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Article

Mapping Priority Areas for Urban Afforestation Based on the Relationship Between Urban Greening and Social Vulnerability Indicators

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Abstract: Analyzing the population's access to ecosystem services offered by urban greening constitutes a measure of environmental justice, as it directly affects the quality of life and health of the population living in cities. This article is committed to proposing a geoenvironmental model in a geographic information system (GIS), envisaged to estimate the share of urban forests and green spaces in territorial planning units (TPUs), corresponding to neighborhoods of a pilot city, using high-spatial-resolution images of the China–Brazil Earth Resources Satellite (CBERS-4A) and the normalized difference vegetation index (NDVI). These data were combined by means of a Boolean analysis with social vulnerability indicators assessed from census data related to income, education, housing, and sanitation. This model ultimately aims to identify priority areas for urban afforestation in the context of environmental justice and is thus targeted to improve the inhabitants' quality of life. The municipality of Goiânia, the capital of Goiás state, located in the Brazilian Central–West Region, was chosen as the study area for this experiment. Goiânia presents 19.5% of its urban territory (82.36 km^2) covered by vegetation. The analyses indicate an inequity in the distribution of urban forest patches and green areas in this town, where 7.8% of the total TPUs have low priority, 28.2% have moderate to low priority, 42.2% have moderate to high priority, and 21.8% have high priority for urban afforestation. This urban greening imbalance is particularly observed in its most urbanized central nuclei, associated with a peripheralization of social vulnerability. These findings are meant to support initiatives towards sound territorial planning processes designed to promote more sustainable and equal development to ensure environmental justice and combat climate change.

Keywords: urban planning; sustainability; social vulnerability; urban life quality; GIS

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1. Introduction

Urbanization has been steadily growing in recent decades, and the amount of people living in urban areas nowadays reaches more than half of the global population (55%) [1]. This share is expected to increase to 67% by 2050 [2]. The urban population is not evenly distributed on a global scale and tends to concentrate in highly urbanized areas [2,3]. This leads to improper land occupation, with limited availability of green areas, and consequently, to a worsening of floods and landslides, adverse climatic conditions, and enhanced noise and air pollution [4,5].

In this context, the United Nations (UN) Agenda 2030, through Sustainable Development Goal (SDG) 11, aims to ensure sustainable cities and communities and indicates that increasing the quality of life of urban populations will be a complex but indispensable challenge in the future [6]. In particular, it is worth highlighting Item 11.7, which proposes universal access to safe, inclusive, accessible, and green public spaces by 2030. This scenario points out the need, especially in developing countries such as Brazil, for projects that reconcile social diagnoses and the increase in urban greening, such as urban forests.

Urban greening has been extensively defined in the literature. Some of these definitions refer to public landscaping and urban forestry projects that create mutually beneficial relationships between city dwellers and their environments [7]. It is basically seen as an increase in the abundance and cover of vegetation [8] or, from a wider perspective, as the incorporation of green spaces and elements into urban environments and infrastructure, such as streets, cities, roofs, and walls [9]. In this work, urban greening is regarded as either urban forests (naturally vegetated areas comprising trees and bushes within the city boundaries) or urban green spaces (parks, squares, trees, and bushy areas along roads, as well as public and private planted, wooded, or shrubby areas and gardens) [10–12].

The benefits that urban greening can provide to city life are unquestionable, mainly because they are major suppliers of ecosystem services. Studies like [13,14] reveal the relationship between urban forests and human health. In terms of environmental benefits, urban green areas and urban forests strongly contribute to biodiversity conservation and the protection of wild life [15,16], improving air quality [17,18], the mitigation of climate change impacts [19–21], water security [22–24], and smoothing urban heat effects [25,26], besides reducing a series of diseases related to pollution and environmental degradation [27,28]. Additionally, the social benefits for urban residents include improvements in mental and physical health, such as stress reduction and relaxation, promoted by exposure to them [29]. Furthermore, proximity to urban green spaces and forests may increase physical activity levels, which is also important for mental health [30].

Social vulnerability, in its turn, can be regarded as the susceptibility of social groups to the adverse impacts of natural hazards and threatening environmental conditions, including disproportionate death, injury, loss, and disruption of or poor livelihood conditions [31,32]. This vulnerability occurs when the disadvantage conveyed by poor social conditions determines the degree to which one's life and livelihood are at risk from a particular and identifiable event in health, nature, or society [33]. In manifold works [34–39], social vulnerability is not directly related to economic standards but rather encompasses a broad spectrum of disadvantages, which concern ethnical and minority groups, disabled people, people with mental issues, elderly people, and the like.

Scientific productions regarding social vulnerability and urban greening have revealed a strong correlation between poverty levels and a lack of urban ecosystem services [40,41]. Refs. [35,36,42,43] warn that inequities in access to urban green spaces often intersect with disadvantaged socioeconomic status, leading to even greater environmental inequalities, which then trigger more severe health inequities. Refs. [30,37,44,45] state that redressing park poverty in communities of color and low-income households can create an urban green space paradox. As more green spaces are established, they can enhance attractiveness and public health, making neighborhoods more desirable, which may lead to gentrification. Such findings are supported by [37,46], who argue that wile greening certainly provides economic, ecological, heath, and social benefits to many, it may create new and deeper vulnerabilities and processes of greening gentrification for historically marginalized residents—working-class groups, minorities, and immigrants.

This context raises the issue of social and environmental justice [34], in which the former one relates to the fair and equitable distribution of wealth, opportunities, and privileges within a society, and the second one refers to an imbalanced share of environmental hazards such as industrial pollution, toxic waste facilities, and lack of access to natural resources and urban greening areas. In this sense, refs. [37,46] highlight the exclusion of urban residents from the city's resources. In the particular case of Brazil, ref. [38] concluded that the white population, and the one with the highest income per capita, potentially benefit more from ecosystem services than color people and the low-income population. Most of the above-mentioned studies conducted analyses based on the literature, interviews, and digital maps, as well as statistical data issued by local governments, crowdsourcing, and other types of information, without relying on remotely sensed data.

Articles that precisely deal with the relations between urban greening distribution and social vulnerability using remote sensing imagery are not many. Ref. [47] integrated remote sensing and social sensing data to detect environmental injustices in eight of New Jersey's northern counties in the United States (US) by means of regression models. The results indicated a negative relationship between the number of Tweets utilizing environmental-justice-relevant terms and the presence of ecosystem services provided by green and blue spaces as captured by the Modified Normalized Difference Moisture Index (MNDWI) and the Automated Water Extraction Index (AWEI) obtained from Landsat imagery. This study suggested that, generally, there is discussion on Twitter about environmental injustice when resources are not present, but the voices of vulnerable populations are often less visible.

Another work using remote sensing data to investigate disparities in the socioenvironmental justice of cities was carried out for the southeastern Paraná state, south of Brazil, by [42]. The authors used high-resolution multispectral images from PlanetScope Dove and employed a machine learning algorithm to accurately map urban forests. A four-dimensional analysis was established considering (i) the settings of urban forests (using fractal landscape metrics); (ii) the provision of ecosystem services (estimated through total biomass—TB, total carbon stock—TCS, carbon dioxide equivalent—CO_2eq, urban heat island—UHI, and available public green areas—PGA); (iii) accessibility to urban forests (assessed by accessibility maps to PGA at distances of 300 and 800 m); and their correlation with six socioeconomic indicators (including the percentage of people in households without adequate water supply and sewerage, the percentage of the population living in urban households without garbage collection service, the illiteracy rate of the population aged 15 years or older, the proportion of people with per capita household income equal to or less than half the minimum wage in 2010, the number of schools, and the number of permanent residents). The magnitude of these correlations was determined by a slope test, and the analyses revealed significant discrepancies between different socioeconomic conditions and the availability of ecosystem services.

Further studies specifically focusing on Brazilian cities and combining cartographic data on urban greening with census data on socioeconomic indicators have been accomplished [38,48]. Nevertheless, none of them used satellite images to generate data on urban forests and green areas. Differently from all the studies that were previously reported, this work is committed to analyze the connections between urban greening and socioeconomic indicators for the greenest state capital in Brazil, Goiânia, counting on eight socioeconomic indicators obtained from the national census, including general demographic characteristics, housing conditions, sanitation status, and literacy, associated with unlimited open access images from a high-spatial-resolution sensor (2 m), not yet explored for this end in the literature, onboard the China–Brazil Earth Resources Satellite (CBERS-4A). Integrating these two products will allow local decision makers to base their decisions on costless refined urban greening data and to indicate priority zones for urban afforestation as an instrument for promoting environmental justice and urban resilience to climate change at a municipal scale. It is expected that the proposed method can be replicable in any urban area in the country and that the obtained results increase interest in studies focused on urban afforestation and environmental vulnerability.

