Mercator, Fortaleza, v. 23, e23026, 2024. ISSN:1984-2201

INTEGRATING SOCIO-ECOLOGICAL CONNECTIONS INTO URBAN PLANNING

https://doi.org/10.4215/rm2024.e23026

Oliveira, N.G.D. [a*] - Domingues, G.F. [b] - Marcatti, G.E. [c] - Santos, A.R. [d] - Vieira, F.A. [e]

(a) Master in Forestry Sciences
ORCID: https://orcid.org/0000-0002-5337-9929. **LATTES:** http://lattes.cnpq.br/7751275307434933.
(b) PhD in Forestry Sciences
ORCID: https://orcid.org/0000-0001-8752-2001. **LATTES:** http://lattes.cnpq.br/7207060342658949.
(c) PhD in Forestry Sciences
ORCID: https://orcid.org/0000-0003-1455-4859. **LATTES:** http://lattes.cnpq.br/3268767286765155.
(d) PhD in Agricultural Engineering
ORCID: https://orcid.org/0000-0003-2617-9451. **LATTES:** http://lattes.cnpq.br/7125826645310758.
(e) PhD in Forestry Sciences
ORCID: https://orcid.org/0000-0003-3347-255X. **LATTES:** http://lattes.cnpq.br/1649941101614454.

Article history:
Received 25 August, 2024
Accepted 08 October, 2024
Published 10 November, 2024

(*) CORRESPONDING AUTHOR
Address: Rua Artur Bernardes,1030, Bom Jardim, CEP: 59618-710, Mossoró (RN), Brazil. Phone ((+ 55 84) 998195626)
E-mail: nardellagardner@gmail.com

Abstract

Urban ecology increasingly recognizes urban vacant lots as spaces with untapped aesthetic, social, and environmental potentials. This study focuses on strategies for converting these lots into green areas in Mossoró, a semi-arid city in Brazil, by analyzing urban connectivity patterns. Using a Geographic Information System, the study identifies priority areas for green space conversion based on factors like urban planning, density, land cover, and vacant lots. The analysis revealed 429 hectares of highly suitable land for conversion. A resistance surface was also created, factoring in public amenities and urban infrastructure, which showed varying levels of resistance to human movement. Areas with well-developed infrastructure had lower resistance, encouraging human and ecological movement. Connectivity modeling highlighted a need for more green infrastructure, especially in peripheral regions, to address socio-spatial fragmentation and enhance urban resilience in Mossoró.

Keywords: Connectivity, Green Infrastructure, Urban Vacant Lots.

Resumo / Resumen

INTEGRANDO CONEXÕES SOCIOECOLÓGICAS NO PLANEJAMENTO URBANO

A ecologia urbana reconhece cada vez mais os vazios urbanos como espaços com potenciais estéticos, sociais e ambientais não explorados. Este estudo foca em estratégias para converter esses terrenos em áreas verdes em Mossoró, uma cidade semiárida no Brasil, por meio da análise de padrões de conectividade urbana. Utilizando um Sistema de Informação Geográfica, o estudo identifica áreas prioritárias para a conversão em espaços verdes com base em fatores como planejamento urbano, densidade, cobertura do solo e vazios urbanos. A análise revelou 429 hectares de terrenos altamente adequados para conversão. Também foi criada uma superfície de resistência, considerando os equipamentos públicos e a infraestrutura urbana, que mostrou níveis variados de resistência ao movimento humano. Áreas com infraestrutura bem desenvolvida apresentaram menor resistência, incentivando o movimento humano e ecológico. A modelagem da conectividade destacou a necessidade de mais infraestrutura verde, especialmente em regiões periféricas, para abordar a fragmentação socioespacial e melhorar a resiliência urbana em Mossoró.

Palavras-chave: Conectividade, Infraestrutura Verde, Vazios Urbanos.

INTEGRANDO CONEXIONES SOCIOECOLÓGICAS EN LA PLANIFICACIÓN URBANA

La ecología urbana reconoce cada vez más los terrenos urbanos vacantes como espacios con potenciales estéticos, sociales y ambientales no explotados. Este estudio se centra en estrategias para convertir estos terrenos en áreas verdes en Mossoró, una ciudad semiárida en Brasil, mediante el análisis de patrones de conectividad urbana. Utilizando un Sistema de Información Geográfica, el estudio identifica áreas prioritarias para la conversión en espacios verdes basándose en factores como la planificación urbana, la densidad, la cobertura del suelo y los terrenos vacantes. El análisis reveló 429 hectáreas de terrenos altamente adecuados para la conversión. También se creó una superficie de resistencia, teniendo en cuenta las comodidades públicas y la infraestructura urbana, que mostró niveles variados de resistencia al movimiento humano. Las áreas con infraestructura bien desarrollada presentaron menor resistencia, alentando el movimiento humano y ecológico. La modelización de la conectividad destacó la necesidad de más infraestructura verde, especialmente en las regiones periféricas, para abordar la fragmentación socioespacial y mejorar la resiliencia urbana en Mossoró.

Palabras-clave: Conectividad, Infraestructura Verde, Terrenos Urbanos Vacantes.

INTRODUCTION

Urbanization is characterized by the increasing occupation of cities at the expense of rural areas and constant modifications of the natural environment in favor of land artificialization (HARARI, 2015; CARVALHO et al., 2022). This phenomenon has been particularly prominent in recent decades concerns about the sustainability of how cities develop and contribute to integrated social well-being and the environmental quality of their landscapes (EGERER et al., 2020). These concerns may sometimes seem to be in conflict and compete for public resources. However, as cities have started to take measures regarding climate change and sustainability, it has become clear that some of the most effective responses are those with multiple benefits, such as enhancing resilience and creating public green spaces in the city. The adoption for strategies that tackle various urban sustainability issues simultaneously has sparked an increasing interest in nature-based solutions (MCCORMICK et al., 2023).

Contemporary American cities face uneven population relocation dynamics influenced by globalization and deindustrialization, leading to significant social, ecological, and technological transformations. Factors such as rising consumer wealth, fluctuating service demands, increased productivity, and global trade expansion contribute to these changes. Post-industrial cities like Detroit have experienced severe decentralization, resulting in substantial losses in population, jobs, and housing, with large areas becoming vacant. These vacancies, often small, oddly shaped, and disconnected, pose regeneration challenges and exacerbate urban decline. Long-term vacant land can amplify crime, reduce quality of life, and lower property values, perpetuating a cycle of depopulation and economic decline, particularly in financially distressed cities (KIM et al., 2020).

This issue is not confined to the United States. For large cities around the world, vacant land and structural abandonment are prevalent problems. Buffalo, New York, for instance, has significant amounts of vacant land and abandoned structures. Land banking, a popular method in Buffalo and other cities for accumulating and repurposing vacant properties, has yielded mixed results. This issue underscores the broader challenges faced by urban areas globally in managing and revitalizing unused spaces (KIM et al., 2020).

Similarly, the municipality of Mossoró, the second-largest city in Rio Grande do Norte, Brazil, has experienced rapid population growth in recent decades. However, the process of urban expansion occurred without adequate public management, a situation mirrored across the entire national territory (PEIXOTO et al., 2021). The lack of urban management in Mossoró is evident in the form of socio-spatial fragmentation, characterized by irregular occupations, real estate speculation, high-end developments, deficient gray infrastructure services, deforestation, and deteriorating water resources. This includes a lack of urban mobility and a deficiency of green areas to provide ecosystem services (SANTOS et al., 2020; SILVA & ESCOBAR, 2022).

