just and resilient urban future.
Key-words: Brasília; Urban planning; Spatial Analysis; Sustainability.

# Desigualdade ambiental e distribuição de áreas verdes urbanas no Distrito Federal – Brasil

**R E S U M O**

Este estudo investiga a distribuição espacial e a acessibilidade das áreas verdes urbanas no Distrito Federal do Brasil, ressaltando seu papel fundamental na promoção da qualidade de vida e da sustentabilidade ambiental. Por meio da aplicação de métodos geoestatísticos avançados, em especial o estatístico Getis-Ord Gi*, a análise revela padrões distintos de concentração e escassez de vegetação entre os setores censitários. Áreas centrais, como o Plano Piloto, apresentam ampla cobertura vegetal e facilidade de acesso — reflexos de um planejamento urbano deliberado —, enquanto regiões periféricas, como Ceilândia e Samambaia, registram menor densidade de vegetação e maiores distâncias até os espaços verdes, evidenciando desigualdades socioambientais arraigadas. Essas disparidades espaciais refletem clivagens socioeconômicas mais amplas, sendo que a limitação no acesso à infraestrutura verde impacta negativamente o bem-estar das populações marginalizadas. Os resultados evidenciam a urgência de políticas públicas integradas voltadas à expansão e à preservação das áreas verdes nas regiões menos favorecidas, contribuindo para a melhoria do microclima urbano, da saúde pública e da coesão social. Uma abordagem holística, que articule perspectivas ecológicas, sociais e de planejamento urbano, é essencial para promover um futuro urbano mais justo e resiliente.
Palavras-Chave: Brasília; Planejamento Urbano; Análise Espacial; Sustentabilidade.

## Introduction

The sustainable management of urban environments has become an increasingly complex challenge, particularly in modern cities grappling with issues such as rapid population growth and unchecked spatial expansion, due to inadequate planning, leading to significant environmental degradation. Within this context, urban green spaces emerge as a crucial element in harmonizing the conflicting demands of development and environmental conservation (Bom et al., 2011; Westerink et al., 2013; Pérez-Urrestarazu et al., 2015; Capolongo et al., 2018; Wolff & Haase, 2019).

Beyond their ecological functions—such as climate regulation and the enhancement of air quality—green spaces provide essential social and health benefits, promoting the physical and mental well-being of urban populations, strengthening social cohesion, and bolstering cities' capacities to adapt to climate change (Fuller & Gaston, 2009; Jennings & Bamkole, 2019; Sanju, 2025).

The World Health Organization (WHO) recommends a minimum of 9 m² of green area per inhabitant to ensure basic conditions for quality of life, and cities with more advanced environmental planning, such as Stockholm and Copenhagen, aim for much higher values, recognizing the role of green areas in promoting health and social well-being (WHO, 2016; WHO, 2017).

To assess the effectiveness and adequacy of green spaces in urban settings, a variety of indicators and indexes have been created, in order to evaluate not only the quantity, but also the quality and accessibility of green areas (Mitchell et al., 2011; Dillen et al., 2011; Texier et al., 2018; Kranjčić et al., 2019; Song et al., 2019; Zhang & Tan, 2019; Kumakoshi et al., 2020; Barbierato et al., 2020).

Among these indexes, the Green Area Index per Inhabitant (GAI), which measures the number of square meters of green area available per inhabitant in a city, stands out, being widely used in urban and environmental studies and often cited as a fundamental parameter for assessing the availability of green spaces (Papa et al., 2013; Papa et al., 2015; Jon et al., 2015; Ramirez Lopez & Grijalba Castro, 2020). However, although the GAI is widely accepted, it is limited by not considering the geographic distribution and accessibility of these spaces, which are equally important for achieving environmental equity (Giannico et al., 2021; Vries et al., 2003).

Another indicator is the Tree Cover Index (RCA), capable of reflecting both the current status and the progress in implementing urban forestry policies (Jim & Chen, 2009; Nowak & Greenfield, 2012; Escobedo et al., 2019) while assessing the presence of trees, that is to say, the proportion of tree cover relative to the total area of a city or specific neighborhood, which are crucial for mitigating urban heat islands, absorbing pollutants, and improving air quality.

Studies indicate that a tree coverage of 40% or more is ideal for large urban centers (although many cities around the world fall far short of this target) as trees play a central role in reducing ambient temperatures, particularly in tropical and subtropical regions, where excessive heat can compromise human health and increase the demand for indoor cooling energy (Zipperer et al., 1997; Armson et al., 2013; Yao et al., 2015; Jiang et al., 2016; Kuehler et al., 2017; Mouratidis, 2019; Szota et al., 2019; Baker et al., 2021)

The Green Area Accessibility Index (GAAI) is an important complementary metric to quantity and connectivity indicators, focusing on citizens' ease of access to green spaces. It considers the proximity of green areas to residences, travel time, and physical or socioeconomic barriers that may limit access to these areas (Le Texier et al., 2018; Zhang et al., 2020; Aleixo et al., 2024).

Research suggests that a distance of 300 to 500 meters between a residence and the nearest green area is ideal for encouraging frequent use by the urban population, therefore, the GAAI serves as a measure of environmental justice, assessing whether all segments of the population, particularly those in more vulnerable areas, have equitable access to benefits provided by green spaces (Artmann et al., 2017; Van den Bosch & Sang, 2017; Ståhle, 2018; Tang et al., 2024).

Green area indexes are fundamental for evaluating the quality of urban environments, addressing key aspects such as quantity, accessibility, economic impact, and capacity for climate adaptation of these spaces, offering a base for public policies aimed at creating intelligent, sustainable, and truly inclusive cities (Zhu et al., 2019; Jabbar et al., 2021, Cade, 2024).

Green area indicators, also, underscore the necessity of equitable distribution, as urban green areas extend beyond their environmental dimension, being essential for fostering social and cultural interactions and strengthening community bonds. Indicators such as square meters per inhabitant, spatial distribution, and connectivity of green areas are crucial for evaluating urban management and its commitment to sustainability (Wolch et al., 2014; Collins et al., 2022).

The presence and quality of green spaces are closely linked to environmental justice and the concept of *the right to the city*, ensuring that all citizens have equitable access to spaces that enhance quality of life. In densely populated areas, green areas alleviate stress, increase biodiversity, and help mitigate the effects of climate change. Also, the connectivity of these spaces, through the creation of ecological corridors, is vital for the movement of species while also providing continuous recreational spaces for human use (Wolch et al., 2014; Zhang et al., 2020; Pamukcu-Albers et al., 2021; Collins et al., 2022; Zhu et al., 2023).

From the perspective of human comfort, urban green areas play an indispensable role when considering the rising global temperatures and the intensification of the urban heat island phenomenon, as vegetation presence significantly contributes to local temperature regulation, fostering more pleasant microclimates and mitigating the adverse effects of high temperatures in urban environments (Jabbar et al., 2021).

Well-planned, dense vegetation—particularly with large trees and diverse species—has proved to be especially effective in absorbing solar radiation, reducing ground temperatures, and providing shade, directly enhancing the thermal comfort of urban populations. Moreover, green areas offer spaces for relaxation, contemplation, and social interaction, allowing citizens a reprieve from the rapid and often stressful pace of urban life (Pataki et al., 2021; Tang et al., 2024b).

Scientific evidence consistently shows that urban green areas promote physical and mental health, reducing the risk of respiratory, cardiovascular, and mental health disorders. These spaces encourage physical activity, helping to prevent chronic illnesses such as obesity and diabetes, while also alleviating stress, anxiety, and depression symptoms, thereby improving overall well-being (Ulrich, 1984; Kaplan & Kaplan, 1989; Jabbar et al., 2021; Pataki et al., 2021; Tang et al., 2024).

The intersection between urban green areas and the Sustainable Development Goals (SDGs), established by the United Nations, highlights the need for integrating urban planning into the global sustainability agenda. Urban green spaces directly contribute to several SDGs, particularly SDG 3 (good health and well-being for all), SDG 11 (promoting inclusive, safe, resilient, and sustainable cities), and SDG 13 (taking urgent action to combat climate change). By ensuring universal access to quality green spaces, cities not only improve the quality of life for their inhabitants but also reinforce their commitment to global sustainability (UN, 2015; Kabisch et al., 2017; Pauleit et al., 2017).

In smart cities, also, green spaces play a dynamic role, transcending aesthetic or recreational functions. When integrated with digital systems, they help address challenges such as climate change, flooding, and pollution, making cities more adaptable, sustainable, and capable of responding effectively to changes in the urban landscape (Geng et al., 2024).

This study advances an innovative approach by employing Brasília as a case study to examine the dynamics of urbanization and the spatial distribution of green areas within Central Brazil. Conceived as an emblem of modernity and meticulous urban planning, the city exhibits a singular spatial configuration, the analysis of which is indispensable for comprehending the region's urban occupation patterns. Situated within the Cerrado biome—an ecosystem pivotal to climate regulation and biodiversity conservation—Brasília contends with the dual challenge of harmonizing urban expansion with environmental stewardship. This inherent duality positions the city as a strategic locus for investigating how urban planning can seamlessly integrate nature-based solutions within a framework of sustainable development.

This study explores the spatial distribution and accessibility of urban green areas in Brazil's Federal District, underscoring their pivotal role in enhancing quality of life and advancing environmental sustainability. Through the application of advanced geostatistical methods, notably the Getis-Ord Gi* statistic, the analysis reveals distinct patterns of vegetation concentration and scarcity across census tracts. Central zones, such as Plano Piloto, exhibit abundant green coverage and ease of access—outcomes of deliberate urban design—whereas peripheral areas like Ceilândia and Samambaia show limited vegetation and greater distances to green spaces, reflecting entrenched socio-environmental disparities. These spatial inequities mirror broader socioeconomic divides, with restricted access to green infrastructure adversely impacting the well-being of marginalized populations. The findings highlight the imperative for integrated public policies that promote the expansion and preservation of green areas in underserved regions, thereby improving urban microclimates, public health, and social cohesion. A holistic approach, bridging ecological, social, and urban planning perspectives, is essential to foster a more just and resilient urban future.