This paper is organized as follows: Section 2 presents (i) the materials employed in this work, comprising a brief report of the study area followed by a description of the satellite images along with cartographic and census data; and (ii) the methodological developments, including the steps for elaborating the urban greening map, the social vulnerability map, and the priority map for urban afforestation. The results are presented in Section 3 and discussed in Section 4, while the findings of the research, its limitations, and recommendations for future work are reported in Section 5.

2. Materials and Methods

2.1. Study Area

Goiânia, the greenest Brazilian capital, underwent one of the greatest urban expansions in the last 12 years [49]. Located in the central–western region of Brazil, the municipality of Goiânia (Figure 1), capital of Goiás state (11th most populous Brazilian state out of 25 states), has a total extension of 729,296 km^2 and an estimated population of 1,437,237 inhabitants, thus accounting for a demographic density of 1970.72 inhabitants per km^2. Its urbanized area extends over 301.55 km^2, and it is the 5th biggest city among all 5568 Brazilian cities. In this scenario of large urban agglomeration, Goiânia corresponds to the Metropolis 1C level in the classification of urban hierarchies proposed by [50]. The urban hierarchy indicates the centrality of the city according to the attraction it exerts on populations from other urban centers to access goods and services and the level of territorial articulation itself [50].

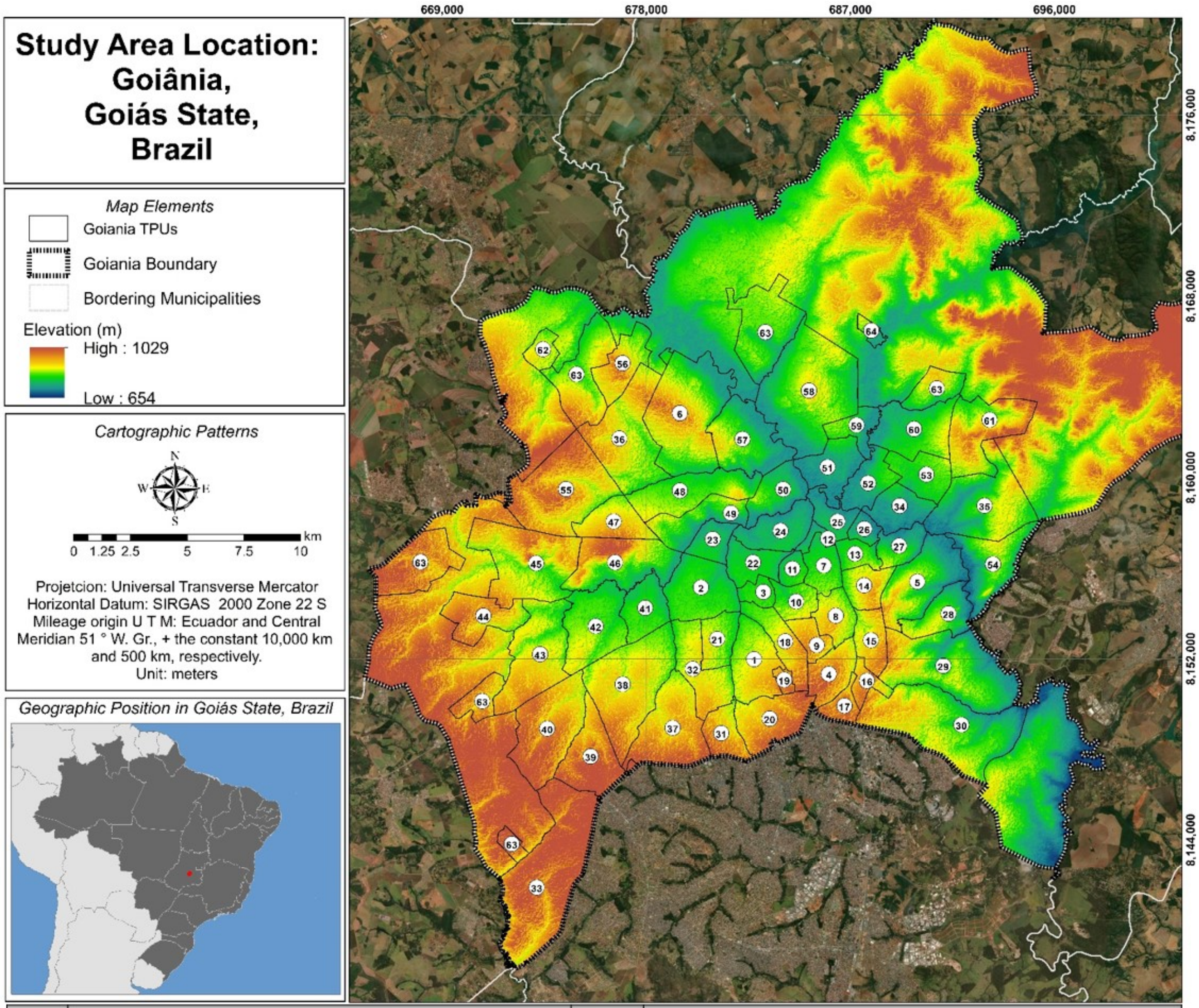
The Brazilian Institute of Geography and Statistics [51], in addition to census tracts (territorial planning units used for the collection of demographic census data), defines another territorial subdivision called a Territorial Planning Unit (TPU). Thus, 64 TPUs were defined, corresponding to sets of census tracts that form urban neighborhoods, presented in Figure 1.

2.2. Data Used

Different sets of geospatial data were used, comprising satellite images, polygonal data of areas of interest, and tabular data with strategic information about the territorial planning units of Goiânia. A summary of the data used, their sources of acquisition, and the corresponding year are presented in Table 1.

Table 1. Data and their respective sources used in this work.

Data	Source	Year
CBERS-4A images	National Institute for Space Research (INPE)	2022
Goiânia Territorial Planning Units (TPUs)	Brazilian Institute of Geography and Statistics (IBGE)	2010
Census Data	Brazilian Institute of Geography and Statistics (IBGE)	2010



Map ID	TPU	Map ID	TPU
1	JARDIM AMÉRICA	33	BALIZA-ITAIPU
2	CIDADE JARDIM	34	JAÓ
3	COIMBRA	35	SANTO HILÁRIO
4	PEDRO LUDOVICO/BELA VISTA/JARDINS DAS ESMERALDAS	36	MUTIRÃO E CURITIBA
5	JARDIM NOVO MUNDO	37	NOVO HORIZONTE/FAIÇALVILLE
6	FINSOCIAL	38	CELINA PARK/RECREIO DOS FUNCIONÁRIOS
7	CENTRAL	39	CARAVELAS
8	SUL	40	PARQUE SANTA RITA
9	MARISTA	41	PARQUE OESTE INDUSTRIAL
10	OESTE	42	JOÃO BRAZ
11	AEROPORTO	43	VILA RIZZO
12	NORTE FERROVIÁRIO	44	PARQUE BOM JESUS
13	VILA NOVA	45	VERA CRUZ
14	LESTE UNIVERSITÁRIO	46	JARDIM PETRÓPOLIS
15	JARDIM GOIÁS	47	VILA REGINA/PARQUE INDUSTRIAL PAULISTA/SANTOS DUMONT
16	ALTO DA GLÓRIA E REDENÇÃO	48	CÂNDIDA DE MORAIS/MARIA DILCE
17	SANTO ANTONIO	49	CAPUAVA
18	BUENO	50	URIAS MAGALHÃES
19	NOVA SUIÇA	51	GOIÂNIA II
20	PARQUE AMAZÔNIA	52	SANTA GENOVEVA
21	SUDOESTE	53	AEROPORTO INTERNACIONAL SANTA GENOVEVA
22	CAMPINAS	54	VILA PEDROSO
23	AEROVIÁRIOS	55	CHÁCARAS SÃO JOAQUIM
24	MARECHAL RONDON	56	SÃO DOMINGOS
25	CRIMÉIA LESTE	57	JARDIM BALNEÁRIO MEIA PONTE/MANSÕES GOIANAS
26	NEGRÃO DE LIMA	58	CAMPUS UNIVERSITÁRIO/CONJUNTO ITATIAIA
27	BAIRRO FELIZ	59	VILA JARDIM SÃO JUDAS TADEU/JARDIM POMPÉIA
28	RIVIERA/ÁGUA BRANCA	60	JARDIM GUANABARA
29	AUTÓDROMO OU PARQUE LOZANDES	61	CEASA/ALDEIA DO VALE
30	PARQUE DAS LARANJEIRAS E JARDIM DA LUZ	62	JARDIM PRIMAVERA (ÁREA URBANA ISOLADA)
31	JARDIM ATLÂNTICO	63	RURAL ZONE
32	JARDIM EUROPA	64	VILA RICA DISTRICT

Figure 1. Location of the study area.