Within this context, recognizing the significance of green spaces in city planning becomes imperative (SILVA et al. 2022). Balancing the quality of semi-natural habitats and sources of urban ecosystem services, with urban growth is a pressing technical aspect all over the world and even more critical in affected climate change areas or extreme weathers like the dry tropical lands in brazilian’s semiarid region, as emphasized by Araujo et al. (2020).

One way to address the problems of urban planning inadequacies is through projects related to the reintegration of residual spaces into the built environment (DESIMINI, 2014), a latent issue for the municipality of Mossoró (FIDELIS-MEDEIROS & GRIGIO, 2019). Whether through the creation of gardens, artistic installations, community gardens, parks, or even the organization of temporary events, the city must implement interventions to address its urban vacant lots (DESIMINI, 2014).

Detroit provides a practical example of this approach by developing a method to establish green corridors through vacant or underused areas, aiming to enhance urban connectivity. With an estimated population of 670,000, the city faces challenges such as population decline, economic difficulties, and significant vacancy rates. These vacancies lead to various social and environmental issues, like contaminated soils and perceived safety risks, which can hinder mobility.

However, repurposing vacant land for green infrastructure could offer ecological habitats, enhance stormwater management, boost property values, and strengthen community empowerment (ZHANG et al., 2019). The Detroit Future City initiative supports the transformation of outdated infrastructure into green infrastructure on these vacant lands (DETROIT WORKS PROJECT LONG-TERM PLANNING STEERING COMMITTEE, 2012).

However, managing urban landscapes is challenging due to high spatial heterogeneity in land composition and use, significant social diversity in demographic terms, and differences in access to resources among populations in different neighborhoods (GERRISH & WATKINS, 2018). In addition to this challenge, there is an established conceptual and methodological framework to evaluate the importance of vacant spaces for their cities (LOKMAN, 2017). Traditional criteria used to determine the importance of open spaces for nature conservation often do not align with dealing with urban spaces. Moreover, they do not reflect the importance of the interaction between people and nature that is inherent to cities. This is why urban habitat assessment methods have incorporated ecological and social criteria, such as accessibility, aesthetics and safety of the limited existing green infrastructure (HERBST & HERBST, 2006).

In the outlined context of insufficient public green areas and the existence of vacant areas influenced by real estate speculation, this research aims to formulate a landscape strategy for developing new interconnected green areas in socio-ecological connectivity networks in Mossoró. This will be achieved through a careful evaluation of the most suitable areas for this purpose, considering the permeability of movement in the landscape based on the biophysical and infrastructural characteristics of the prioritized locations. The application of circuit theory will allow the creation of complex structural connectivity maps representing various aspects of movement in the landscape. Indeed, incorporating multifunctional green spaces into the urban landscape is crucial to driving flows of ecosystem services capable of providing improvements in quality of life, well-being, and urban resilience in developed and developing cities around the world.

MATERIALS AND METHODS

STUDY AREA

The municipality of Mossoró, located in the interior of the State of Rio Grande do Norte, Brazil (Fig. 1), has a population of 264,577 people, with 91.3% residing in urban areas and 8.7% in rural settings. Covering an area of 2,099.334 km², Mossoró has a population density of 126.03 inhabitants per square kilometer (IBGE, 2022). The city's sanitation coverage reaches 64.6% of its territory, with a municipal Human Development Index of approximately 0.720 (IBGE, 2010).

Figure 1 - Highlight of the urban area of the municipality of Mossoró, Rio Grande do Norte, Brazil.

Mossoró plays the typical roles of a medium-sized city in sectors like higher education, healthcare, commerce, and specialized services. Additionally, it fulfills a significant role in supplying the needs of the main productive activities in its sphere of influence, contributing to the establishment of a broader urban and economic network in the locality (ALMEIDA et al., 2021). Regarding environmental data, Mossoró has an urbanized area of 73.55 km², with 75.5% of its public roads lined with trees. Approximately 4.5% of urban households on public roads have adequate urbanization, including drainage, sidewalks, paving, and curbs (IBGE, 2010).

DATA PROCESSING

MEASURING HABITAT CONNECTIVITY IN THE URBAN LANDSCAPE

Mapping habitats with high intensity of ecological flows will be modeled using Circuitscape v4.0 software, based on focal nodes and resistance rasters (MCRAE, et al., 2008). The first raster map specifies the areas between which connectivity should be modeled, and the second raster provides the difficulty, or resistance, to movement on this surface. From these, the program generates a map with accumulated flow that flows through the focal nodes (ANANTHARAMAN et al., 2020). The resistance values are obtained through consultation of specialized literature, including works by Anderson et al. (2019) and Egerer et al. (2020), and, as well as discussions with experts in urban forestry.

In raster-pairwise mode, Circuitscape iterates through each possible source and sink pair and sets up a linear system for each pair. This process will create a theoretical resistance model for the city of Mossoró, based on social and ecological characteristics, representing the theoretical degree of environmental resistance imposed by land cover characteristics on the flow of ecosystem services and the theoretical degree of resistance to human well-being flows (EGERER et al., 2020).

The research was followed as shown in Fig. 2.

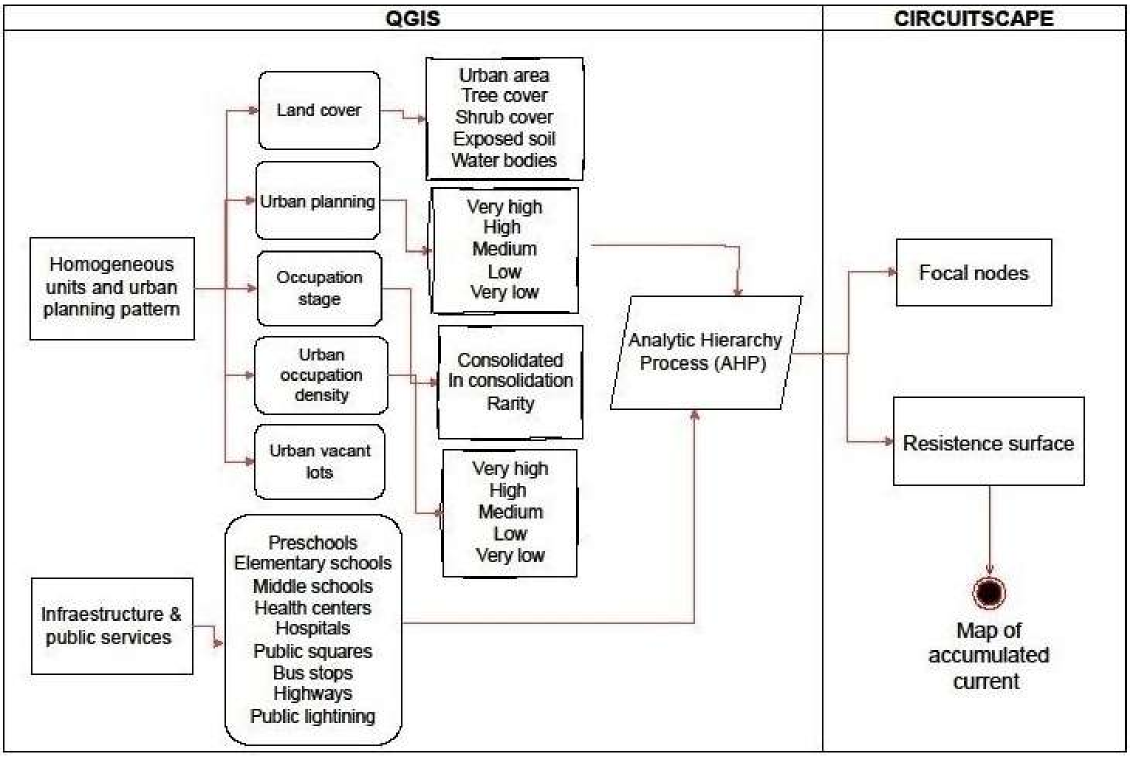


Figure 2 - Work method flowchart.