**Study Area: The case of Brasília**

The creation of the Federal District (Image 1), which houses Brazil's capital, Brasília, represents a milestone in its nation's history, symbolizing the modernization and interiorization of national development, as the proposal to relocate the capital from the coast to the interior emerged in the 1950s, motivated by a political initiative promoting the occupation and development of then underutilized central regions. Under the presidency of Juscelino Kubitschek, with the motto "fifty years in five", the creation of a new capital city emerged as a symbol of modernity and progress.

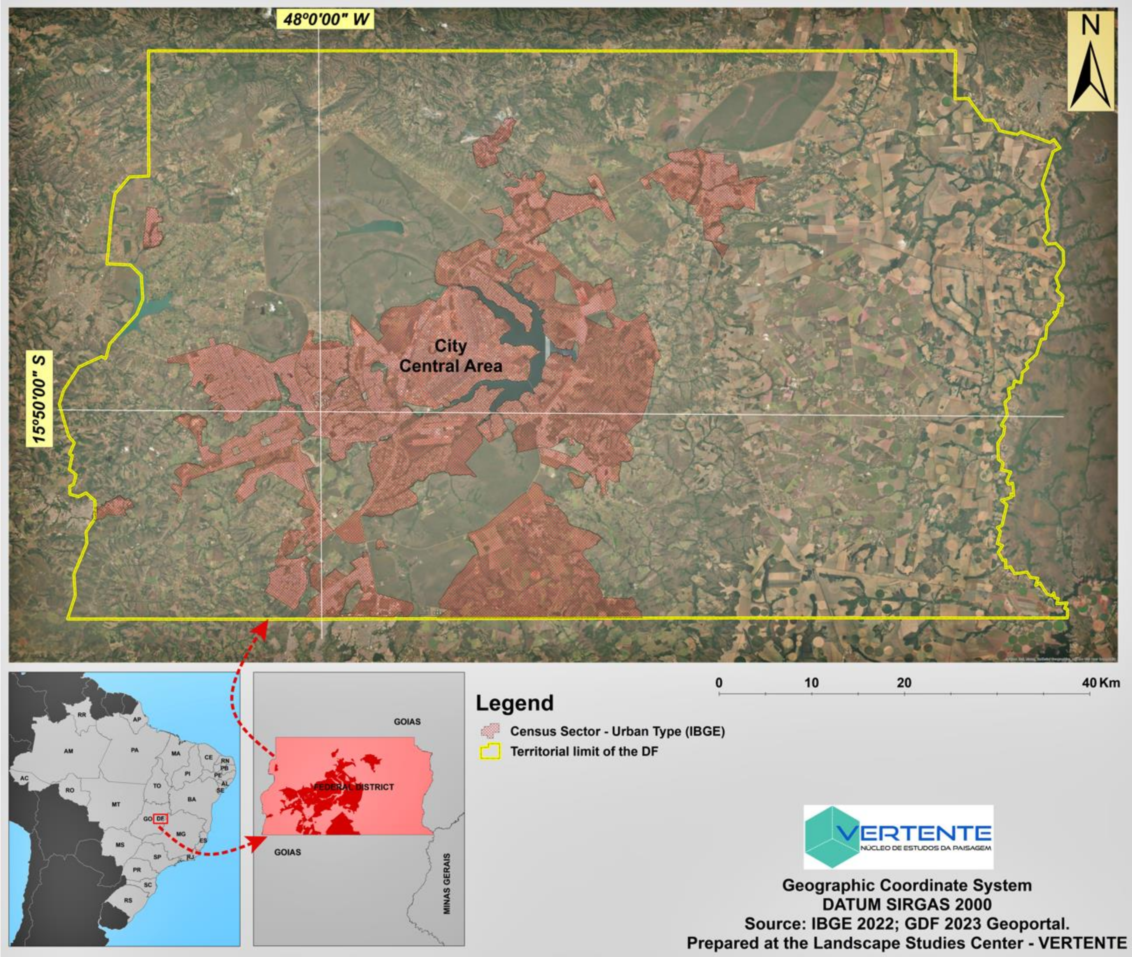

Image 1: Location of Brazil's Federal District.

Cartographic studies which identified the strategic position and abundant water resources in the Central Plateau region were critical factors for the feasibility of the new capital city (Oliveira & Steinke, 2020; Oliveira et al., 2023), Brasília.

Although the creation of the Federal District and the construction of Brasília marked a significant step in the modernization of Brazil, this area, by then, was already occupied by rural and urban settlements, including villages and small communities (Image 2). The beginning of Brasília's construction in 1956 had a profound impact on these villages, altering the landscape and incorporating part of the local population into the construction workforce. The modernity represented by Brasília reshaped these areas, reorganizing urban and rural spaces and establishing a new centrality in the Central Plateau, balancing modern infrastructure pre-existing occupation patterns (Reis Júnior, 2010).

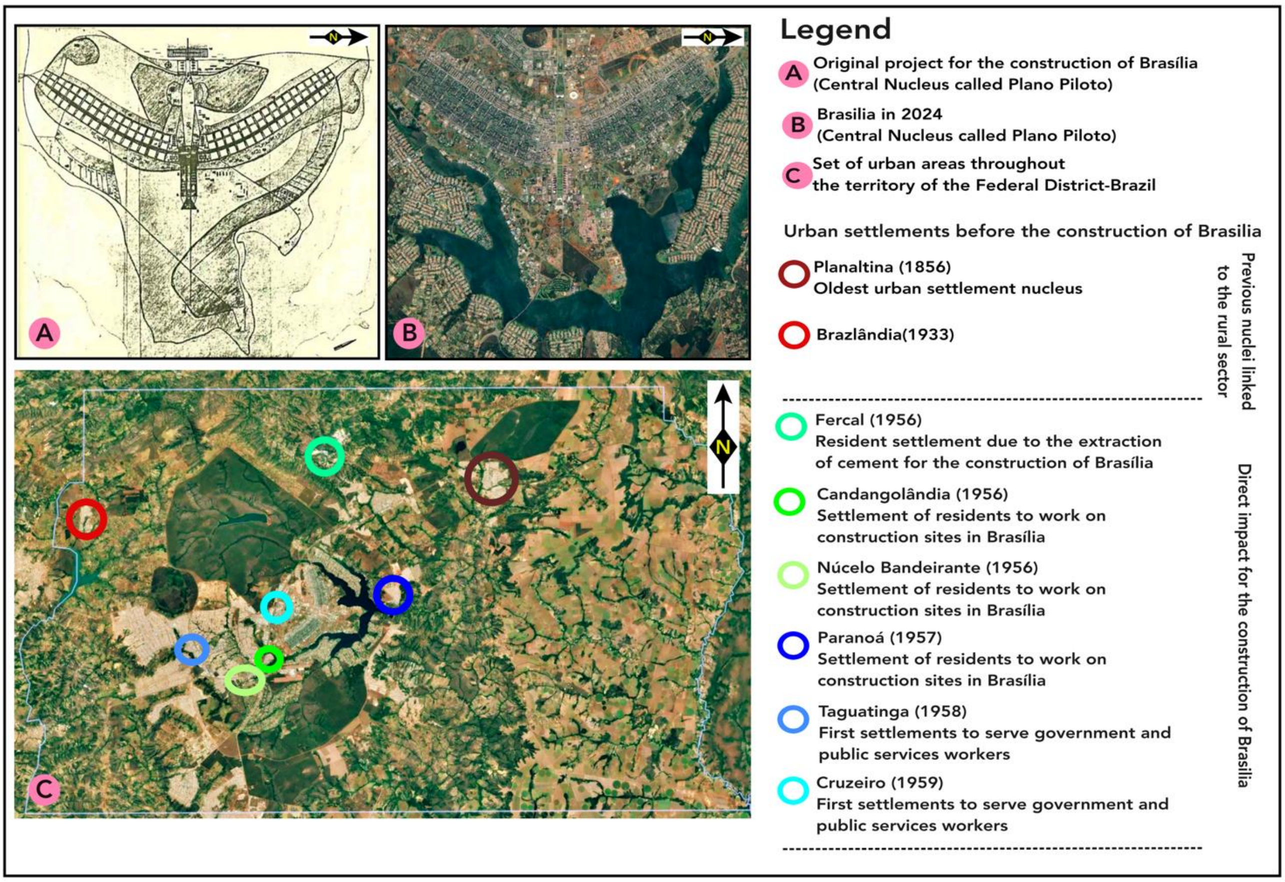


Image 2: Winning project for the construction of the new capital, (A) Brasília – Plano Piloto (B), and the urban settlements prior to the construction of Brasília, including those created for housing workers.

Brasília, designed by architects Lúcio Costa and Oscar Niemeyer, had its inauguration on April 21, 1960. Its urban planning was innovative for its time, characterized by a design that divided the city into specific sectors for housing, commerce, services, and green spaces, reflecting the principles of "modern urbanism" and prioritizing collective well-being. In recognition of its architectural and urban significance, Brasília was designated a UNESCO Cultural Heritage of Humanity in 1987 (Oliveira, 2007; Ribeiro & Silva, 2018).

Originally envisioned as a modern city integrated with nature, Brasília stands as one of the most iconic examples of 20th-century urban planning, as Costa and Niemeyer's idea of a harmonious relationship between built environment and extensive green areas, emphasizing the human well-being. Brasília's Plano Piloto, notable for its vast green spaces, which serve both ecological and social functions, is structured around monumental, residential, and bucolic scales, with heavily wooded superblocks and large urban parks, enhancing quality of life by providing thermal comfort, recreational areas, and a consistent connection to nature. The green area index per inhabitant in Plano Piloto (Administrative Region I – Brasília), which greatly exceeds international standards, exemplifies the success of this concept, with a privileged average of 138 m² of green space per inhabitant, a figure which ensures the central population has regular access to natural environments.

However, while this approach was both innovative and effective in the context of the 1960s, it was predominantly applied to the central core of the city: Plano Piloto, with a design not uniformly extended to peripheral areas and newer neighborhoods which now constitute the broader urban landscape of the Federal District, which upon closer examination reveals that, as the city expanded beyond its well-known and carefully "planned" central area, with the development of new administrative regions and neighborhoods, this planning philosophy was not consistently maintained.

While Brasília is celebrated globally for its innovative urban planning, the concentration of these innovations in the central area shows the need for a more inclusive and equitable approach across its urban territory. It is essential that future urban planning in Brasília addresses these disparities, ensuring that all residents benefit from a sustainable urban environment integrated with nature, as originally envisioned for Plano Piloto.