2.2.1. China–Brazil Earth Resources Satellite-4A (CBERS-4A) Imagery

Launched in 2019, CBERS-4A is an optical imaging satellite collaboratively operated by the China Centre for Resources Satellite and Data Application (CRESDA) and Brazil's National Institute for Space Research (Instituto Nacional de Pesquisas Espacias—INPE). CBERS-4A flies in a sun-synchronous orbit with an altitude of 629 km and an inclination of 97.9°. CBERS-4A has three imaging instruments on board: (i) a high-resolution optical imager, a wide-scan panchromatic and multispectral camera (WPM), as well as two different multispectral radiometers, (ii) a multispectral camera (MUX) and (iii) a wide-field imager (WFI). All three instruments collect data in three visible bands (blue, green, red) and one near-infrared (NIR) band. The WPM also contains one panchromatic band with a spatial resolution of 2 m and visible and NIR bands with a resolution of 8 m and revisits of 31 days. The WPM operates in push-broom mode, with a swath of 92 km, which makes it possible to reach up to ±500 km at large off-nadir pointing angles. The MUX has a resolution of 16 m at the nadir with revisits of 31 days. It also operates in push-broom mode with a swath width of 120 km, able to image up to ±500 km off-nadir. Lastly, the WFI has a resolution of 55 m with revisits of 5 days and a swath width of 684 km [52].

In this work, the red (Band 3) and near-infrared (Band 4) spectral bands of a scene collected on 18 August 2022, were used. The month of August was chosen for data acquisition in this study since it corresponds to the driest period in the Brazilian Central–West Region, where there is less presence of clouds in the scenes, significantly reducing atmospheric interference in the results. CBERS-4A images are produced, pre-processed, and made available free of charge by [52].

2.2.2. Goiânia Territorial Planning Units (TPUs)

The geographic limits of the TPUs correspond to the neighborhoods of Goiânia, which are in turn subdivided into census tracts. By using TPUs instead of census tracts, the interpretation of results and the application of the resulting guidelines by local decision makers is much easier. Once most municipal-scale planning processes in Brazil are targeted to neighborhoods, as they are regarded as more homogeneous planning units. The TPU borders are rendered available together with the census tracts network for the municipality of Goiânia at a scale of 1:10,000 by [51].

2.2.3. Census Data

The Brazilian demographic census is carried out and published by IBGE every 10 years. It presents information about the living conditions of the population in each of the 5568 municipalities found within the country. This information is a very important territorial picture for the implementation of public policies in a country of continental size such as Brazil. However, due to the pandemic, there was a two-year delay in the last census, which was carried out only in 2022. Therefore, the most recently available data at the census tract level are those from the 2010 census, which were used in this study.

To diagnose social vulnerability in the municipality of Goiânia, we used data relating to three large thematic groups: (i) housing and sanitation; (ii) income; (iii) and education. In the context of housing and sanitation, we analyzed data on household property, access to the general water supply network, access to the sewerage network, the existence of a bathroom in the home, access to solid waste collection, and access to electricity supply. As for income, we used data referring to the per capita income of households. As for the educational context, data on youth and adult literacy rates were explored. All census data were obtained in the format of a table containing numeric and string values on the IBGE website [49] and were then further spatially linked to the corresponding TPUs in ArcGIS® version 10.8 (Redlands, CA, USA).

2.3. Methods

Figure 2 illustrates the methodological procedures adopted to identify priority areas for urban afforestation and, consequently, areas with greater environmental justice/injustice in Goiânia, Brazil. The approach consists of the implementation of remote sensing and social cartography techniques divided into three main steps: (1) processing the orbital remote sensing images to indicate the percentage of urban greening in each TPU; (2) processing and analysis of census data to produce a social vulnerability map; and (3) integrating the products resulting from steps 1 and 2 to map and identify priority areas for urban afforestation.

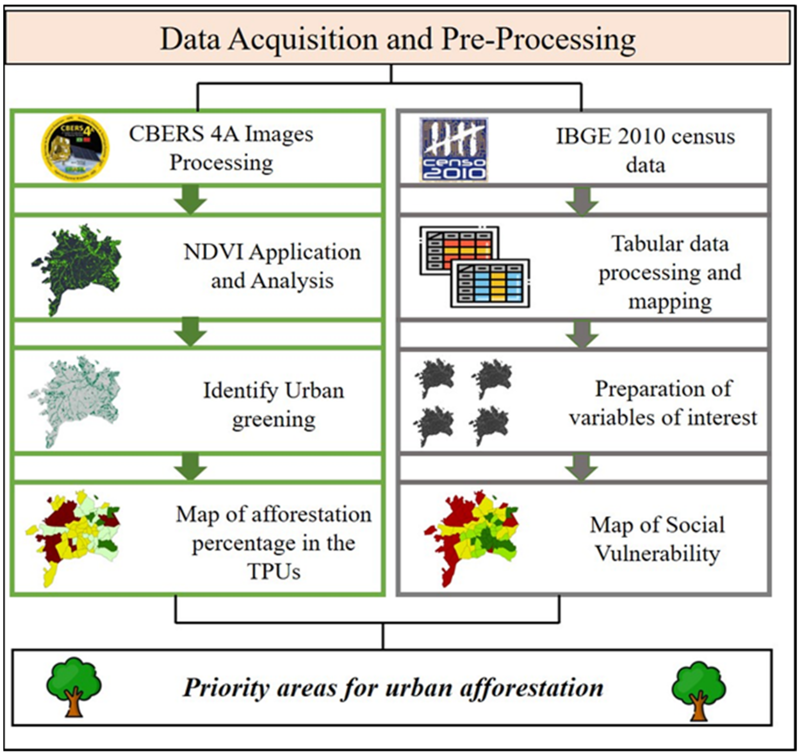


Figure 2. Methods illustration.

2.3.1. Urban Greening Mapping

As mentioned previously, urban greening is considered in this study as ecosystem services providers, and hence, a measure of environmental justice. These benefits are essential to the well-being of communities, mainly in combating climate change and fully meeting the UN Sustainable Development Goals.

The urban greening map was generated by means of the normalized difference vegetation index (NDVI) applied to CBERS-4A images, previously subjected to an atmospheric correction using the Dark-Object Subtraction (DOS) method [53,54]. This index, proposed by [55], is a metric meant to quantify biomass, vegetation health, and density. Thus, the NDVI is also capable of highlighting the presence or absence of vegetation, calculated from the normalized difference between the red (highly absorbed by healthy vegetation to fuel photosynthesis and create chlorophyll) and near-infrared (which is strongly reflected by healthy plants) spectral bands [56]. In CBERS-4A, the red and near-infrared bands correspond to Bands 3 and 4, respectively. The NDVI was calculated in ArcGIS version 10.8, according to Equation (1):

$$\text{NDVI} = (NIR - Red)/(NIR + Red) \quad (1)$$

where NIR is the pixel reflectance in the near-infrared band and *Red* is the pixel reflectance in the red band.

The resulting raster presents values from -1 to 1 for the entire analyzed scene. These values indicate variations between the absence and presence of vegetation [57]. Thereafter, aiming to find out which value threshold best represents the presence of vegetation in the municipality of Goiânia, we carried out value tests comparing the NDVI results with a true color composition of a CBERS-4A image. As a result, values greater than 0.25 were chosen to indicate the presence of urban greening in Goiânia. This threshold was heuristically set for the specific case of this city, which was later confirmed after field inspection. Next, we used the "Tabulate Intersection" tool in ArcGIS version 10.8 to calculate the percentage of urban greening in relation to the total area of each TPU, allowing us to establish a relationship based on the ranges of such percentages, leading to the definition of four classes of environmental justice/injustice, translated into priority for afforestation, as shown in Table 2.

Table 2. Definition of environmental justice classes based on the percentage of urban greening.

Percentage of Urban Greening in the TPUs	Priority for Afforestation	Description	Assigned Value to Urban Greening Percentage Classes
<10	High	Areas where access to ecosystem services provided by urban greening is highly restricted, being a local indicator of improper environmental justice for citizens and low resilience to climate change. In this context, the priority for afforestation projects in such areas is maximum.	40
10–20	Moderate to High	Areas that represent a transition range between poor and moderate conditions for the provision of ecosystem services by urban greening in the context of environmental justice. Resilience is still considered low and afforestation projects have high priority.	30
20–30	Moderate to Low	Areas with an acceptable presence of urban greening but still need vegetation improvements to contribute to an effective supply of ecosystem services for environmental justice.	20
>30	Low	Areas where urban forests and green spaces have a greater capacity to provide ecosystem services to their residents, indicating positive resilience in facing climate change and greater positive influence on environmental justice.	10

2.3.2. Social Vulnerability

Social vulnerability in this work is expressed as an index that depicts the living conditions of a population, making it possible to diagnose socio-territorial inequalities. Thus, it becomes an instrument for identifying failures in the supply of public goods and services in the analyzed territory. In the context of this study, we adopted the premise that social vulnerability and incipient access to urban forests and green spaces are closely linked and result in processes of socio-environmental injustice that prevent/hinder the sustainable development of urban communities in Brazil. The social vulnerability mapping in the study area was carried out based on methodological adaptations of the works conducted by [58,59]. We analyzed parameters related to housing and sanitation, income, and education, contained in the 2010 Brazilian census with the greatest detailing level available [60]. The eight analyzed parameters in each interest group are summarized in Table 3.