MAP OF AREAS MOST SUITABLE FOR CONVERSION INTO GREEN SPACES (FOCAL NODES)

The cartographic base used to create the suitability map of focal areas consists of vector products derived from spatial data by (FIDELIS-MEDEIROS & GRIGIO, 2019). These data were processed in QGIS software version 3.22 with coordinates in the UTM system, Zone 24 South, Datum SIRGAS 2000. Evaluation criteria for mapping included land cover, urban occupancy density, stage of urban occupation, urban vacant lots, and urban planning. Analytic Hierarchy Process (AHP) was employed to prioritize vacant urban spaces for conversion into public green areas (SAATY & KATZ, 1990). Criteria were manually classified based on satellite image interpretation. In QGIS, the map with continuous value ranges was reclassified into the following suitability classes for conversion into green areas: very high, high, medium, low, and very low.

The land cover criterion comprises various sub-criteria, namely:

a. Urban area: includes densely populated areas consisting of buildings and road systems. It encompasses residential, commercial, and service urban areas, residential condominiums, and scattered occupations with low building density such as farms, small estates, located away from urban areas or along highways and access roads.

b. Tree cover: class primarily composed of tree components. It includes riparian forests and open caatinga vegetation (areas with open vegetation with small patches of exposed soil, native pasture, and agricultural species planting) and closed (dense shrubby tree size, medium-sized trees, areas with high density).

c. Shrub cover: comprises areas covered by grasses or legumes, ranging in height from decimeters to meters, also pasture and grazing areas.

d. Exposed soil: spaces of human intervention that have undergone earthworks or plowing, being spaces in transition of use or still eroded areas.

e. Water bodies: rivers, streams, canals, and other linear water bodies, regulated natural lakes, and artificial reservoirs (FIDELIS-MEDEIROS & GRIGIO, 2019).

The urban occupancy density criterion is related to the intensity of land use, denoting the link between the size or quantity of lots per unit area. This criterion is a constant measure, which does not vary over time, considering the predominance of areas for class determination. There are five sub-criteria of urban occupancy density, namely: very high (verticalized buildings and occupancy on lots up to 150 m²), high (lots up to 250 m²), medium (lots from 250 to 450 m²), low (lots larger than 450 m²), and very low (areas with farms and estates) (FIDELIS-MEDEIROS & GRIGIO, 2019).

The stage of urban occupancy criterion refers to the phase in which the occupation is located. It is related to the quantity of built lots and empty lots in the sector. This criterion is subdivided into three sub-criteria, namely: consolidated stage, comprising areas with more than 80% of lots occupied with buildings; in consolidation, areas with between 30% and 80% of built lots; rarefied, areas with occupancy in the initial stage, that is, with less than 30% of built lots (FIDELIS-MEDEIROS & GRIGIO, 2019).

The urban planning criterion comprises three essential components shaping urban infrastructure. These elements are urban tree planting, street paving, and road system design. The urban planning is subdivided into five sub-criteria that are given according to the existence of these urban elements. Thus, there are: areas of very high planning (locations equipped with a complete road system layout, paving, and urban tree planting), areas of high planning (spaces featuring both road system and paving), areas of medium planning (having a structured road system, possibly accompanied by urban tree planting), areas of low planning (have only urban tree planting available), and areas of very low planning (spaces devoid of road system, paving, and urban tree planting (SÃO PAULO, 2016).

The urban vacant lots criterion is composed of areas that have undergone earthworks, which mainly have spontaneous vegetation in different successional stages. These are territories located in the urban area, typified by the absence of buildings, and are targeted for real estate expansion (FIDELIS-MEDEIROS & GRIGIO, 2019).

The evaluation criteria were based on green infrastructure concepts, with the aim of assessing the potential of urban vacant lots in creating landscapes that provide ecological and social services. Qualitative indicators were drawn for each defined criterion, which were later converted into numerical values to generate a classification score for the evaluated areas.

The weighting of the criteria studied for the suitability map was carried out based on a review of specialized literature, such as the authors: Loboda et al. (2005), Sanches & Pellegrino (2016), Fidelis-Medeiros & Grigio (2019), Cavalcanti et al. (2022), Ferreira et al. (2022) and consultation with specialized professionals.

The maps underwent rasterization, converting vector data into matrix data, with a resolution of 12.5 m (Fig. 3), depicting the urban perimeter boundaries. The combination of matrix data for each criterion through raster calculation resulted in determining the suitability level for transforming urban vacant lots into formal green areas.