**Data set and Methodological Approach**

This research's aim was to analyze the distribution and accessibility of urban green spaces in the Federal District, using urban census sectors as the territorial unit of analysis, as defined by the Brazilian Institute of Geography and Statistics (IBGE), with a methodological approach based on a set of variables, such as number of isolated trees, tree mass, and green areas with vegetation typical of the Cerrado biome. Quantitative techniques, such as indicator analysis and statistical and geospatial methods, were employed to explore the relationship between green areas and the population.

The chosen variables definitions and data sources were:

a) Urban Census Sectors: territorial division provided by IBGE which defines urban areas based on demographic and geographic criteria (IBGE, 2022);

b) Number of Isolated Trees: total count of isolated trees within each census sector (IPE-DF, 2023);

c) Tree Mass: area covered by trees arranged continuously or without significant interruption (IPE-DF, 2023);

d) Green Areas with Cerrado Vegetation: public or private green areas featuring native or typical vegetation of the Cerrado biome (Adapted from IPE-DF, 2023).

Data was collected from IBGE databases, thematic maps, satellite imagery, and fieldwork. The urban census database obtained from the IBGE website was complemented by spatial data from remote sensing and tree inventory information provided by the municipal environmental department.

The following key calculations were performed as to construct the database for each census sector in preparation for spatial analysis:

a) Green Area per Inhabitant (AVH) – to calculate the amount of green area available per inhabitant in each census sector, the following formula was applied:

$$AVH_i = \frac{A_{verde_i}}{H_i}$$

*Where:*

$AVH_i$: Green Area per Inhabitant in census sector $i$ (m²/inhabitant);

$A_{verdei}$: Total green area for census sector $i$ (m²);

$H_i$: Residential population in census sector $i$ (inhabitants).

b) Access to Green Areas (AAG) – to calculate the access to housing in green areas, an analysis based on geospatial buffers was applied, considering the maximum distance of 300 meters from house to green area:

$$AAG_i = \frac{M_{acesso_i}}{M_{total_i}} \times 100$$

*Where:*

$AAG_i$ : Percentual of houses with access to green areas in census sector $i$

$M_{Acesso\ i}$ : Number of houses with access (within 300 meters of a green area);

$M_{total\ i}$ : Total number of houses in a census sector

c) Geostatistical Analysis of Green Area Distribution – the spatial distribution of green areas was analyzed using geostatistical tools; the Moran $I$ index was utilized to calculate the degree of spatial autocorrelation in green areas:

$$Moran's I = \frac{N \sum_i \sum_j w_{ij}(A_{verde_i} - \bar{A_{verde}})(A_{verde_j} - \bar{A_{verde}})}{S_0 \sum_i (A_{verde_i} - \bar{A_{verde}})^2}$$

*Where:*

$N$ : Number of urban census sectors

$W_{ij}$ : Spatial weight between sectors $i$ and $j$

$A_{verde\ i}$ : Green area in sector $i$

$A_{verde}$ : Average green area in sectors

$S_0$ : Total spatial weight

The flowchart presented in Image 3 methodically and hierarchically illustrates the process of analyzing urban green areas within the territory of Brazil's Federal District. This diagram outlines three critical phases which, collectively, form the geospatial and statistical research methodology, aiming to understand the relationship between distribution of green areas and human occupation in the urban space.

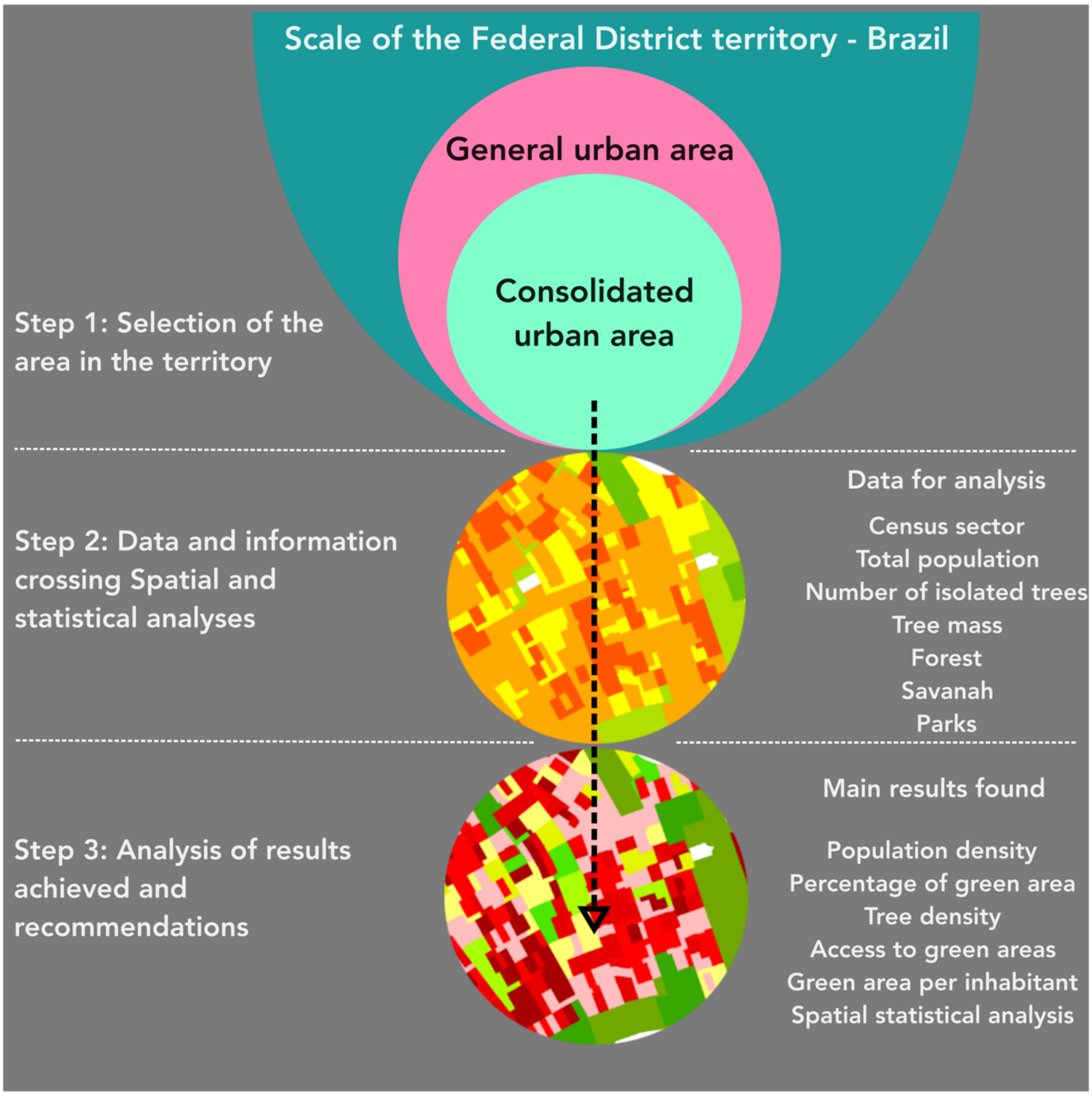


Image 3: General flowchart of data collection stages, with systematization, analysis, and presentation of results.

Selecting a study area within the territory was the first step, where the scale of analysis is determined based on an initial delineation of the general urban area, focusing on the consolidated urban area, which represents the densest and most established inhabited core of the urban space. This methodological choice ensures greater precision, as consolidated urban areas typically exhibit higher population density and more complex socio-environmental dynamics.

The second step encompassed data integration, along with spatial and statistical analysis, forming the core of this investigation, wherein a variety of data related to census sectors is collected and integrated (including total population, number of isolated trees, extent of tree mass, and distribution of forests, savannas, and parks) and then processed using advanced geoprocessing and statistical techniques (GIS – geographic information systems). The primary objective of this phase is to identify spatial patterns and correlations between distribution of green areas and population density, as well as to analyze accessibility to these areas considering different sociodemographic characteristics in the census sectors under study.

The third and final step was to analyze the results and formulate recommendations, interpreting the processed data from key indicators such as population density, percentage of green area per census sector, tree density, population access to green spaces, and green area per inhabitant. Additionally, spatial statistical analysis techniques were applied to ensure a robust and well-founded data interpretation. Based on these findings, recommendations were formulated for urban planning, focusing on improving green infrastructure, ensuring equitable access to green spaces, and strengthening urban sustainability, considering the interactions between environmental and social dynamics in the urban context, providing essential support for the formulation of public policies aimed at creating greener, fairer, and more sustainable cities.

**Results and analysis**

Statistical analysis of the variables studied revealed distinct distribution patterns, as through histograms and descriptive statistics it was possible to observe varying levels of dispersion, asymmetry, and concentration, reflecting the complexity of variables such as population, demographic density, vegetation cover, and the distribution of isolated trees, which suggest the presence of extreme values and non-normal distributions, with long tails and high variability in certain variables.

**Table 1**: Descriptive statistical data of the main data groups used

| | ***Total Population*** | ***% of Green Area*** | ***Population Density*** | ***Isolated Trees*** |
|---|---|---|---|---|
| ***N*** | 4150 | 4150 | 4150 | 4150 |
| ***Min*** | 0 | 0 | 0 | 0 |
| ***Max*** | 3109 | 96.4 | 2374 | 7004 |
| ***Sum*** | 2494931 | 40170.32 | 518486 | 629872 |
| ***Mean*** | 601.1882 | 9.679595 | 124.9364 | 151.7764 |
| ***Std. error*** | 3.865876 | 0.2213057 | 2.019759 | 6.352569 |
| ***Variance*** | 62021.74 | 203.2512 | 16929.63 | 167473.8 |
| ***Stand. dev*** | 249.0417 | 14.25662 | 130.1139 | 409.2356 |
| ***Median*** | 596.5 | 3.435 | 102 | 40 |
| ***25 prcntil*** | 461 | 0.92 | 54 | 20 |
| ***75 prcntil*** | 743 | 11.595 | 164 | 92 |
| ***Mode*** | 0 | 0 | 0 | 0 |
| ***Skewness*** | 0.6766122 | 2.133711 | 5.069465 | 7.045515 |
| ***Kurtosis*** | 5.231858 | 4.439016 | 48.32995 | 71.29147 |
| ***Geom. mean*** | 0 | 0 | 0 | 0 |
| ***Coeff. var*** | 41,42491 | 147,2853 | 104,1441 | 269,6306 |

According to the data, the Total Population variable exhibits a mean of 601.1882 and a median of 596.5, indicating a slightly asymmetric distribution, with extreme values extending the right tail, further confirmed by a skewness of 0.6766 and a kurtosis of 5.2319. This variation is considerable, reflected in a standard deviation of 249.0417.