Table 3. Social vulnerability parameters.

Indicators That Compose the Diagnosis of Social Vulnerability		
Cluster	**Parameter**	**Description**
Housing and sanitation	Percentage of non-owned households	Owned homes imply less vulnerability as they avoid the impacts of rent payment.
	Percentage of households without access to the water supply network	Household quality indicator regarding basic sanitation
	Percentage of households without solid waste collection	Household quality indicator regarding basic sanitation
	Percentage of households without access to electricity supply	Household quality indicator regarding economic development
	Percentage of households without access to the sewerage network	Household quality indicator regarding basic sanitation
	Percentage of households with 5 (five) or more residents	Home comfort indicator
Income	Percentage of households with per capita income below 2 minimum wages	Quality of life indicator, considering that per capita income below 2 minimum wages results in social risk and decreased well-being.
Education	Percentage of literate people aged 15 years or older	Minimum educational quality indicator

Based on the census data survey and the definition of the parameters of interest, the tabular data for each TPU representing each of the eight analyzed parameters were converted into rates, ranging from 0 to 1. Subsequently, the social vulnerability index was calculated from the weighted average of these eight parameters analyzed for each TPU, as indicated in Equation (2):

$$SV = \frac{(P1 + P2 + P3 + P4 + P5 + P6 + P7 + P8)}{n} \quad (2)$$

where SV refers to social vulnerability; P1, P2, P3, P4, P5, P6, P7, and P8 are, respectively, the percentage of non-owned households (rate), percentage of households without access to the water supply network (rate), percentage of households without solid waste collection (rate), percentage of households without access to electricity supply (rate), percentage of households without access to the sewerage system (rate), percentage of households with 5 or more residents (rate), percentage of households with per capita income less than 2 minimum wages (rate), and percentage of literate people aged 15 years or older (rate); n represents the number of parameters.

Finally, the values obtained for the social vulnerability index in each TPU were reclassified using the quartile method, leading to four vulnerability classes, as shown in Table 4.

Table 4. Values and classes of social vulnerability.

Social Vulnerability Value	Social Vulnerability Classes
>0.367	high vulnerability
0.319–0.367	moderate to high vulnerability
0.285–0.319	moderate to low vulnerability
<0.285	low vulnerability

2.3.3. Mapping Priority Areas for Urban Afforestation

The map of priority areas for urban afforestation aims to integrate the spatial relationship between the analyzed spatial variables, the percentage of urban greening, and the social vulnerability assessed for each TPU. Furthermore, it indicates which locations in Goiânia need more investment in afforestation. From this perspective, this mapping works to reduce environmental injustices in terms of democratic access to essential ecosystem services provided by urban forests and green spaces. Therefore, we apply the geospatial analysis function known as geographic layer overlay to model the relationship between the variables of interest in a GIS environment. For this end, we assigned generic values to the urban greening percentage classes per TPU, scaled within the range from 10 to 40 in an increasing order of afforestation priority. Like these urban greening percentage classes, generic values were also assigned to the social vulnerability classes (from 1 to 4) per TPU. Table 5 illustrates the intersection between the social vulnerability and the urban greening percentage classes, expressed by a Boolean integration of the corresponding values in the format of two-digit numbers. For example, a TPU belonging to the second group of the urban greening percentage classes (20) and lying within the third class of social vulnerability (3) would be reclassified as 23 (20 + 3), and hence, is regarded as moderate to high in the ranking of priority classes for afforestation.

Table 5. Intersection between the variables of interest.

Urban Greening Percentage Classes	Social Vulnerability			
	1	2	3	4
10	11	12	13	14
20	21	22	23	24
30	31	32	33	34
40	41	42	43	44

Table 6 classifies these values, indicating the respective afforestation priority classes. It is worth mentioning that the highest priorities are assigned to areas where there is greater social vulnerability and less access to urban forests and green areas. Consequently, the lowest priorities are represented by areas that have a high amount of urban greening and low social vulnerability.

Table 6. Classification of the values resulting from the intersection between the variables of interest.

Resulting Values	Map Legend	Classes of Priority for Afforestation
34, 43, 44		High Priority
14, 23, 24, 33, 42		Moderate to High Priority
13, 22, 31, 32, 41		Moderate to Low Priority
11, 12, 21		Low Priority

3. Results

3.1. Urban Greening Map

The map of urban greening in Goiânia indicated that 19.5% of the municipal urban territory (82.36 km^2) is composed of vegetation, while 80.5% (341.5 km^2) accounts for other uses, such as urbanized areas, unused urban spaces, brownfields, and bare soil, among others. The distribution of urban forests and green areas by territorial administrative units is crucial to support ordering plans more efficiently, as the greater the presence of urban forest in a TPU, the greater the ecosystem services provided and, consequently, the greater the quality of life of its residents. The map with the percentage of urban greening in each TPU (Figure 3) provides insight into which neighborhoods offer greater access to vegetation and green spaces to their residents.

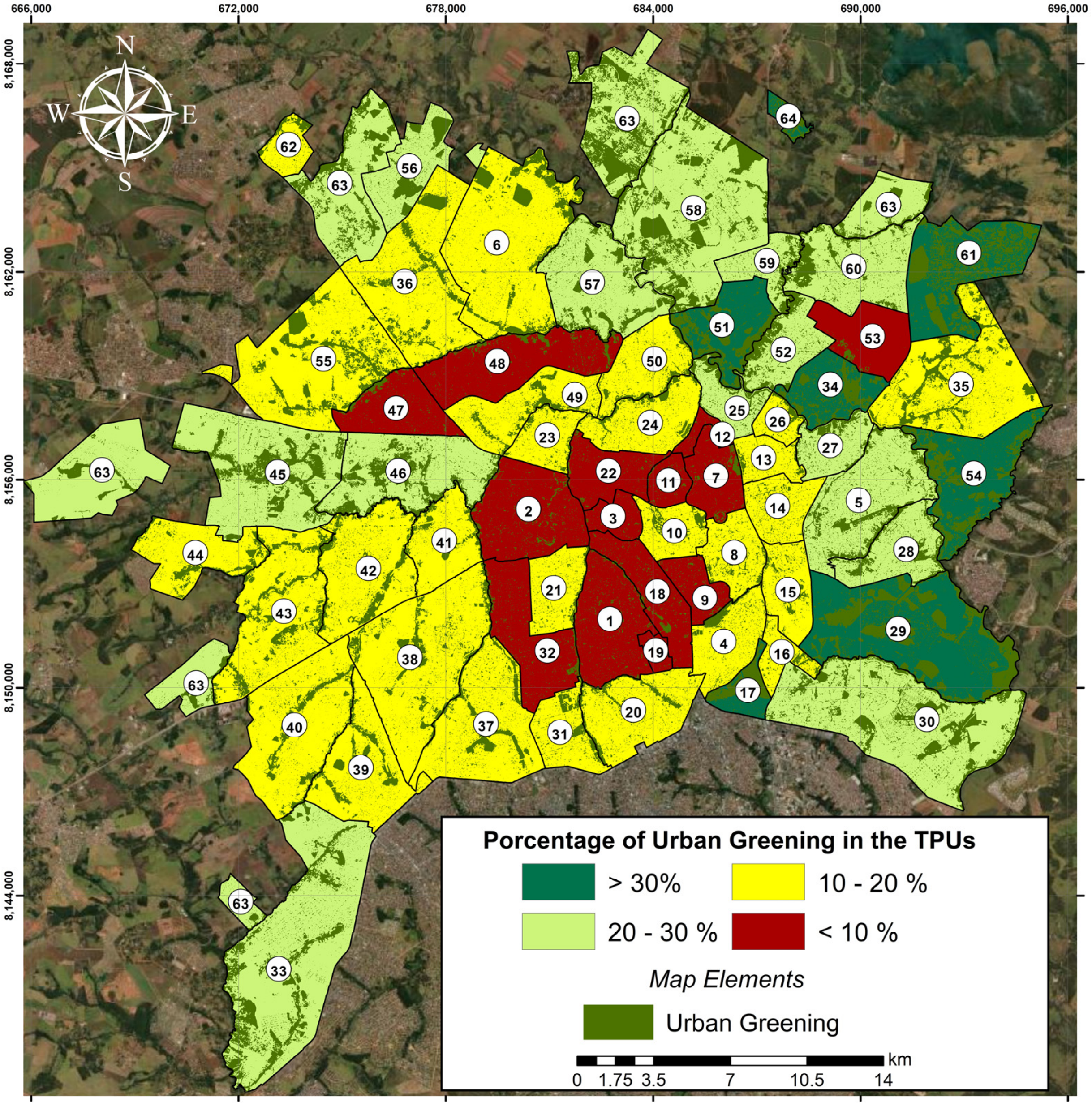


Figure 3. Percentage of urban greening in the TPUs of Goiânia, Brazil. The TPUs numbers are seen in the legend of Figure 1. TPU 63 accounts for rural areas scattered within the city boundaries, as indicated in Figure 1.