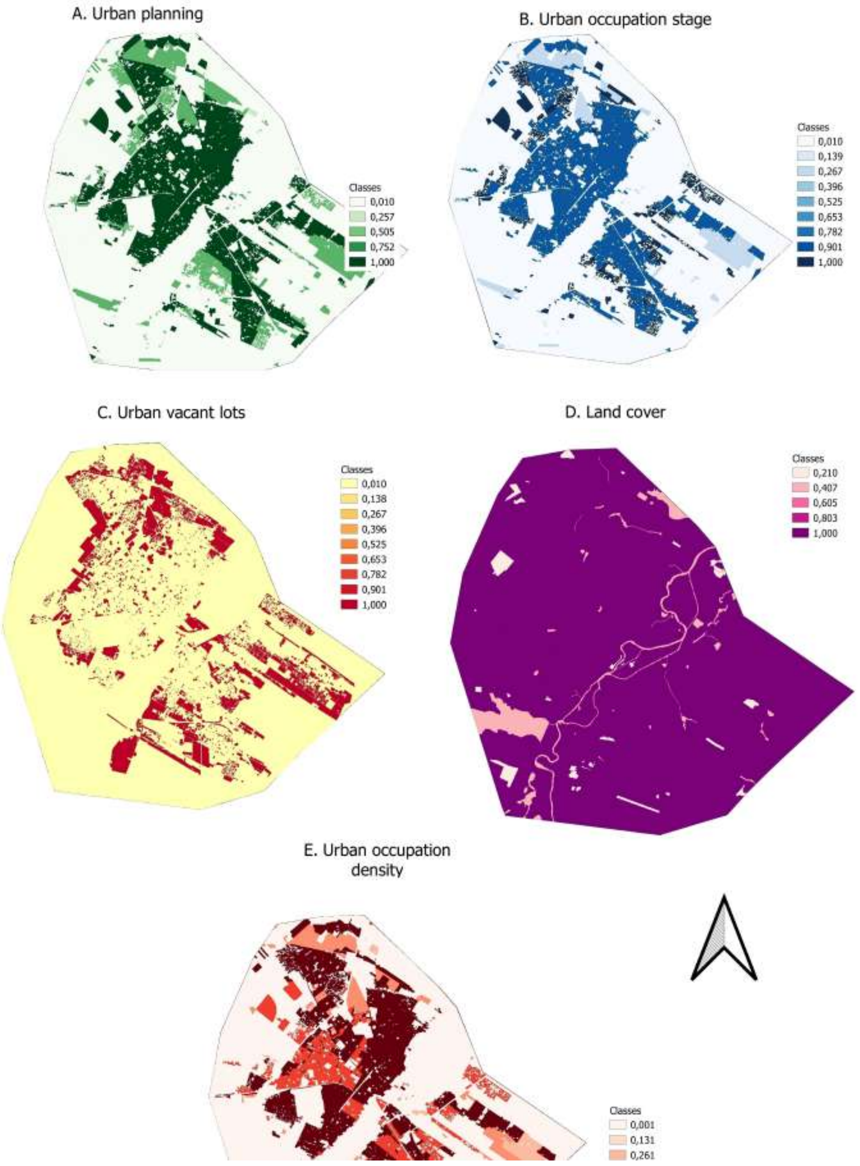


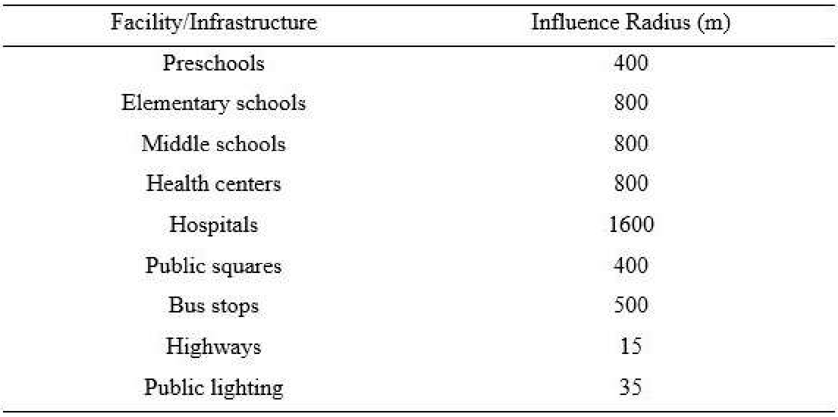
Figure 3 - Maps used to determine the priority for conversion into urban green areas. A. Prioritization classes of the urban planning criterion; B. Prioritization classes of the urban occupation stage criterion; C. Prioritization classes of the urban vacant lots D. Prioritization classes of the land cover criterion; E. Prioritization classes of the urban occupation density criterion.

RESISTANCE SURFACE OF PUBLIC SERVICES AND EQUIPMENT

In order to assess the permeability of the urban landscape for the establishment of new urban green areas, a resistance surface (ANDERSON et al., 2019) needs to be prepared, determining the hindrance of organism movement into the city of Mossoró (LEONARD et al., 2017). Vector products of Mossoró's urban footprint from (VIEIRA, 2022). were utilized, with a resolution of 12.5 m, in UTM Zone 24 South coordinates, SIRGAS 2000 Datum.

From this research, mapping of community public facilities was extracted, including schools (from early childhood to high school levels), parks, health centers, hospitals, and urban infrastructure such as bus stops, street lighting, and highways. Education facilities were sourced from Qedu and INEP (2022) (National Institute of Educational Studies and Research Anísio Teixeira); bus stops were mapped using Cittamobi (2022), the app routes, and highways from IBGE (2019) (Brazilian Institute of Geography and Statistics) databases.

In a GIS environment, the influence radius (Table 1) of each facility and infrastructure was assigned following the guidelines proposed by (PITTS, 2004), (PONTA GROSSA, 2023), and the Land Subdivision Law (Law No. 6.766/1979) (BRASIL, 1979). The influence radius refers to the area in meters where a facility or infrastructure service efficiently covers the local population. Subsequently, in QGIS, vector data is converted to a raster, and the data is normalized.



Facility/Infrastructure	Influence Radius (m)
Preschools	400
Elementary schools	800
Middle schools	800
Health centers	800
Hospitals	1600
Public squares	400
Bus stops	500
Highways	15
Public lighting	35

Table 1 - Influence radius of facilities and infrastructure in Mossoró, RN, Brazil.

To develop the resistance surface, the Analytic Hierarchy Process (AHP) was used to define the weights that equipment and infrastructure services possess for achieving the objective. In a GIS environment, results are generated using the raster calculator tool, which multiplies the contributions of each element by the normalized matrix file. Methodological references supporting variable selection include Herbst & Herbst (2006), Staples (2006), and Egerer et al. (2020). The presence of public equipment or services, presented here as criteria, indicates the ease or difficulty of movement for various actors, such as humans and other organisms, through the urban landscape according to the characteristics of the location and its surroundings. In order of priority for achieving the objective of this study, they are arranged as follows: hospitals, health centers, high schools, elementary schools, bus stops, squares, preschools, public lighting, and highways.

RESULTS AND DISCUSSION

MULTICRITERIA ANALYSIS FOR THE FOCAL NODES MAP

Obtaining the relative contribution of each criterion, Eq. 1 can be written and inserted into the QGIS raster calculator to map areas of greater interest.

Raster Calculator Expression = ((Occupation stage * 0,048) + (Urban density * 0,041) + (Land cover * 0,132) + (Urban planning * 0,285) + (Urban vacant lots * 0,494)) (1)

The resulting consistency ratio was 0.026, indicating that the criterion priorities were accurately inserted, as this value should be less than 0.1, according to Saaty & Katz (1990). Thus, it was possible to obtain a thematic map of the suitability of urban vacant lots for conversion into urban green areas, presented as five priority classes (Fig. 4).