The Percentage of Green Area variable shows a mean of 9.6796%, with a median of 3.435%, suggesting that most areas have less vegetation than the mean. This variable also shows high variability, with a standard deviation of 14.2566 and a skewness of 2.1337, indicating the presence of areas with substantially higher proportions of vegetation.

Population Density has a mean of 124.9364 and a median of 102, displaying a wide dispersion in the data, evidenced by a standard deviation of 130.1139. The high skewness of 5.0695 reflects a concentration of areas with densities significantly higher than the mean.

Finally, the Number of Isolated Trees variable, with a mean of 151.7764 and a median of 40, presents extreme asymmetry, with a skewness of 7.0455, indicating the existence of a few areas with a high concentration of trees, contrasted by a majority of areas with relatively fewer trees.

All four variables analyzed demonstrate highly asymmetric distributions, with the presence of outliers heavily influencing the descriptive statistics, which suggest caution is needed when interpreting these results, as the high variability and skewness imply that the mean may not adequately represent the central tendency of the data.

The histograms in Image 4 illustrate the distribution patterns of variables, each exhibiting distinct characteristics in terms of asymmetry, dispersion, and concentration:

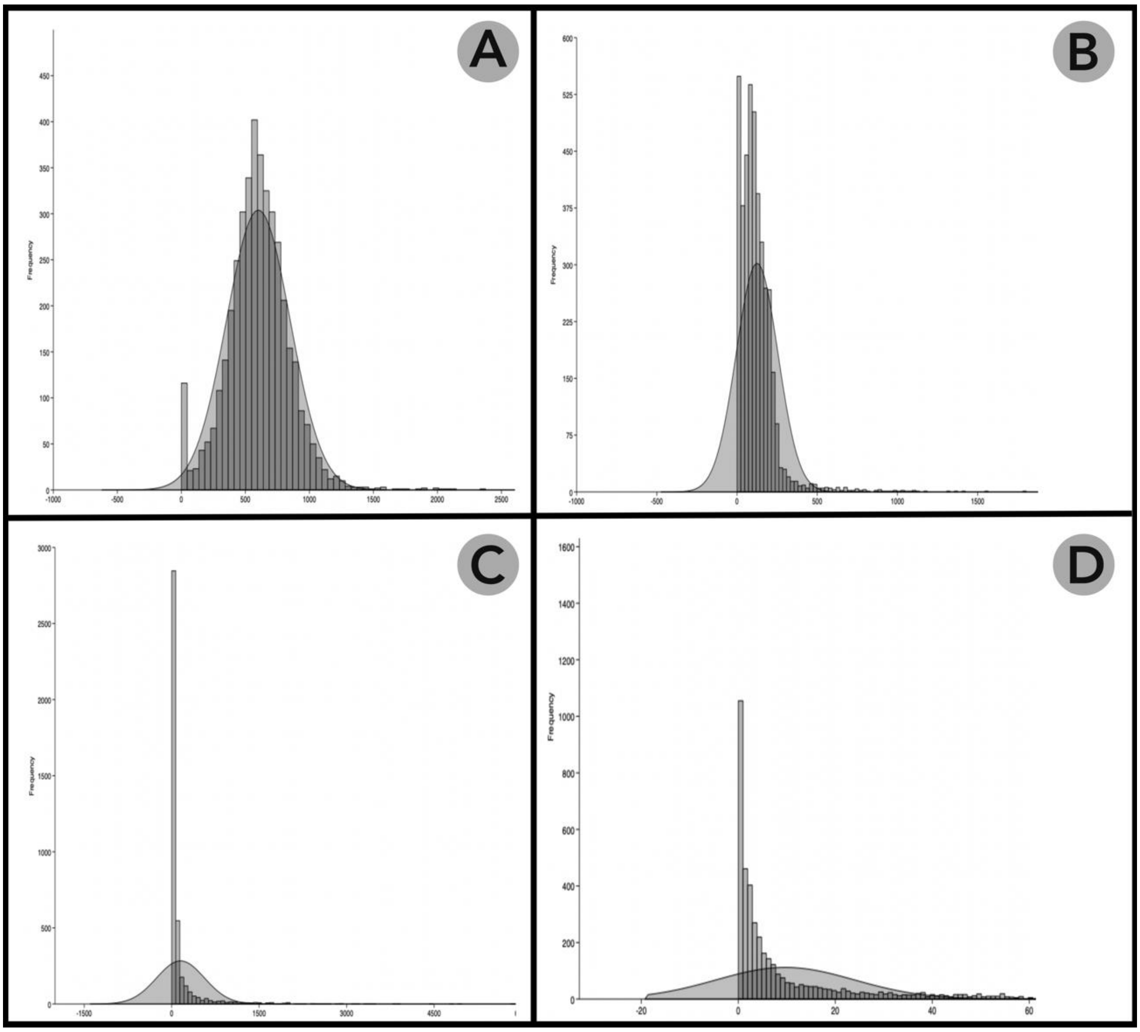


Image 4: Histograms of the main data used in A) Total population by census tract; B) Population density (Ha); C) Isolated trees by census tract; and D) Percentage of green area by census tract.

Image 4-A shows a histogram with a distribution close to normality and a slight positive skew. Most values are concentrated around a central point, with frequencies gradually decreasing toward the tails. The slight rightward skew indicates the presence of outliers, consistent with the positive asymmetry observed in the previous analysis of "Total Population." Data tend to cluster in the range of 500 to 1000, with values above 1500 being relatively rare.

Image 4-B illustrates a highly skewed distribution with a long right tail, with a concentration of values near the minimum, likely close to zero, and a few extreme values extending the tail. This pattern matches the Population Density variable, highlighting disparities in density across census tracts. The pronounced skewness and long tail confirm a non-normal distribution.

Image 4-C, representing the Isolated Trees variable, shows a strong concentration of values at the minimum, with a long tail extending to the right. Most observations cluster near zero, with few areas exhibiting higher values, which indicates that, while some census tracts contain many isolated trees, the majority have few or none. This extreme skewness and concentration at a single value characterize this distribution as highly asymmetric.

Image 4-D, similar to the Isolated Trees data, reveals a high concentration of values near a specific point, with a long tail on the right. However, the range of values is narrower, with slightly less dispersion. This histogram reflects the Percentage of Green Area, where most census tracts have low or no vegetation cover, with a few exceptions showing significantly higher proportions. Its long tail suggests that while most areas are sparsely vegetated, some have much higher levels of green cover, skewing the distribution.

The population map (Image 5) depicts the demographic distribution across census sectors, highlighting areas with the highest and lowest population concentrations. Peripheral regions, such as Ceilândia and Samambaia, exhibit high population density, while central and higher-income areas, including Plano Piloto and Lago Sul, show lower density.

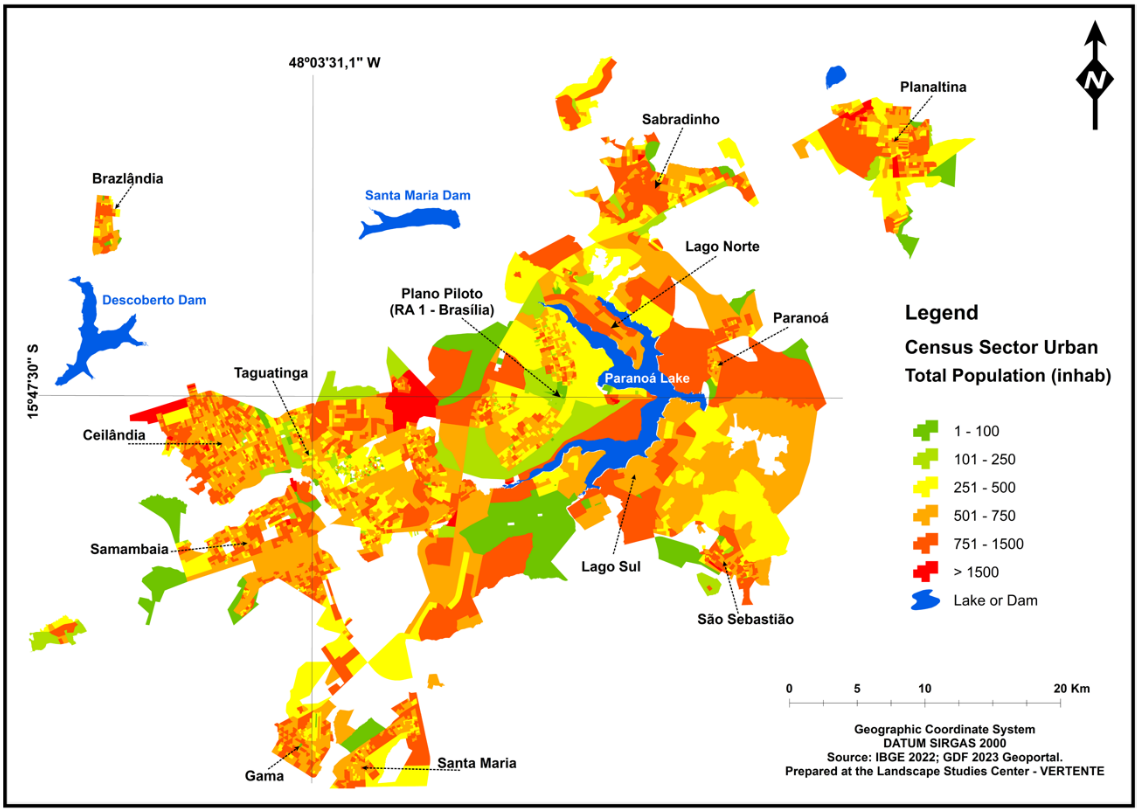


Image 5: Map of absolute population for urban census sectors in the Federal District.