Seven TPUs have more than 30% of their territory covered by urban greening: Santo Antônio, CEASA/Aldeia do Vale, Vila Pedroso, Jaó, Goiânia II, Autódromo/Parque Lozandes, and the Vila Rica district. These TPUs are outside the central region, suggesting that higher urbanization levels correspond to lower vegetation presence. Additionally, several high-rise residential condominiums in these areas use green spaces as a marketing appeal to enhance their appeal.

Interestingly, but not surprisingly, the 14 TPUs that contain 20 to 30% of their territories covered by urban greening follow the same spatial pattern as the previously described class (i.e., with a concentration in the most peripheral areas and distant from the municipality's highly urbanized centralities). It is also possible to find high and medium-high standard residential condominiums, summer garden condominiums, as well as areas with a lower degree of urbanization. However, not all TPUs in this class represent rich neighborhoods, considering that the rural zones, Baliza-Itaipu and São Domingos, for example, are low-income areas but still have urban forests thanks to low current urbanization levels. This decorrelation between urban greening and better social indices was observed in the work of [35].

The yellow class on the map indicates neighborhoods that have 10 to 20% of their area covered by urban greening. This class represents a negative transition range in terms of the local population's access to forest ecosystem services. Overall, 28 TPUs were diagnosed in this condition, with 26 located in the immediate surroundings of the central region and the other 2 in more peripheral regions.

The class of TPUs with greening coverage of less than 10% indicates the locations where residents have the most limited access to the essential benefits promoted by forests and green spaces in an urban environment. It goes far beyond urban aesthetics but directly affects the local quality of life [61]. Fourteen TPUs were identified in this class. Except for TPU 53 (Santa Genoveva International Airport), the others are concentrated in the central portion of the municipality. When analyzing the classes with the lowest greening coverage in general, it is noted that 42 of the 64 TPUs have less than 20% of urban forests or green spaces. With a few exceptions, there is a spatial pattern of low levels of vegetation, characterized by the proximity to the central region of the municipality, which can be explained by the fact that the intense urbanization of Goiânia did not prioritize green areas in its process.

3.2. Social Vulnerability Map

Figure 4 shows social vulnerability throughout the 64 TPUs in Goiânia. The social vulnerability map demonstrates the location patterns of the four classes of vulnerability we diagnosed, which can be considered an important strategic planning tool, mainly in the context of the pressing need to reduce inequalities/vulnerabilities proposed by SDG 11 of the 2030 Agenda.

Fifteen TPUs were classified as presenting low social vulnerability in Goiânia (dark green in Figure 4) and they are homogeneously spatially concentrated, mainly in the central–south and northeast portions of the municipality, revealing a pattern of income concentration.

The low–moderate vulnerability class (illustrated in light green in Figure 4) is represented by 16 TPUs, which indicate a high to moderate presence of urban housing and sanitation equipment, a low rate of households with low-income residents, and a moderate educational level. The main highlighted TPUs in this class are Jardim América (1), Central (22), Cidade Jardim (2), Coimbra (3), and Parque Amazônia (20). The spatial characteristic of most of them is their proximity to the central core of the municipality. Not coincidentally, the areas of low–moderate social vulnerability are adjacent to those of low vulnerability. This reveals the homogeneous nature of income concentration in Goiânia. It can also be observed that the gradual distinction of this spatial standard in the south-central portion reflects increased vulnerability.

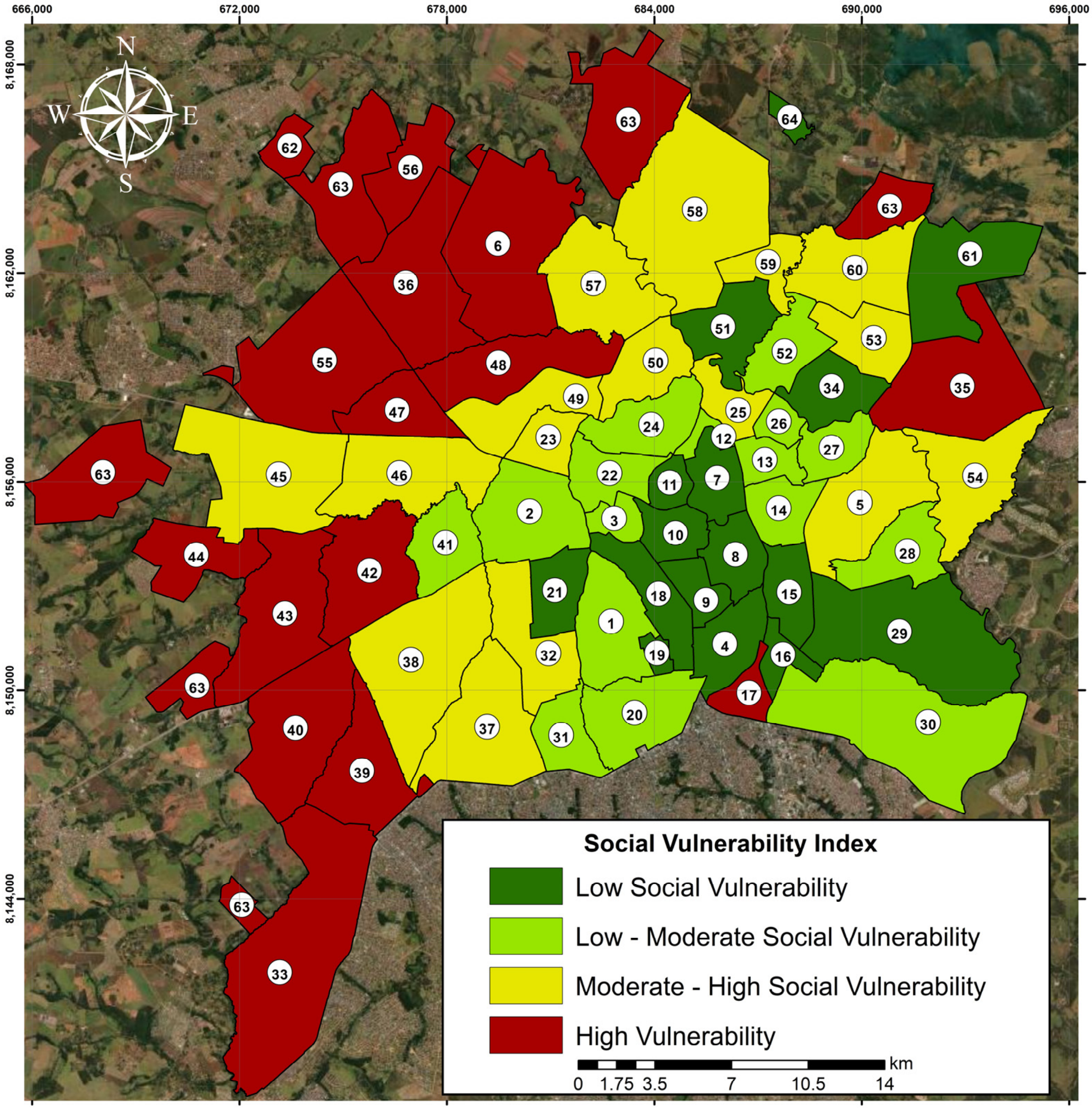


Figure 4. Social vulnerability map of Goiânia, Brazil. The TPUs numbers are seen in the legend of Figure 1. TPU 63 accounts for rural areas scattered within the city boundaries.

The moderate-to-high-vulnerability class represents a transition towards worrying living conditions for residents, while the high-vulnerability class indicates the worst diagnosed conditions. Such classes represent less access to quality housing and sanitation equipment, potentially lower incomes, and below-average educational rates.

Lastly, it is worth noting that social vulnerability increases towards the north and west of the municipality, indicating that the central nucleus of Goiânia shows a concentration of wealth and better living standards. As one moves away from this nucleus, the population's living conditions deteriorate.