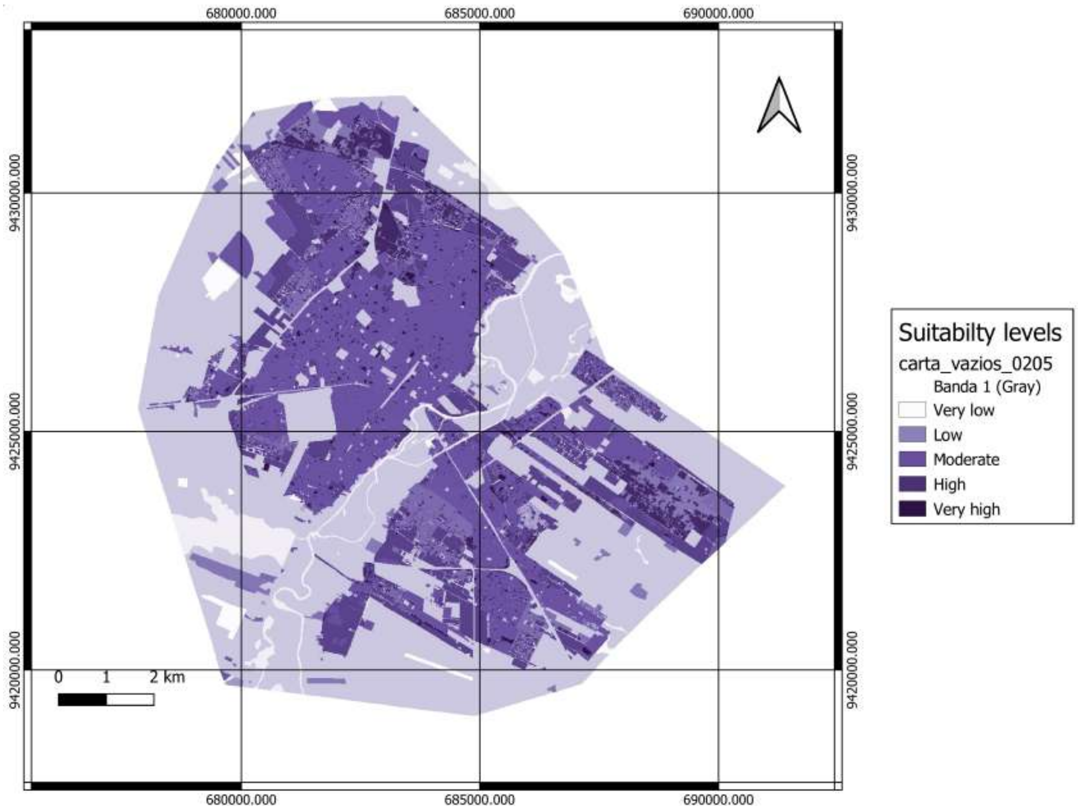


Figure 4 - Map of suitability levels for converting urban vacant lots into urban green areas.

In Table 2, the areas occupied by each of the five classifications presented on the map of suitability for converting urban Vacant lots into green areas are quantified in hectares. The continuous values of the priority classes ranged from 0.036 to 1.

Suitability	Area (ha)
Very low	6380,891
Low	790,781
Moderate	2681,531
High	1242,922
Very high	429,562

Table 2 - Quantitative assessment of the suitability classes for conversion into urban green areas.

The definition of the boundaries of each suitability class was given based on the ranges of continuous values. The first range, very low suitability, presented continuous values ranging from 0.036 to 0.28. This comprises most of the urban perimeter, occupying 6380.891 hectares, occurring mainly in areas with discontinuous occupation, low density, very low or low urban planning, and peri-urban characteristics. These areas consist of tree and shrub cover and water bodies, with the main one being the Apodi-Mossoró river, which divides the city into two portions, north and south.

The low, moderate, and high suitability classes presented the following values, respectively: 0.28 to 0.422; 0.422 to 0.614; and 0.614 to 0.807. They occur in areas with medium, high, and very high urban planning, residential areas, commercial and service areas, large facilities such as cemeteries, retail networks, industrial warehouses, squares, subdivisions, and urban vacant lots. These areas have consolidated or consolidating occupancy stages, with densities ranging from medium to very high intensity. These classes together occupy 4715.234 hectares of urban space.

Finally, 429.562 hectares correspond to urban vacant lots located in areas of very high, high, or medium occupancy density, with a consolidated or consolidating physical pattern, and with very high or high urban planning. In other words, these are places where there is a concrete need for green areas. Urban vacant lots here are pervasive spaces interwoven in areas of large facilities, commerce, services, and residences, which have varied habitats and serve as shelter for pioneer species, trees, and shrubs forming constantly changing plant communities (FIDELIS-MEDEIROS & GRIGIO, 2019).

The combination of these specificities indicates that these vacant spaces have the potential to be converted into urban green areas, offering multiple project possibilities for the development of squares, artistic installations, gardens, and urban gardens in small and medium-sized spaces. Additionally, due to their presence in all neighborhoods of the city, these spaces incorporate the nature of their surroundings (FIDELIS-MEDEIROS & GRIGIO, 2019) and can play ecological and aesthetic roles, provide environmental services, and provide recreational services for the population (SANCHES & PELLEGRINO, 2016).

In Mossoró, the presence of green spaces is scarce compared to other urban land use typologies, covering only 21 hectares. Most of these spaces are squares, and there is only one urban park, the Maurício de Oliveira Ecological Park, which covers 7.8 hectares (FIDELIS-MEDEIROS & GRIGIO, 2019). In the park, there is a predominance of exotic vegetation over native vegetation, but both are responsible for various provisioning and regulatory services, such as providing food for wildlife, shelter, scenic beauty, shade for visitor well-being by mitigating insolation and temperature, and maintaining soil biogeochemical conditions (OLIVEIRA & MEDEIROS, 2023).

WEIGHTING CRITERIA FOR THE RESISTANCE SURFACE OF PUBLIC SERVICES AND EQUIPMENT

The surface resistance determining the permeability of Mossoró's urban area relies on public equipment and services fostering human well-being and community cohesion (EGERER et al., 2020). With relative contributions of each criterion, Eq. 2 can model the resistance surface for movement in Mossoró's urban landscape using raster calculator in GIS. The consistency ratio was 0.047, aligning with Saaty's criteria for multicriteria analysis (SAATY & KATZ, 1990).

$$\text{Raster Calculator Expression} = ((\text{Highways} * 0{,}312) + (\text{Public lighting} * 0{,}230) + (\text{Preschools} * 0{,}116) + (\text{Public squares} * 0{,}116) + (\text{Bus stops} * 0{,}107) + (\text{Elementary schools} * 0{,}033) + (\text{Middle schools} * 0{,}033) + (\text{Health centers} * 0{,}031) + (\text{Hospitals} * 0{,}020) \quad (2)$$

Resistance values, influenced by city infrastructure, range from 212 to 1000; higher values imply greater difficulty in movement (Fig. 5) (EGERER & ANDERSON, 2020).

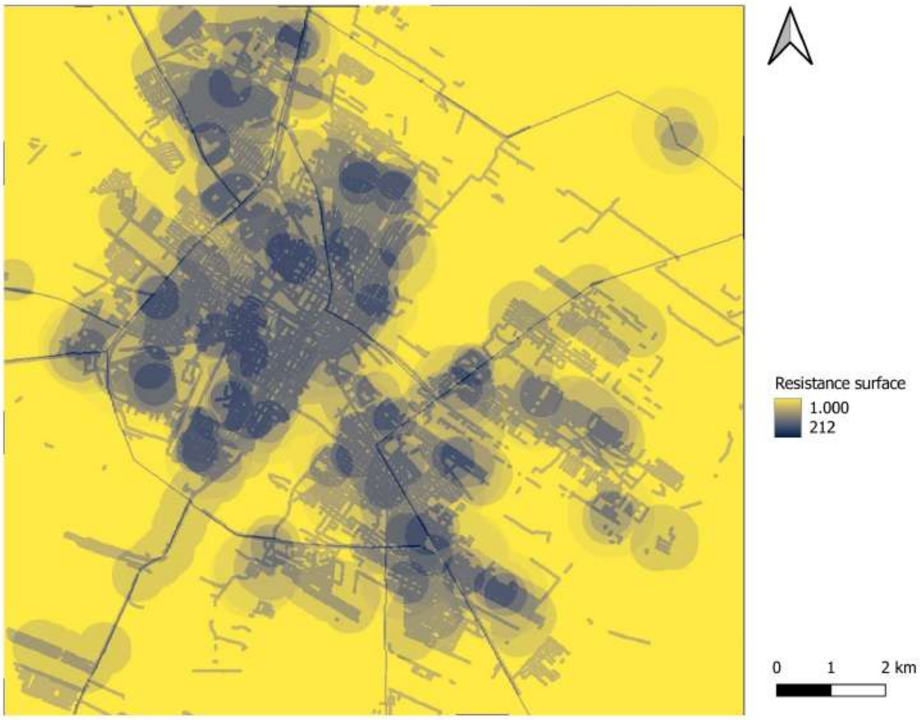


Figure 5 - Resistance surface.