In this map, green denotes low density, while red indicates high density. Peripheral regions, such as Ceilândia, Taguatinga, and Samambaia, are predominantly shown in red, reflecting a high population concentration. In these areas, the population density exceeds 1,500 inhabitants per sector, representing significant agglomeration.

In contrast, Plano Piloto shows a more varied population distribution, with census sectors of both high and low density. Northern regions such as Sobradinho and Planaltina are characterized by intermediate to low population densities, with a predominance of census sectors shaded in yellow and green, representing a lower inhabitant concentration.

This distribution reveals an urbanization pattern that concentrates much of the population in peripheral areas, a historical consequence of Brasília's urban planning, which envisioned Plano Piloto as an administrative center with lower density, while satellite cities such as Ceilândia and Taguatinga expanded to accommodate a growing population.

This map also highlights socio-spatial disparities, where densely populated peripheral areas face greater demands for infrastructure and public services, while central areas host a relatively smaller population despite their greater support capacity.

Image 6 presents the population density by census sector:

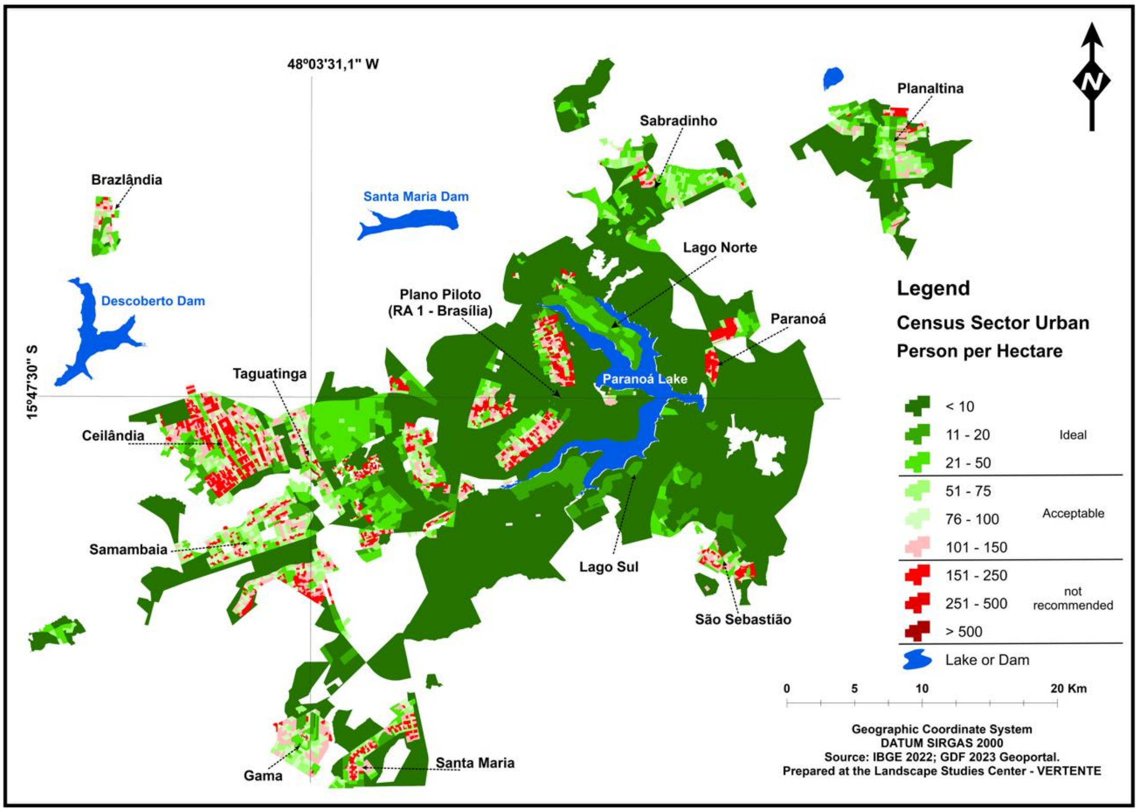


Image 6: Population density map for urban census sectors in the Federal District.

This map presents population density in terms of inhabitants per hectare, using a color scale ranging from green, indicating areas of low population density, to red, which marks areas of high density. These categories are designed to separate areas considered ideal (fewer than 50 inhabitants per hectare) from areas with acceptable densities and those deemed unsuitable for housing due to excessive density (greater than 250 inhabitants per hectare).

Areas marked in red, denoting densities exceeding 500 inhabitants per hectare, are primarily concentrated in areas such as Ceilândia, Taguatinga, Samambaia, and parts of Planaltina, showing the highest population concentrations and, consequently, the areas where pressure on urban infrastructure, public services, and quality of life is most acute, likely a result of rapid urbanization and population growth over the past few decades.

Conversely, dark green areas, indicating ideal densities (fewer than 10 inhabitants per hectare), are predominantly located in regions such as Lago Sul, Lago Norte, and areas adjacent to Plano Piloto, traditionally characterized by larger residential lots and lower housing densities, showing a more relaxed urbanization pattern and a contrasting socioeconomic reality.

Intermediate regions, including Sobradinho, Gama, and Santa Maria, display more moderate population densities, represented by shades of light green and white, suggesting a balanced occupation with acceptable densities. However, in some areas within these regions, pockets of high density are noticeable, as indicated by sectors shaded in red and light pink, demonstrating that even predominantly less dense areas may contain sectors of intensified population concentration.

The map in Image 7 highlights the variation in vegetation cover across urban sectors in the Federal District. Central regions such as Plano Piloto and Lago Sul exhibit a higher concentration of green spaces, while peripheral areas, including Ceilândia and Samambaia, show a scarcity of vegetation.

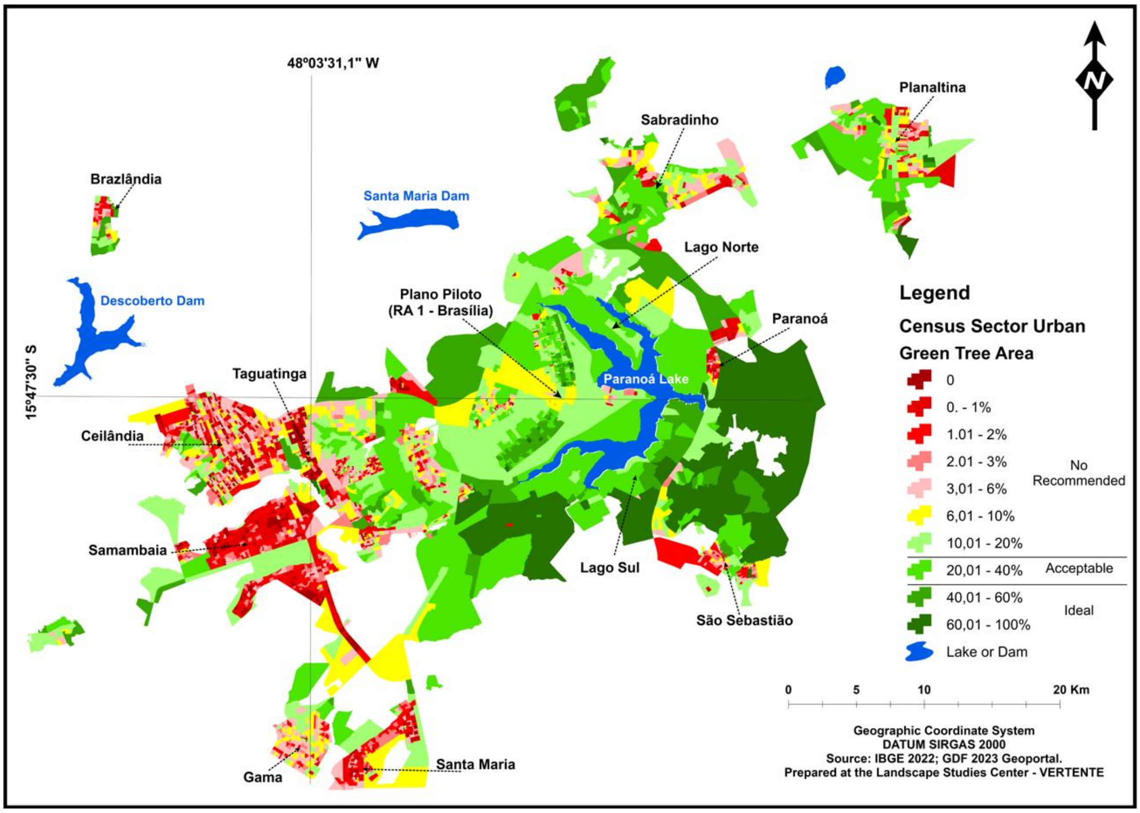


Image 7: Map of the percentage of green areas by urban census sectors in the Federal District.

This map uses a color scale ranging from red, indicating the absence of green areas, to dark green, representing a high concentration of trees. Peripheral regions, such as Ceilândia, Samambaia, Gama, and parts of Planaltina, exhibit minimal or no tree cover, reflecting high urban density and a scarcity of green spaces, with negative consequences for both quality of life and the urban microclimate.

In contrast, areas such as Plano Piloto, Lago Sul, and Lago Norte display significant tree cover, with some sectors having up to 100% vegetation, indicating greater environmental preservation, while regions like Sobradinho, Santa Maria, and São Sebastião present a mix of sectors with both acceptable and ideal levels of tree coverage, suggesting a balance between urban development and green space preservation.

This map reveals a clear socio-spatial pattern: higher-income areas are more densely forested, while denser, lower-income regions suffer from a lack of tree cover.

A similar pattern is observed in Image 8, which shows the density of green area per inhabitant, measured in square meters, across the census sectors in the Federal District.