3.3. Priority Areas for Urban Afforestation

Considering that urban forests and green spaces represent an essential ecosystem services provider, environmental justice promoted by a city with greater equity of access to afforestation also reflects an increase in the quality of life of its inhabitants. When afforestation projects also take socioeconomic aspects into account, we can say that we are closer to fully achieving what the EPA (2022) understands as environmental justice [62]. In turn, environmental justice takes into account fair treatment of the population with significant involvement of different communities, regardless of color, origin, race, or income in the development, implementation, and application of environmental policies. The map of priority areas for urban afforestation (Figure 5) had precisely this objective by conceiving a cartographic product that allows guiding the implementation of public policies both for urban afforestation and for the promotion of socioeconomic development. Thus, Figure 5 presents the final results obtained in this research, spatially indicating four classes/levels of prioritization for urban afforestation projects in the TPUs of Goiânia, relying on the spatial analysis of the relationship between urban greening and social vulnerability assessed in these units.

Table S1 (Supplementary Material) shows, for each TPU, the values of the indicators used to calculate the social vulnerability index. The first column of Table S1 indicates the degree of afforestation priority, and the cells of this column are colored following the legend of Figure 5, namely red for high priority, yellow for moderate to high priority, light green for moderate to low priority, and dark green for low priority.

The lowest priority areas for urban afforestation (dark green TPUs in Figure 5) correspond to places of low social vulnerability and high access to ecosystem services promoted by urban afforestation, representing an ideal scenario of environmental justice combined with excellent living conditions for the average local population. However, zones like these can be considered outliers in the municipality of Goiânia, as well as for other Brazilian municipalities, reflecting the enormous socio-environmental inequalities historically observed in the country. This argument is valid in Goiânia as only five TPUs (7% of the total) present these better conditions, namely Autódromo or Parque Lozandes (29), Jaó (34), Goiânia II (51), Aldeia do Vale (61), and the district of Vila Rica (64), where all of them have high-standard condominiums with heightened social indicators in addition to containing green areas notably used to advertise the better quality of life of these developments.

The moderate- to low-priority areas (light green TPUs in Figure 5) indicate a positive relationship between the population's living conditions and the presence of urban greening. In general, they represent the relationship of areas with moderate to low social vulnerability and more than 20% of urban forests and green spaces. For the low- and moderate-to-low-priority areas, the recommendation is that actions should be implemented to maintain the vegetation quality, mainly aiming to guarantee the consistency of social and environmental equity already diagnosed in these locations. However, in the TPUs Vera Cruz (45) and Jardim Petrópolis (46), despite the number of urban forests and green areas, public policies must be implemented to reduce the social vulnerability of the population.

The moderate- to high-priority class (yellow TPUs in Figure 5) shows areas where the ecosystem services provided by urban greening are incipient, mainly due to the absence of green areas. It is feasible to divide the 25 TPUs belonging to this class into two groups: an initial group that corresponds to places with good social indices, but with very low greening coverage that renders the provision of ecosystem services unfeasible; and a second group that refers to places where there is a balance between low afforestation and low social indicators, located on the outskirts of the municipality, where the presence of more urban forests and green spaces can effectively contribute to improving the quality of life. For this class, it is recommended that the actions should be conceived according to the specific characteristics of the two groups mentioned above, aiming at a greater effectiveness of public initiatives.

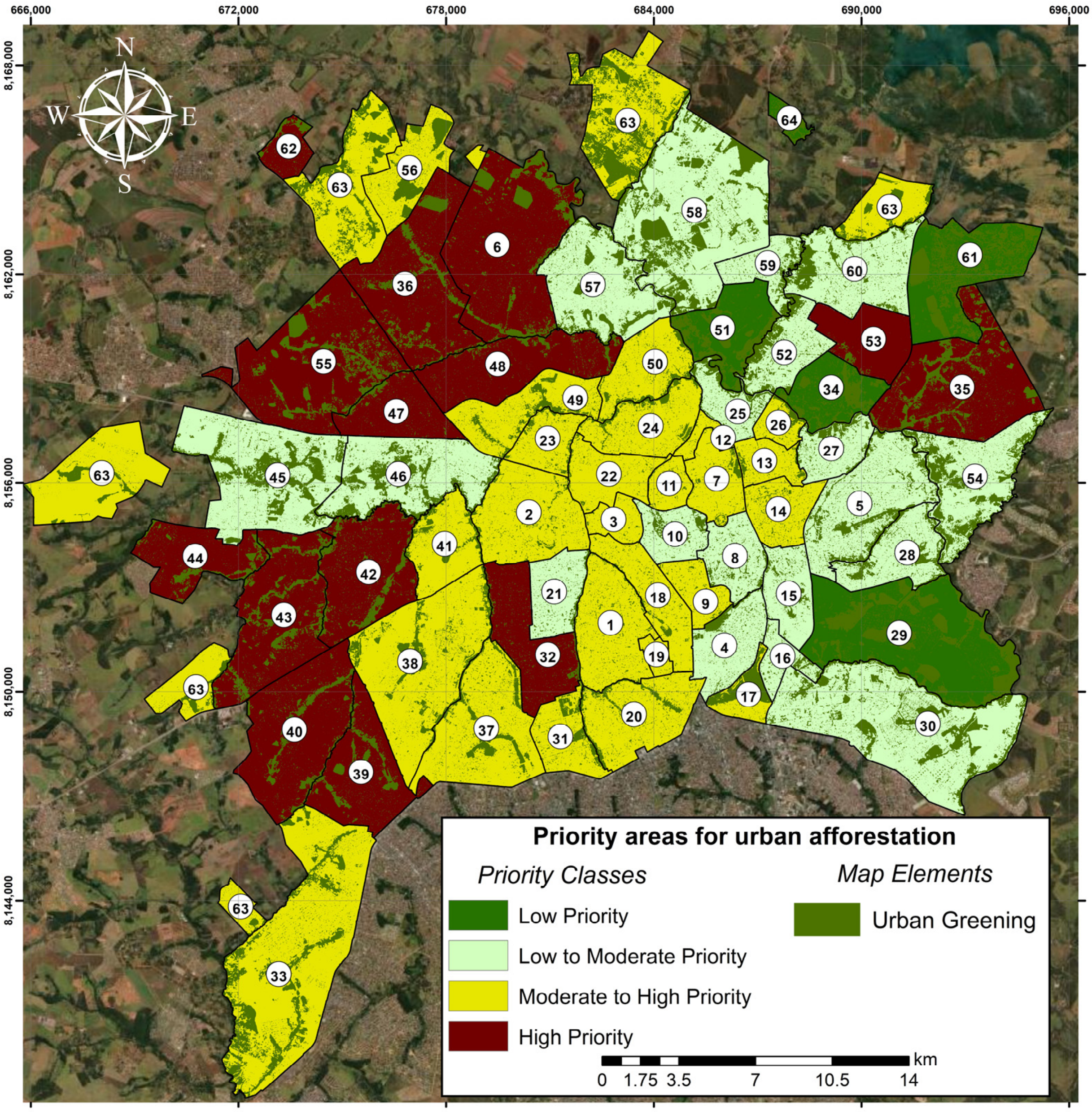


Figure 5. Map of the priority areas for urban afforestation in Goiânia, Brazil. The TPUs numbers are seen in the legend of Figure 1. TPU 63 accounts for rural areas scattered within the city boundaries.

In the first group, composed of TPUs such as Jardim América, Cidade Jardim, Coimbra, Central, Marista, Leste Universitário, Bueno, Nova Suiça, Parque Amazônia, Jardim Atlântico, Campinas, and Parque Oeste Industrial, projects should be implemented primarily focusing on urban afforestation. In turn, in the second group, which covers TPUs such as Aeroviários, Novo Horizonte, Celina Park, Capuava, and Urias Magalhães, joint efforts are needed towards afforestation and social development, aiming to minimize the identified injustices and increase the provision of local ecosystem services. However, two TPUs (Veracruz—45 and Jardim Petrópolis—46) presented characteristics that differ from the standard. They were classified as moderate to high vulnerability but contain high greening coverage (>30%), which guarantees ecosystem services that increase the local quality of life. Both of them comprise patches or urban forests within its boundaries, but they present poor socioeconomic indicators, and hence, public policies must be implemented that focus on reducing the social vulnerability of their population as a priority.