North Mossoró shows higher flow-favorable points due to well-established infrastructure, while the south is characterized by residences and sparse physical patterns, limiting movement (SILVA et al., 2022). Areas lacking public amenities exhibit higher resistance, hindering pedestrian flow (MCRAE et al., 2008).

Presence of communal facilities encourages human mobility, offering leisure, education, and health options (EGERER & ANDERSON, 2020). Areas with hospitals, schools, and public spaces experience higher mobility compared to areas lacking such amenities (MCRAE et al., 2008).

PREDICTION FOR CONNECTIVITY AMONG URBAN VACANT LOTS IN MOSSORÓ

The Circuitscape modeling enables the visualization of areas with high electrical current density, indicating potentially intense flows within the city (Fig. 6).

The urban area studied comprises 1,132,790 nodes and, 1035 unique node pairs. By connecting neighboring cells with average cost using Circuitscape v4.0's pairwise mode, a cumulative current map simulating electrical flow between all node pairs on the rasterized surface was created (MCRAE et al., 2008). The current density in a pixel, resulting from simulated electrical current flow, correlates with the probability of movement among urban vacant lots in Mossoró (HAN et al., 2022).

Density of current, being mappable, is particularly useful for applications like urban planning where mapped routes are vital (MCRAE et al., 2008). In the Mossoró modeling, the current density ranged up to 4.23 amperes. High current density in singular paths suggests limited habitat availability for flows in Mossoró's urban landscape (KUMAR & CUSHMAN, 2022). High-density urban vacant lots significantly impact the network, which is crucial for maintaining connectivity amid the acquisition of new urban green areas. Few nodes with lower current densities indicate landscape redundancy, emphasizing the need for more greenways, crucial for creating a multifunctional neighborhood or city-scale network (MCRAE et al., 2008). Nodes with high current density but a lack of contribution to new independent paths indicate restricted connectivity due to a lack of public infrastructure promoting mobility in Mossoró's urban landscape (EGERER et al., 2020).

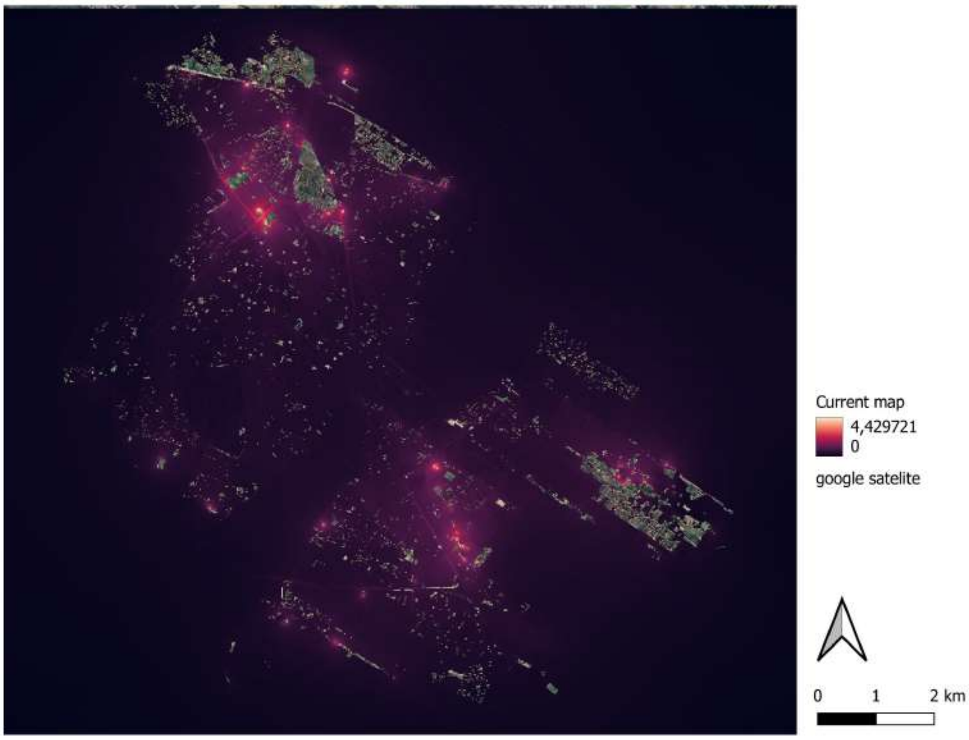


Figure 6 - Map of accumulated current (amperes) used to predict important connections between urban vacant lots in Mossoró. Lighter colors indicate areas with higher current density. Nodes without surrounding connectivity lack correspondence between pairs.

The overlay of the accumulated current map over Mossoró's neighborhoods (Fig. 7) reveals low current density nodes in areas like Redenção, Planalto Treze de Maio, Barrocas, Alto do Sumaré, Belo Horizonte, Aeroporto, and Alagados, constrained by the current urban environment. Higher current density nodes are found in Abolição, Presidente Costa e Silva, Santo Antônio, Santa Delmira, Dom Jaime Câmara, and Rincão, mostly in peripheral regions with limited public services, reflecting social exclusion (TEIXEIRA et al., 2022).

Investment focus by the state in northwest-southwest areas with commercial hubs, universities, and high-end real estate leaves peripheral neighborhoods neglected (TEIXEIRA et al., 2022). These areas lack continuous basic services, unlike elite zones. Social vulnerability is high in Santo Antônio, Barrocas, Santa Delmira, Rincão, Alto do Sumaré, and Dom Jaime Câmara, demanding urgent public policy attention (SILVA et al., 2016).

Rincão, Dom Jaime Câmara, Santa Delmira and Alto do Sumaré are neighborhoods characterized by a lack of both traditional and green infrastructure, exhibit high-current density nodes serving as stepping-stones for commuting activities (HAN et al., 2022; SILVA et al., 2022). Residents value urban nature, planting diverse fruit, ornamental, and medicinal species, and providing thermal comfort and moisture in Mossoró's semi-arid context (ARAUJO et al., 2020). Homicide rates are highest in Santo Antônio, Belo Horizonte, and Planalto Treze de Maio, aligning with ecological factors influencing crime distribution (BEATO, 2008). Public spaces are scarce or abandoned in peripheral regions, which leads to the need for community action to improve infrastructure (BENDER, 2022).