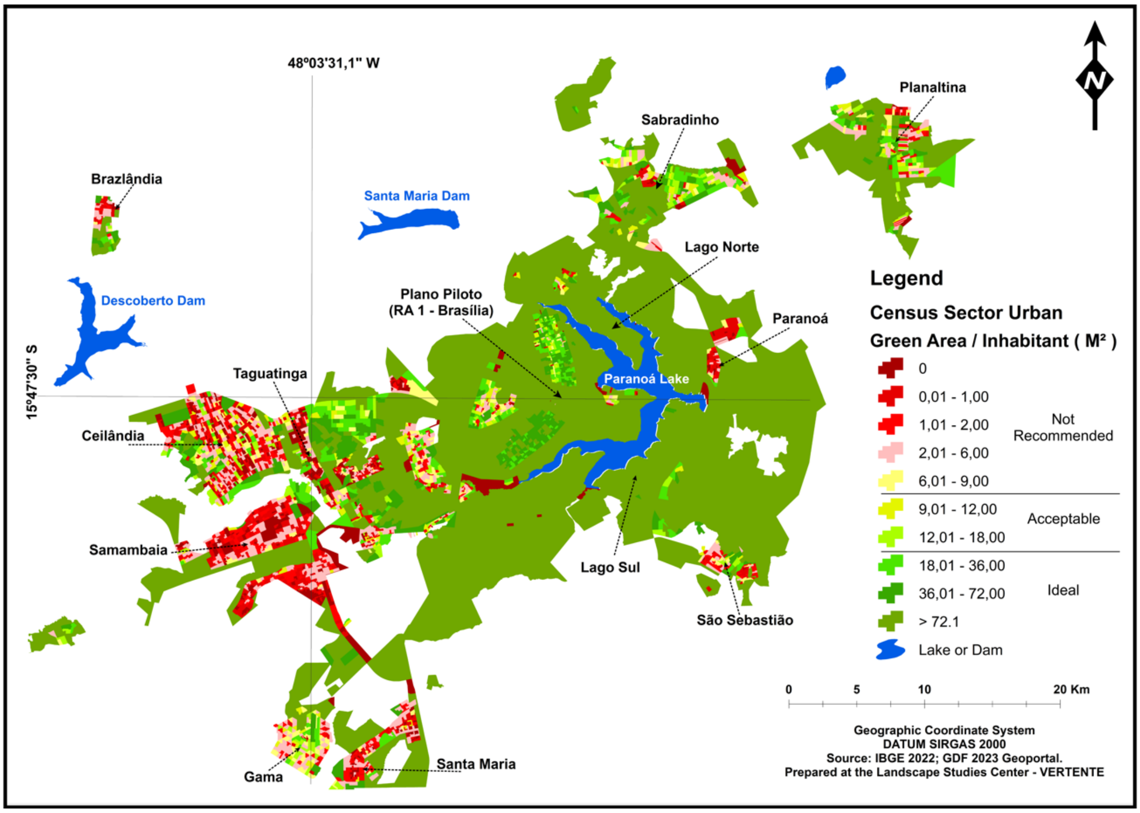


Image 8: Map of green areas (m²) per inhabitant for urban census sectors in the Federal District.

The map uses a color scale ranging from red, to show regions without vegetation, to dark green, representing areas with more than 72 m² of green area per inhabitant.

The most problematic regions, characterized by inadequate green coverage (less than 6 m² per inhabitant), are concentrated in peripheral areas such as Ceilândia, Samambaia, Gama, and parts of Planaltina, marked in red and pink, signaling a critical shortage of green spaces, compromising environmental quality.

Conversely, central areas like Plano Piloto and wealthier regions such as Lago Sul, Lago Norte, and parts of Sobradinho show a significantly higher amount of green space per inhabitant, exceeding 36 m² in many sectors. This abundance of vegetation reflects an urban development pattern centered on well-being and environmental preservation.

Intermediate zones, including parts of Taguatinga and Santa Maria, show acceptable levels of green area per inhabitant, with values ranging between 9 and 18 m².

The map in Image 9 reveals a higher concentration of isolated trees in central and higher-income areas, in contrast to peripheral regions, which exhibit low densities of isolated trees, reflecting socio-environmental disparities.

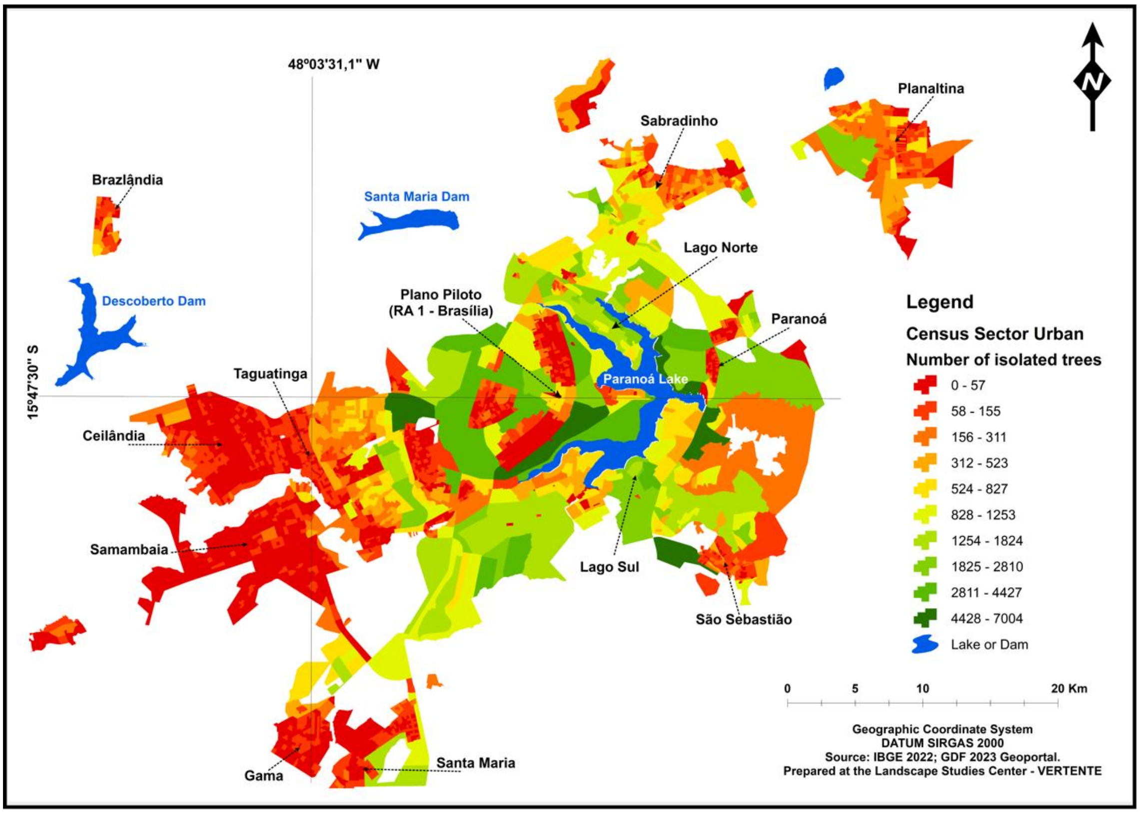


Image 9: Map of isolated trees distribution in the Federal District.

This map uses a color scale that ranges from red, representing a low number of trees (0 to 57), to dark green, indicating a high concentration of isolated trees (up to 7,004). Peripheral regions such as Ceilândia, Samambaia, Gama, and parts of Planaltina are predominantly shaded in red and orange, suggesting a low presence of isolated trees, indicative of the high urban density and the limited presence of areas of vegetation, where intense urbanization restricts the capacity for maintaining a large numbers of trees.

In contrast, areas such as Plano Piloto, Lago Sul, Lago Norte, and parts of Paranoá have a higher concentration of isolated trees, represented by green and yellow shades, a consequence of urban planning policies which prioritize green space preservation and lower population density, showing a greater integration between built environments and vegetation, enhancing both environmental quality and urban aesthetics.

Intermediate regions, including Sobradinho and parts of Santa Maria, exhibit a mixed distribution, with sectors ranging from low to moderate tree presence, which may indicate a balance between urbanization and vegetation.

The observed pattern reinforces the socio-environmental inequalities in the Federal District, highlighting the need for urban interventions to expand tree coverage in poorer regions, improving quality of life, urban microclimate regulation, and enhanced ecosystem services.

Image 10 provides a detailed view of the density of isolated trees per hectare in the census sectors of the Federal District.

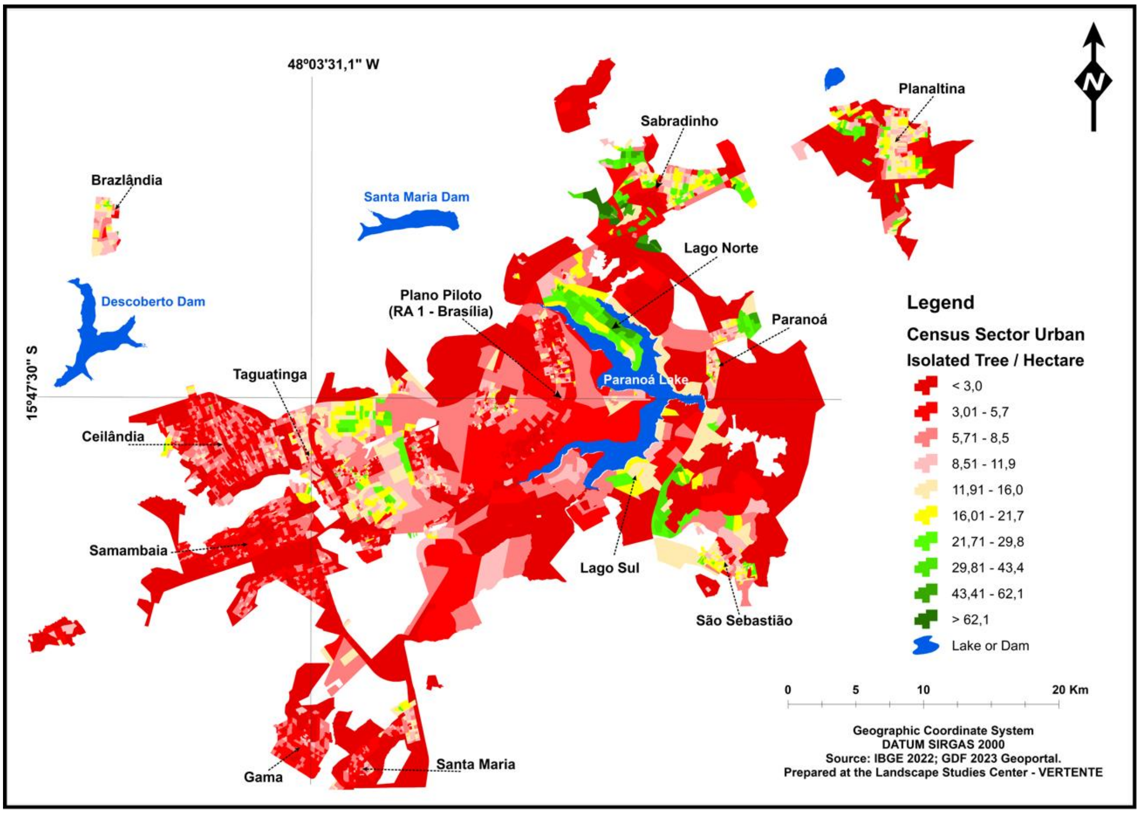


Image 10: Map of isolated trees per hectare in urban census sectors of the Federal District.