We can consider the areas diagnosed with the highest priority for urban afforestation projects (red TPUs in Figure 5) as being those with greater environmental injustice. In these areas, there is less access for the resident population to the ecosystem services promoted by urban forests and green spaces combined with greater social vulnerability in terms of income, housing, and access to basic services. In total, 14 out of the 64 TPUs in Goiânia have this high level of priority (21.8%). The TPUs in this class are Finsocial, Jardim Europa, Santo Hilário, Mutirão, Caravelas, Parque Santa Rita, João Braz, Vila Rizzo, Parque Bom Jesus, Vila Regina, Cândida de Morais, Santa Genoveva International Airport, Chácaras São Joaquim, and Jardim Primavera. Therefore, in these 14 TPUs, the pressing need for actions by municipal public authorities to mitigate inequity in the access to environmental, social, and landscape benefits promoted by urban greening is evident. It can be noted that all of these TPUs are located in peripheral areas of the municipality. Their diagnosis alone indicates very high social and environmental inequality, corroborated by the fact that they present similar characteristics: low greening coverage and high or moderate to high social vulnerability.

Figure 6 illustrates the percentage of occurrence of each priority class (by the total number of TPUs). It shows that 7.8% of the total TPUs have low priority, 28.2% have moderate to low priority, 42.2% have moderate to high priority, and 21.8% have high priority. From this finding, it is important to highlight that even though it is considered one of the greenest cities in Brazil [50], Goiânia still has 64% of its total TPUs in the moderate to high and high classes of priority need for afforestation. In this context, the increase in vegetation cover, mainly in the TPUs of the moderate- and high-priority categories, would result in effective benefits to the health, well-being, and comfort of the residents in these regions.

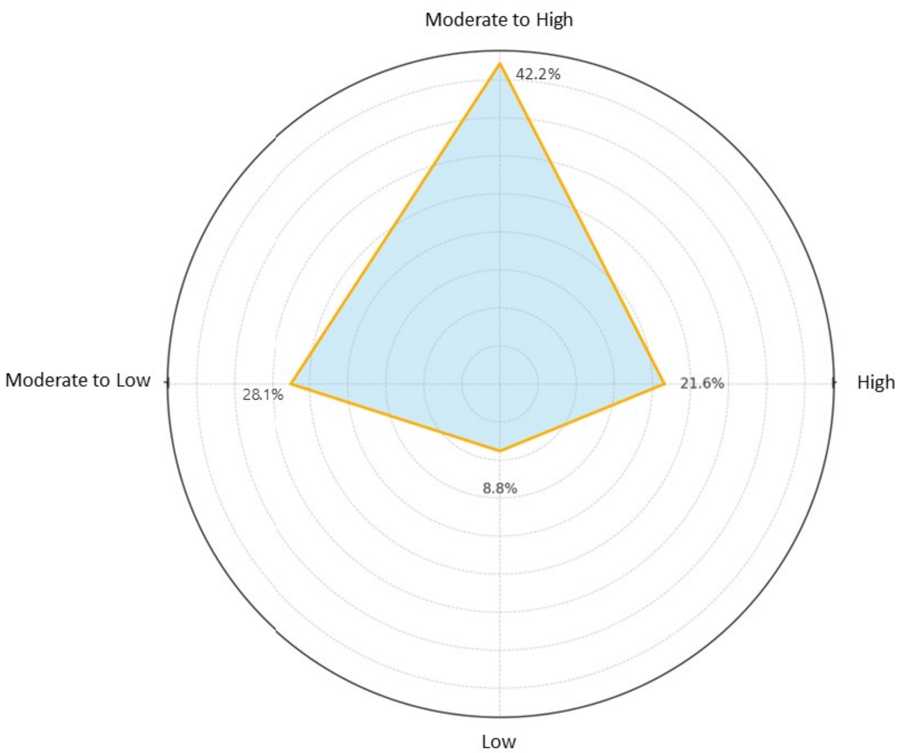


Figure 6. Percentage of occurrence of each priority class in the TPUs of Goiânia, Brazil.

4. Discussion

As shown in the initial results of this study, the municipality of Goiânia presents a strong correlation between income and afforestation, where the higher the income of a sector, the greater its afforestation, demonstrating a severe concentration of income. The phenomenon of income concentration observed in Goiania was also reported in other studies, such as those by [63,64], which discussed how income concentration extends beyond material wealth and is also reflected in racial and urban injustices within the municipality. In this respect, the work of [34] discusses the inequity of urban greening in cities from the point of view of discrimination and marginalization based on factors like race, ethnicity, gender, sexual orientation, disability, and class. This is supported by [37], who affirm that for the study of urban green spaces, issues of environmental justice relate to the "right to the city" debate, raising the question of whose city it is.

In addition to the concentration of afforestation by income, we observed that the intense urbanization of Goiania resulted in a lack of afforestation in the central area of the municipality seat. Other studies that reveal the decrease in the presence of urban greening in areas close to large urban centers and, therefore, in the quality of ecosystem services, have already been conducted by other authors, such as [65,66]. This demonstrates that this is not a unique trend in the city of Goiânia. Furthermore, ref. [67] already emphasized the importance of analyzing the spatial arrangement of urban networks, as land use and green coverage are fundamental elements for understanding global climate change, terrestrial ecosystem processes, and hydrological and biogeochemical cycles.

Regarding the mapping of socio-economic vulnerability in Goiania, we identified that the areas of greatest vulnerability are spatially concentrated in a homogeneous manner, mainly in the most peripheral areas of the municipality, also revealing a pattern of income concentration. The argument proposed by [68] helps to understand the concentration of the lowest vulnerabilities in specific areas of the city. This author affirmed that the process of valorization of TPUs located further south of Goiânia occurred thanks to emblematic constructions implemented in the region in the 1970s and 1980s (e.g., the International Racetrack of Goiânia, the Serra Dourada Soccer Stadium, and the high-standard Flamboyant Shopping Center). This argument can also be expanded to TPU 61 (Aldeia do Vale), which includes one of the most luxurious residential condominiums in the city, a factor that explains why it is the TPU with the lowest vulnerability, most isolated from the others. It is worth mentioning that all of these projects are in TPUs diagnosed as being of low vulnerability, indicating the mapping methodology's effectiveness. Furthermore, ref. [63] indicates that the verticalization phenomenon in the form of luxury constructions occurred in these less vulnerable TPUs. This phenomenon also reflects the high-income concentration in such TPUs, mainly because they host many high-income families in small areas of the municipality. This scenario is also related to an argument raised by [69], who states that the urban structuring and verticalization of these regions were the main factors that promoted land appreciation, something that reinforced the idea of a noble place in the citizens' imagination.

On the other hand, the most vulnerable areas also indicate poorer conditions for the population to access quality housing, basic sanitation, and high-level education. In this context, ref. [70] states that such urban problems are strongly connected to the economic system, in which wealth production processes are linked to processes of destruction of natural ecosystems and precarious working conditions that lead to unemployment, underemployment, poverty, social risks, and vulnerabilities.

As shown in Figure 5, 33 of the 64 TPUs analyzed are contained in these worrying social conditions (moderate to high and high vulnerability). They are geographically located in a context of spatial 'peripheralization', a phenomenon resulting from the difficulties of lower-income residents in accessing better employment, education, and housing opportunities [71]. This process is not exclusive to Goiânia, as demonstrated by [71,72], who report the occurrence of peripheralization also in other Brazilian metropolises, such as Curitiba and São Paulo. This factor was also diagnosed by [70], who, even using a different social vulnerability methodology, found very similar results, especially in the case of the growing vulnerability in the municipality of Trindade (west of Goiânia). For example, ref. [73] noted that as the Goiás metropolis expanded and its urban fabric was progressively fragmented, a large part of the population (generally the poorest and most vulnerable) was displaced towards the outskirts, a movement that made the control of urban space by current planning mechanisms based on rationality and functionality ineffective. This historical spatial configuration is still reflected today in the dynamics of local social vulnerability.

The mapping of areas for urban afforestation demonstrated that only five TPUs present the best possible conditions in terms of low social vulnerability and high urban forest index, revealing evident territorial inequalities. Corroborating this result, ref. [74] analyzed socio-spatial and environmental variables and delimited these five regions as the most privileged in Goiânia, both in the social aspect and in environmental terms, given the coexistence of their residents with urban forests and green spaces. In several areas with large urban forest concentrations, it is noted that high-rise real estate developments, such as residential condominiums, utilize the green areas as a marketing strategy associated with the sustainability appeal to enhance their products, as reported by [61].

By stating that the production of urban space responds to the logic of capital that transforms land into merchandise, ref. [75] makes important notes about real estate speculation and appreciation based on agents, such as shopping centers and commercial spaces, which overvalue certain locations in a city and limit democratic access based on the inhabitants' purchasing power. From this perspective, the results diagnosed for Goiânia indicate that urban forests and green areas can also enter the hall of speculative agents and indicators of better living conditions for the population that has greater access to their ecosystem services.