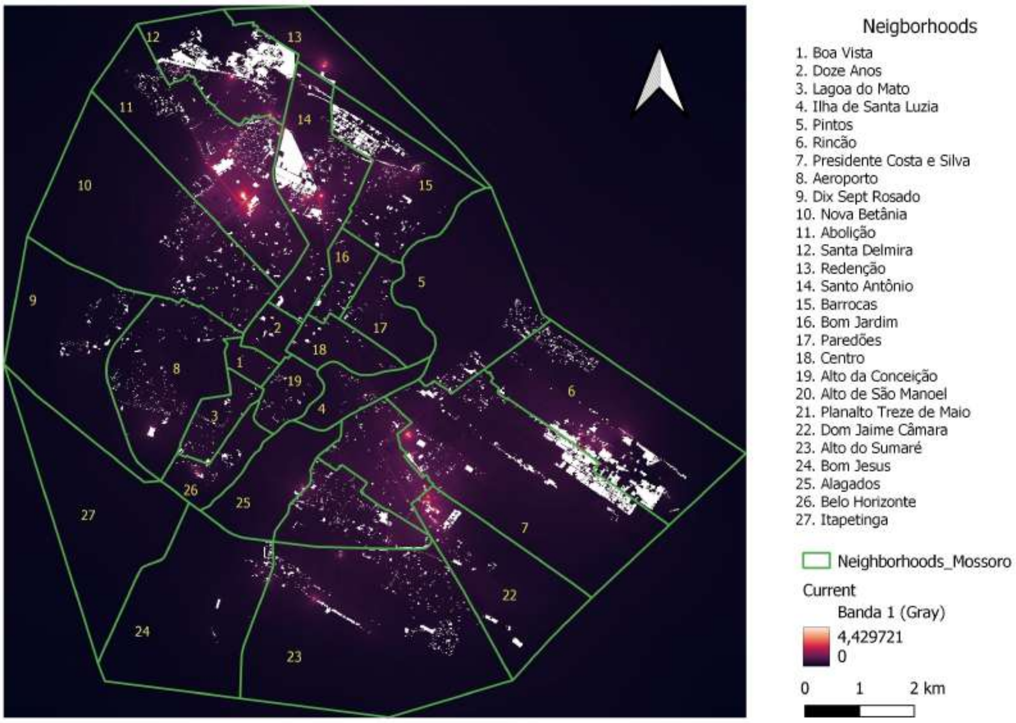


Figure 7 - Overlay of the accumulated current map (amperes) onto the neighborhoods of Mossoró.

In this challenging context, employing connectivity modeling to pinpoint areas conducive to ecological flow offers valuable insights for prioritizing investments in green infrastructure in Mossoró. This approach aligns with the objective of bolstering urban resilience amidst the impacts of climate change. Federal programs exist to support urban planning initiatives, with a focus on peripheral regions, and to formulate financial strategies for their execution. These initiatives encompass the preservation of green spaces, fostering sustainable land use practices, and promoting environmentally friendly modes of mobility (MINISTÉRIO DAS CIDADES, 2023).

Valuing abandoned urban areas, alongside cultural innovation, and urban environment enhancement, can regenerate Mossoró's urban fabric, reducing socio-spatial fragmentation among neighborhoods (ELSAWAH et al., 2020). Neglected spaces serve as investment catalysts, stimulating revitalization and enhancing urban surroundings, adding value and quality of life (SANCHES & PELLEGRINO, 2016). When converting abandoned spaces into green areas, however, the entire connectivity analysis undergoes changes. The insertion of a new green area affects the movement of humans and other organisms across the urban landscape. Consequently, the connectivity analysis provides only a momentary snapshot of the city's current situation (HAN et al., 2022).

This is an issue that hinders the modeling and analysis of connectivity networks (KUMAR & CUSHMAN, 2022). However, studies on socio-ecological networks are essential to increase the city's resilience through its urban vacant lots. These socio-ecological systems spread across neighborhoods can serve as sources of ecosystem services citywide, contributing to biodiversity conservation, well-being, and fulfilling citizens' rights (ELSAWAH et al., 2020).

CONCLUSIONS

Connectivity analysis reveals how the diversity of biophysical and social landscape characteristics forms an interconnected network in the city, providing precise insights into the movements of urban people and organisms and identifying the most relevant urban vacant lots to be converted into formal green areas. Despite the complexities involved, advances in technologies and methodologies enable increasingly effective integration, as demonstrated by flexible models using explicit spatial data in multicriteria methods, strengthening socio-ecological connections in the city.

Although vacant lots don't have continuous connectivity like green corridors, they can act as stepping-stones for urban green networks and are important in ecological planning. Urban vacant lots in Mossoró represents valuable resources, concentrated in peripheral neighborhoods lacking public investment, offering opportunities for the implementation of green infrastructure. Studies of this kind have the potential to positively impact biodiversity, promote resilience to climate and socio-economic changes, and enhance urban quality of life. Additionally, they underscore the importance of interdisciplinary research in landscape conservation and ecology, encouraging the development of models and practices aligned with local realities and promoting urban regeneration as a crucial strategy in the context of rapid urbanization and socio-environmental transformations.

This proposal is also applicable to other cities, bringing positive consequences for urban planning. Implementing similar strategies in different urban contexts can lead to improved ecological connectivity, increased green spaces, and enhanced biodiversity. Furthermore, it can foster social cohesion, reduce urban heat islands, and improve air quality, ultimately contributing to the overall well-being of urban populations. Such interdisciplinary approaches in urban planning can drive sustainable development and resilience in the face of global environmental challenges.

ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

REFERENCES

ALMEIDA, R.E.S.; COSTA, A.A.; BENEVIDES, H.J.; SOUSA, E.A. A condição de Mossoró-RN como cidade média em sua área de influência. Revista da Casa da Geografia de Sobral, Sobral/CE, v. 23, p.221-136, 2021. ISSN 2316-8056

ANANTHARAMAN, R.; HALL, K.; SHAH V. B.; EDELMAN, A. Circuitscape in Julia: High Performance Connectivity Modelling to Support Conservation Decisions. JuliaCon Proceedings, v. 1, n. 1, p. 58, 2020.

ANDERSON, C.B.; SEIXAS, Cristiana S.; BARBOSA, O.; FENNESSY, M. S.; DÍAZ-JOSÉ, J.; HERRERA-F., B. Determining nature's contributions to achieve the sustainable development goals. Sustainability Science, [S.L.], v. 14, n. 2, p. 543-547, 2018. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s11625-018-0643-5.

ARAUJO, A.M.; GRIGIO, A.M.; SILVA, M.R.F.; SARAIVA, A.L.B.C. Importância da arborização em quintais residenciais: um estudo microclimático em duas residências do bairro Rincão, Mossoró/RN. Revista Nacional de Gerenciamento de Cidades, v.8, n. 57, p. 36-51, 2020. ISSN 2318-9472

BEATO, C. (Org.). Compreendendo e avaliando: projetos de segurança pública. Belo Horizonte: Editora UFMG, 2008. 219 p

BENDER, P. Fragmentação socioespacial e temporal do espaço público em Chapecó, Mossoró e Marabá. Revista Invi, [S.L.], v. 37, n. 106, p. 1-26, 2022. Universidad de Chile. http://dx.doi.org/10.5354/0718-8358.2022.67158.

BRASIL. Lei Federal N.º 6.766, de 19 dez. 1979. Dispõe sobre o parcelamento do solo urbano e dá outras providências.

CARVALHO, R.; SOARES, I.A.; PAIVA, A.C.Q.; FERREIRA FILHO, J.M. Importância das áreas verdes urbanas no contexto da pandemia da Covid-19: estudo no parque municipal Maurício de Oliveira –Mossoró –Rio Grande do Norte. Revista Geográfica Acadêmica, v. 16, n. 2, p. 24 – 37. 2022.