This map displays a clear contrast between central and peripheral areas, where regions such as Ceilândia, Samambaia, Gama, and Santa Maria, shaded in red, exhibit a low density of trees, reflecting intense urbanization and a scarcity of vegetation, while sectors in Plano Piloto, Lago Sul, Lago Norte, and parts of Sobradinho and Paranoá, shown in green and yellow, demonstrate a higher density of trees.

This disparity underscores the socio-environmental inequalities within the Federal District, where wealthier regions enjoy more abundant tree cover, while lower-income areas are marked by a lack of vegetation, which negatively impact quality of life and the urban climate.

The map in Image 11 and Image 12 reveals significant inequality in access to green spaces:

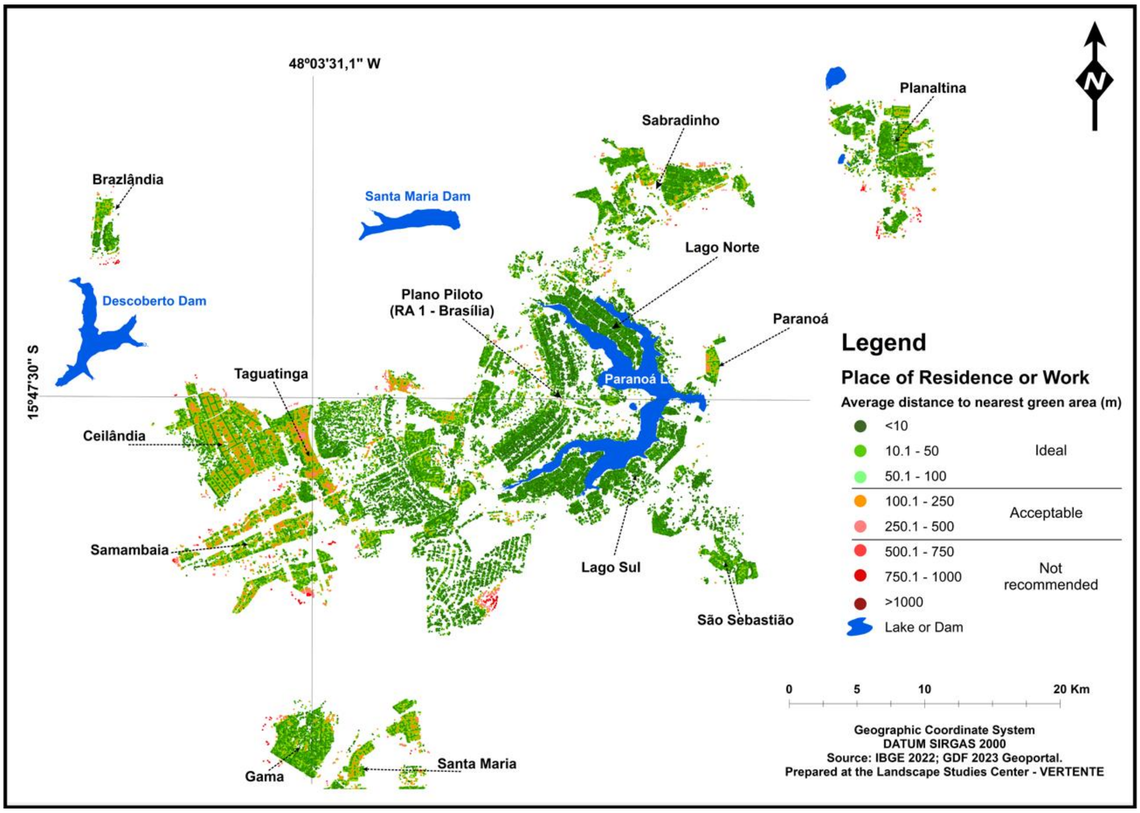


Image 11: Map of access from residence/workplace to green areas in urban census sectors of the Federal District.

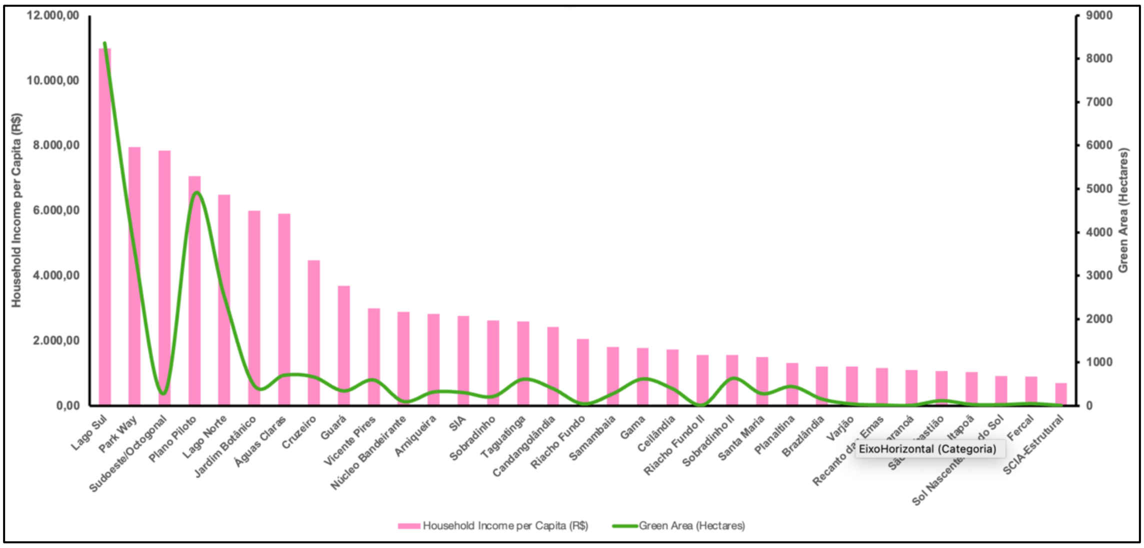


Image 12: Relationship between per capita household income and available green area.

The two images together offer a compelling visual narrative about the socio-spatial inequalities in access to green spaces across the Federal District. The map depicts the average distance between residences or workplaces and the nearest green areas, using a gradient color scale. Dark green shades represent ideal distances of less than 10 meters, while red indicates distances exceeding 1,000 meters, which are considered undesirable. The central regions—Plano Piloto, Lago Sul, and Lago Norte—are largely shaded in green, reflecting that residents in these areas benefit from excellent access to green spaces, with distances generally below 100 meters, ensuring an enriched quality of urban life.

Conversely, the peripheral regions, including Ceilândia, Samambaia, Gama, and segments of Planaltina, are marked in shades of orange and red, indicating limited access to green areas. In these lower-income, densely populated regions, residents may need to travel more than 250 meters, and in some cases, beyond 1,000 meters, to reach a green space. The graph further reinforces this disparity by demonstrating a correlation between higher per capita household income and greater availability of green areas. Regions with higher incomes enjoy better-planned green infrastructure, contributing to enhanced environmental quality and quality of life. In contrast, marginalized communities face reduced accessibility to these critical urban amenities, exposing a clear inequality in the distribution of environmental resources. These patterns underscore the urgent need for urban policies that promote equitable access to green spaces through inclusive planning and sustainable, nature-based solutions.

Further analysis using geostatistical models such as Getis-Ord Gi was essential for identifying spatial patterns of green area concentration or scarcity (Image 13), detecting "hot spots" (areas of high concentration) and "cold spots" (areas of low concentration), revealing where vegetation and environmental resources are abundant or lacking. Integrating this data with population distribution and access to green areas provides a more comprehensive understanding of socio-environmental inequalities.

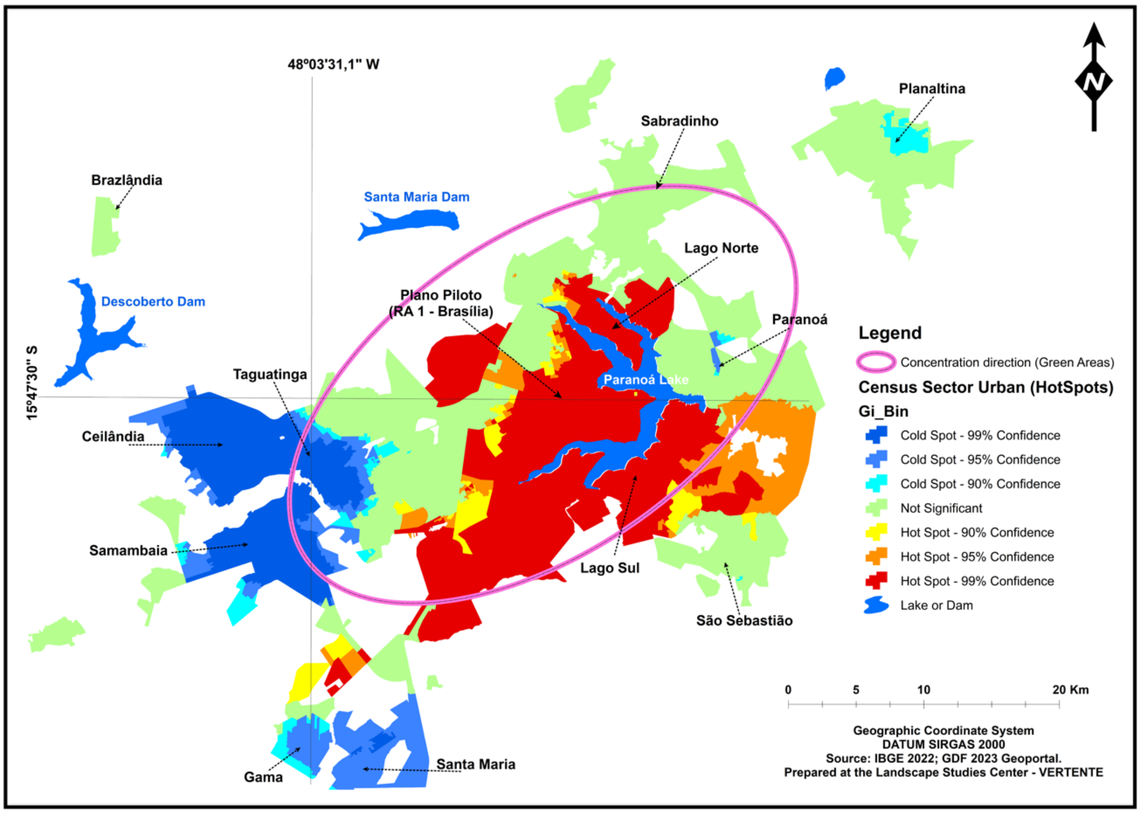


Image 13: Map of geostatistical distribution in urban census sectors of the Federal District and direction of concentration of green spaces

In this map, areas shaded in red represent hot spots with 99% confidence, while areas in blue indicate cold spots, with varying confidence levels (90%, 95%, and 99%).