Thus, afforestation projects, in addition to prioritizing the provision of ecosystem services to the population, ought to be wisely conceived and implemented to avoid undesirable land appreciation without concerns about environmental quality, a phenomenon that occurs in Goiânia, as mentioned by [61]. Ref. [76] showed that the process of urban afforestation in Goiânia would have an impact on varied ecosystem services, and afforestation in two different microclimatic conditions in the municipality would contribute to a reduction in temperature and increase in relative humidity. In addition, they found that temperature, direct light, and wind speed were lower in areas containing green spaces than in areas without them.

Regarding municipal public policies, the Municipal Urban Afforestation Plan [77] indicates that strategic afforestation planning was initially carried out for 70 randomly chosen census tracts, contained within 16 neighborhoods (or TPUs) in Goiânia, namely Aeroporto, Bela Vista, Bueno, Campinas, Centro, Centro Oeste, Coimbra, Aeroviários, Jardim América, Marista, Nova Suíça, Oeste, Pedro Ludovico, Serrinha, Sul, and Universitário. Out of these 16 units, only one was identified in our study as having high priority, a dissonance that raises the question of whether or not the strategic planning of the Municipal Plan took into account factors of environmental injustice and social vulnerability regarding the access to ecosystem services provided by urban greening in its action protocols. As explained by [78], inefficient environmental management regarding the urban afforestation process in Goiânia is not a recent phenomenon, dating back to the beginning of the city's planning, a factor that resulted in a low frequency of native species and high use of exotic species. Furthermore, ref. [79] highlighted that the spatial configuration of green spaces in the urban area of Goiânia outlined over the years reproduces a scenario of low connectivity among forest fragments, a factor that can hinder or prevent the provision of ecosystem services.

Finally, from the perspective of public policies, the evidence demonstrates the urgency of formulating and applying more effective and efficient strategies to combat social inequalities and improve the environmental quality of cities, especially in large world metropolises [80]. In the specific context of our study area, for high-priority TPUs, effective intervention by municipal public authorities is recommended in the implementation of urban afforestation projects in compliance with technical and methodological regulations. Sound initiatives are able to preserve the long-term quality and durability of planted species and the proposition and implementation of social mitigation/compensation actions that ensure a higher quality of life for its residents, mainly concerning the aspects evaluated in this study: education, income, housing, and sanitation. It is worth mentioning that afforestation projects in urban environments are crucial for meeting SDG 11 of the 2030 Agenda. However, to guarantee the provision of essential ecosystem services, it is necessary to implement efficient environmental planning and management processes on a long-term basis, where the input data regarding socioeconomic indicators and urban greening mapping are continuously updated throughout time. This has been reported in several studies, such as [30,78,81,82].

5. Theoretical and Political Implications

This research conceived a methodological protocol for assessing classes of priority for urban afforestation based on the joint analysis of urban greening and socioeconomic data, with the latter expressed by a social vulnerability index constructed with indicators extracted from the national census. Our approach has the differential of relying on open access satellite imagery with high spatial resolution, which represents an opportunity for municipal leaders to base their decisions on free and detailed urban greening data.

Regarding the characteristics of priority areas for afforestation, taking into account the percentage of urban greening and social conditions, it is clear that the municipality still needs to enhance its Municipal Urban Afforestation Plan in a balanced way, since out of the 64 TPUs, only 5 (five) presented low priority, that is, good social conditions combined with satisfactory greening coverage. Moreover, the spatial distribution of priority zones for afforestation projects reinforces the concern about the environmental injustice observed in Goiânia. Except for TPU Jardim Europa (39), all other TPUs classified as high-priority are in the farthest locations and distant from the central nucleus of the municipality, proving that the process of peripheralization of the low-income population was accompanied by less access to better living conditions and ecosystem services provided by urban forests and green spaces.

It is expected that the results obtained here can contribute to the process of sustainable territorial planning in Goiânia and can also be able to reinforce the democratization of access to environmental benefits. Furthermore, it is also expected they can reduce socio-environmental inequalities and injustices, in addition to increasing the well-being of the local population, and they can contribute to the fulfillment of the sustainable development goals proposed by the UN Agenda 2030. In addition to that, we hope to encourage the dissemination of the concept of urban greening as an essential ecosystem services provider in the context of environmental justice to other studies at a municipal scale that consider the disparities among TPUs (neighborhoods), thus aiming to strengthen sound territorial planning processes and, consequently, enhancing initiatives for more sustainable and equal development to combat climate change.

6. Limitations and Directions for Future Work

We ought, though, to acknowledge some limitations of this research. Initially, we must say that our study did not consider the population's accessibility to urban forests and green spaces in terms of walkability metrics and public transportation availability. It would be ideal to consider the safe and easy access of the different social and age groups to such areas. Another shortcoming relates to the fact that the maintenance and usability conditions of the urban greening infrastructure in Goiânia have not been assessed, e.g., the presence of outdoor fitness equipment, leisure and recreational areas, sports fields, and sensory gardens, among other things. These points should be addressed in further developments of this work.

Based on the findings of this study, several recommendations for future research can be made. First, expanding the geoenvironmental model to incorporate additional variables beyond social vulnerability—such as air quality, temperature regulation, and biodiversity—would offer a more comprehensive understanding of the benefits provided by urban forests and green spaces. This would facilitate a more nuanced prioritization of areas for afforestation efforts. Furthermore, the application of this model to other cities with differing urban layouts and socioeconomic conditions could help validate its effectiveness and adaptability, providing valuable insights for urban planners in diverse contexts.

Additionally, future research should consider longitudinal studies that assess the long-term impacts of newly implemented afforestation projects in identified priority areas. By monitoring changes in social vulnerability indicators and ecosystem services over time, researchers could better evaluate the success of urban greening interventions in improving environmental justice. This approach would also contribute to refining the model by incorporating real-world feedback and adjusting strategies to ensure more equitable access to urban green spaces across all social groups.

7. Conclusions

The spatial configuration of the distribution of forests and green spaces in Goiânia demonstrated that the more central a TPU is, the lower its amount of urban greening. Additionally, we identified that all 21 TPUs that had more than 20% of greening coverage are located in peripheral regions, and it is worth noting that 5 (five) of them correspond to areas of luxury condominiums where the presence of vegetation is a means of overvaluing the housing units.

In a diverse way, social vulnerability mapping was characterized by the peripheralization of the worst indices, where the further away a TPU is from the central city core, the greater the vulnerability of its residents in terms of access to better living conditions. Such an unequal distribution of social vulnerability reflects Goiania's inequity regarding the access to income, education, and housing for its residents. However, the spatial representation of this inequity, as conducted in this research, may support local decision makers in conceiving integrated plans designed to tackle such problems.

It is important to highlight that until the production and writing of this study, the results of the 2022 National Census disaggregated at a scale of census tracts had not yet been released. The delay in the collection and dissemination of Brazil's census data, besides being a limiting factor in the performed analyses, makes it difficult to produce an up-to-date diagnosis of the Brazilian population. This scenario reduces the consistency and effectiveness of public policies aimed at the country's social and economic development, mainly affecting the poorest and most vulnerable populations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16060936/s1, Table S1: Percentage of urban greening, social vulnerability indicators, and afforestation priority ranking for each of the 64 TPUs.

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Data Availability Statement: All Census data are maintained by the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística—IBGE) and can be downloaded at https://www.ibge.gov.br/geociencias/organizacao-do-territorio/malhas-territoriais/26565-malhas-de-setores-censitarios-divisoes-intramunicipais.html (accessed on 11 October 2024) and https://censo2010.ibge.gov.br/ (accessed on 20 October 2024); CBERS-4A images are maintained by National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais—INPE) and are available at https://data.inpe.br/big/web/ (accessed on 15 September 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GIS	Geographic Information System
TPUs	Territorial Planning Units
CBERS-4A	China–Brazil Earth Resources Satellite 4A
NDVI	Normalized Digital Vegetation Index
UN	United Nations
SDG	Sustainable Development Goals
US	United States
MNDWI	Modified Normalized Difference Moisture Index
AWEI	Automated Water Extraction Index
TB	Total Biomass
TCS	Total Carbon Stock
CO_2eq	Carbon Dioxide Equivalent
UHI	Urban Heat Island
PGA	Public Green Areas
INPE	National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais)
IBGE	Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística)
CRESDA	China Centre for Resources Satellite and Data Application
WPM	Wide-Scan Panchromatic and Multispectral Camera
MUX	Multispectral Camera
WFI	Wide Field Imager
DOS	Dark-Object Subtraction
NIR	Near-Infrared
Red	Red band
FAPESP	São Paulo Research Foundation (Fundação de Amparo à Pesquisa do Estado de São Paulo)

CNPq	Brazilian National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico)
AEB	Brazilian Space Agency (Agência Espacial Brasileira)

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