Central regions, such as Plano Piloto, Lago Sul, and Lago Norte, are prominent hot spots, indicating a high concentration of well-preserved green spaces. In contrast, peripheral areas such as Ceilândia, Samambaia, Gama, and parts of Taguatinga are predominantly shaded in blue, signifying cold spots, or regions with a low concentration of green spaces. These sectors are marked by intense urbanization and a lack of vegetation.

The area outlined in pink shows the direction of green space concentration, indicating that most green areas are located in wealthier central regions, while peripheral areas, which are more densely populated and have lower incomes, suffer from a lack of vegetation.

The selected sample images in Image 14 visually illustrate the urban and environmental disparities previously identified, capturing the spatial reality of different regions, considering patterns of land occupation, population density, and the distribution of green spaces. Seeing these, it becomes evident how socioeconomic disparities directly impact environmental quality and access to resources such as vegetation and green spaces.


Image 14: Mosaic with satellite image clippings that illustrate the disparities in the distribution of green areas in the urban area of the Federal District.

This image presents sample photos depicting spatial configuration and occupation patterns, ranging from densely urbanized sectors, such as Ceilândia (A), Brazlândia (B), and Gama (C), to areas with more preserved green areas, such as Lago Norte (F) and Park Way (L).

The photo of Park Way (L) is particularly illustrative, showcasing large residential lots and extensive green coverage, an urban pattern typical of wealthier regions in the Federal District, which demonstrates a balanced relationship between population density and environmental preservation, favoring green spaces, while in peripheral and lower-income regions, such as Ceilândia, Samambaia (I), Itapoã (H), and Taguatinga (K), the photos reveal a high density of buildings with minimal or no presence of green areas ("cold spots" from previous maps) which are linked to unfavorable social indicators, including lower quality of life and reduced access to leisure spaces.

In contrast, wealthier and higher-income areas such as Asa Sul (D), Asa Norte (E), and Lago Norte exhibit lower population density and a greater abundance of vegetation, confirming the "hot spots" from previous analyses, wherein vegetation is integrated into the urban landscape, contributing to higher quality of life, enhanced environmental comfort, and better socioeconomic indicators.

## Discussion

Urbanization in tropical countries of the southern hemisphere has been marked by intense and accelerated social, economic, and political transformations, often characterized by chaotic and uncontrolled growth. Beginning in the mid-20th century, a massive rural-to-urban migration started, with millions of individuals leaving rural areas in search of better employment opportunities and living conditions in urban centers (Maricato, 2000; Monte-Mór, 2006; Ribeiro & Santos Junior, 2017), driven by easier access to employment, education, and healthcare services, in contrast to the more precarious conditions in rural areas. However, this rural exodus exacerbated a series of structural challenges that remain to this day (Schneider, 2010; Mattei, 2015).

In countries across Latin America, Africa, and Asia, rapid urban expansion has been accompanied by a host of critical issues, such as uncontrolled proliferation of informal settlements, inadequate basic infrastructure, and increasing environmental degradation, compounded by a colonial legacy, which shaped urban planning primarily to serve the interests of colonial elites, while relegating the majority of the population to marginalized and precarious living conditions.

The effects of this exclusionary urbanization process remain visible in the socio-spatial segregation which perpetuates deep social, economic, and environmental inequalities in tropical cities of the southern hemisphere, with an entrenched stark divide between well-serviced urban areas, typically occupied by elites, and underdeveloped peripheries, often neglected by public authorities (Bueno & Dias, 2015; Mohanty, 2020; Soliman, 2021; Aboulnaga et al., 2021; Balbim, 2022; Nigussie et al. 2024).

The management of urban areas in these developing regions presents, therefore, a multifaceted challenge, as cities are expanding at a rate far exceeding the capacity of local governments to provide adequate services and infrastructure (Megerle, 2025). The lack of basic sanitation, inefficient public transportation, and substandard housing are direct outcomes of this imbalance. Urban governance must, then, be rethought through an integrated approach which considers economic, social, and environmental dimensions as part of a unified strategy, decentralizing public administration and promoting active community participation to effectively respond to evolving needs.

In this context, collaboration between the public and private sectors becomes crucial, as investments in quality urban infrastructure, aligned with sustainability policies, require the mobilization of substantial resources and the expertise of diverse actors. Also, smart technologies which enhance efficiency in resource management, alongside nature-based solutions such as the preservation of green spaces and sustainable management of natural resources, represent promising alternatives for addressing the urban challenges of the 21st century. These innovations have the potential to transform tropical cities into more resilient spaces, capable of adapting to climate change while offering improved living conditions for their inhabitants (Katsou et al., 2020; Ferreira et al., 2020, Kusi, 2025).

Studies on urban green spaces in Latin America highlight their importance for enhancing urban quality of life and promoting environmental sustainability, as the presence of green areas has been consistently associated with numerous benefits, including the mitigation of urban heat island effects, improved air quality, and increased biodiversity (Dobbs et al., 2019). In the Brazilian context, cities such as São Paulo, Rio de Janeiro, and Curitiba have been focal points of research into the equitable distribution of green area, showing that proximity to parks and green spaces correlates directly to higher levels of usage by the population, as well as to improvements in citizen's physical and mental health (Celuppi et al., 2023).

However, a pronounced inequality in the distribution of green spaces persists, with peripheral regions, typically inhabited by low-income populations, being notoriously deficient in green areas, perpetuating cycles of environmental and social exclusion. A recent study of the metropolitan areas of São Paulo and Mexico City revealed that uncontrolled urbanization has led to significant green space loss, jeopardizing the provision of critical services (Wendel et al., 2012; Rigolon et al., 2018). As an effective solution, the creation of ecological corridors has been identified to connect isolated vegetation fragments and promote urban biodiversity, facilitating the movement of species and supporting essential ecosystem services, such as regulating water flow and local climate (Alivio et al. 2025).

The need to integrate green areas into urban planning is urgent, as without proper management, the continued loss of green spaces could severely hinder cities' ability to adapt to climate change. The scientific literature consistently emphasizes the importance of spatial planning which incorporates ecosystems as integral components of the urban landscape, advocating for ecological restoration and the establishment of new green spaces, particularly in underserved peripheral regions (Capotorti et al., 2019; Venter et al., 2021).

Another significant issue, highlighted by studies on urban ecology and green spaces in Brazil, is the concentration of research in areas with a higher Human Development Index, such as São Paulo and Rio de Janeiro, often at the expense of low-income regions. This research gap points to the need for a more comprehensive approach that not only examines ecological interactions but also addresses the social dimensions and dynamics of exclusion prevalent in tropical cities (Buccheri Filho & Nucci, 2006; Sartori et al., 2023).

Considering the historical process of urbanization in tropical countries of the southern hemisphere, along with the management of urban areas in developing nations, the role of urban green spaces, especially in Brazil, emerges, then, as a pivotal factor in building more inclusive, resilient, and sustainable cities. Implementing public policies that prioritize the creation and maintenance of urban green areas is crucial for addressing future environmental and social challenges, as the integration of ecological, social, and economic factors in urban management, supported by effective and participatory governance, is essential for building cities that cater to the needs of all its inhabitants.

## Conclusions

This study reveals significant inequalities in the distribution of green areas across the Federal District, highlighting its socio-environmental disparity. Analyses demonstrate that central regions, such as Plano Piloto, Lago Sul, and Lago Norte, show a higher concentration of vegetation and easier access to green areas, which contribute to better quality of life and a more balanced urban environment, as the proximity to areas of vegetation provides numerous benefits, including mitigating the effects of urban heat islands, improving air quality, and offering recreational areas which enhance social cohesion and promote the physical and mental well-being of the population.

In contrast, peripheral regions, such as Ceilândia, Samambaia, Gama, and Planaltina, predominantly inhabited by lower-income populations, suffer from a lack of vegetation, considerable distances to green spaces, and urban planning that neglects environmental sustainability. The scarcity of green areas in these regions adversely affects their microclimate, contributing to higher temperatures, increased pollution, and a shortage of public spaces for social interaction, exacerbating already existing socioeconomic vulnerabilities.

The application of geostatistical models, such as *Getis-Ord Gi*, was instrumental in identifying areas with hot spots (high vegetation concentration) and cold spots (low vegetation concentration), highlighting the concentration of green areas in wealthier regions and their scarcity in peripheral areas, confirming the existence of an unequal urbanization pattern, which perpetuates disparities in access to environmental benefits, and, clearly, indicating where urban interventions are most urgently needed.

Considering these findings, formulating public policies to reduce these inequalities, promoting the creation and preservation of green areas in the most disadvantaged regions, and strengthening urban planning to ensure that new green spaces are accessible to all citizens, regardless of their location or income, becomes an imperative. Furthermore, to build more resilient cities, capable of addressing future challenges, these policies must be integrated with climate change mitigation strategies.

In conclusion, this study not only exposes the inequalities in green area distribution within the Federal District, but also suggests pathways to creating a more just, sustainable, and socially inclusive city, by implementing strategies to integrate vegetation into the urban fabric of peripheral regions and, therefore, improving overall quality of life while fostering social cohesion throughout the city.

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