CAVALCANTI, E.R.; MORETTI, J.A.; BRASIL, A.B.; MORETTI, R.S. Movimentos sociais na ocupação de imóveis vazios nas áreas centrais e o enfrentamento inclusivo das mudanças climáticas: os casos de São Paulo e Natal. Revista de Direito da Cidade, [S.L.], v. 14, n. 1, p. 138-169, 2022. http://dx.doi.org/10.12957/rdc.2022.54363.

CITTAMOBI. Cittamobi. 2022. Disponível em: https://www.cittamobi.com.br/home/. Acesso em: 23 de jun. de 2023.

DESIMINI, J. From Planned Shrinkage to Formerly Urban: Staking Landscape Architecture's Claim in the Shrinking City Debate. Landscape Journal, v. 33, n. 1, p. 17–35, 2014.

DETROIT WORKS PROJECT LONG-TERM PLANNING STEERING COMMITTEE. Detroit future city: Detroit strategic framework plan, December 2012.

EGERER, M.; ANDERSON, E. Social-Ecological Connectivity to Understand Ecosystem Service Provision across Networks in Urban Landscapes. Land, [S.L.], v. 9, n. 12, p. 530, 2020. MDPI AG. http://dx.doi.org/10.3390/land9120530.

EGERER, M.; FOUCH, N.; ANDERSON E.C.; CLARKE, M. Socio-ecological connectivity differs in magnitude and direction across urban landscapes. Scientific reports, [S.L.], v. 10, n. 1, p. 327-345, 2020. https://doi.org/10.1038/s41598-020-61230-9.

ELSAWAH, S.; FILATOVA, T.; JAKEMAN, A.J.; KETTNER, A.J.; ZELLNER, M.L.; ATHANASIADIS, I.N. HAMILTON, S.H., AXTELL, R.L., BROWN, D.G., GILLIGAN, J.M., JANSSEN, M.A., ROBINSON, D.T., ROZENBERG, J., ULLAH, I.I.T., LADE, S.J. Eight grand challenges in socio-environmental systems iocon ng. Socio-Environmental Systems Modelling, [S.L.], v. 2, e16226, 2020. http://dx.doi.org/10.18174/sesmo.2020a16226.

FERREIRA, G.A.C.; MOZINE, T. O.; FERREIRA, G.L. Metodologia de análise espacial para priorização das áreas de aplicação do Parcelamento, Edificação ou Utilização Compulsórios (PEUC) em vazios urbanos no município de Vila Velha, Espírito Santo. Urbe. Revista Brasileira de Gestão Urbana, [S.L.], v. 14, p. 1-17, 2022. http://dx.doi.org/10.1590/2175-3369.014.e20210132.

FIDELIS-MEDEIROS, F.; GRIGIO, A.M. Identificação das Unidades Homogêneas e Padrão da Ocupação Urbana (uhct) como subsídio ao ordenamento territorial em Mossoró, rn – Brasil. EURE, [S.L.], v.45, n.135, p. 245-270, 2019. ISSN: 0250-7161.

GERRISH, E.; WATKINS, S.L. The relationship between urban forests and income: a meta-analysis. Landscape And Urban Planning, [S.L.], v. 170, p. 293-308, 2018. Elsevier BV. http://dx.doi.org/10.1016/j.landurbplan.2017.09.005.

HAN, L.; WANG, Z.; WEI, M.; WANG, M.; SHI, H.; RUCKSTUHL, K.; YANG, W.; ALVES, J. Small patches play a critical role in the connectivity of the Western Tianshan landscape, Xinjiang, China. Ecological Indicators, [S.L.], v. 144, p. 109542, nov. 2022. Elsevier BV. http://dx.doi.org/10.1016/j.ecolind.2022.109542.

HARARI, Y.N. Sapiens: uma breve história da humanidade. Porto Alegre: L&PM, 2015.

HERBST, H.; HERBST, V. The development of an evaluation method using a geographic information system to determine the importance of wasteland sites as urban wildlife areas. Landscape And Urban Planning, [S.L.], v. 77, n. 1-2, p. 178-195, 2006. Elsevier BV. http://dx.doi.org/10.1016/j.landurbplan.2005.02.005.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE. Censo demográfico de 2010. Disponível: https://cidades.ibge.gov.br/brasil/rn/mossoro/panorama. Acesso em: 11 maio 2023.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE. Diretoria de Geociências, Coordenação de Meio Ambiente, Áreas Urbanizadas do Brasil, 2019. Disponível: https://cidades.ibge.gov.br/brasil/rn/mossoro/panorama. Acesso em: 11 maio 2023.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE. Área da unidade territorial.

Rio de Janeiro: IBGE, 2022. Disponível: https://cidades.ibge.gov.br/brasil/rn/mossoro/panorama. Acesso em: 11 maio 2023.

INSTITUTO NACIONAL DE ESTUDOS E PESQUISAS EDUCACIONAIS ANÍSIO TEIXEIRA – INEP. 2022. Disponível em: https://www.gov.br/inep/pt-br. Acesso em: 20 de abr. de 2023.

KIM, G.; NEWMAN, G.; JIANG, B. Urban regeneration: Community engagement process for vacant land in declining cities. Cities. V.102. 2020. https://doi.org/10.1016/j.cities.2020.102730

KUMAR, S.U.; CUSHMAN, S.A. Connectivity modelling in conservation science: a comparative evaluation. Scientific Reports, [S.L.], v. 12, n. 1,16680, 2022. Springer Science and Business Media LLC. http://dx.doi.org/10.1038/s41598-022-20370-w.

LEONARD, P.B.; SUTHERLAND, R.W.; BALDWIN, R.F.; FEDAK, D. A.; CARNES, R. G.; MONTGOMERY, A. P. Landscape connectivity losses due to sea level rise and land use change. Animal Conservation, [S.L.], v. 20, n. 1, p. 80-90, 2016. Wiley. http://dx.doi.org/10.1111/acv.12289.

LOBODA, C.R.; ANGELIS, B.L.D. Áreas verdes públicas urbanas: conceitos, usos e funções. Ambiência, v.1, n.1, p. 125-139, 2005. https://https://revistas.unicentro.br/index.php/ambiencia/article/viewFile/157/18. 09 maio 2023.

LOKMAN, K. Vacancy as a laboratory: design criteria for reimagining social-ecological systems on vacant urban lands. Landscape Research, v. 42, n. 7, p. 728–746, 2017.

MCCORMICK, K.; EVANS, J.; VOYTENKO PALGAN, Y.; FRANTZESKAKI, N. A research agenda for sustainable cities and communities. In A Research Agenda for Sustainable Cities and Communities. 2023. https://doi.org/10.4337/9781800372030

MCRAE, B.H.; DICKSON, B.G.; KEITT, T.H.; SHAH, V.B. Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology, [S.L.], v. 89, n. 10, p. 2712-2724, 2008. Wiley. http://dx.doi.org/10.1890/07-1861.1.

MINISTÉRIO DAS CIDADES. Novo programa federal 'Cidades Verdes e Resilientes' é destaque na COP28. 2023. Disponível em: https://www.gov.br/cidades/pt-br/assuntos/noticias-1/novo-programa-federal-cidades-verdes-e-resilientes-e-destaque-na-cop28. Acesso em: 26 dez. 2023.

OLIVEIRA, P.D.; MEDEIROS, W.D.A. Serviços ecossistêmicos de provisão promovidos pelo parque municipal Professor Maurício de Oliveira, Mossoró/RN. Revista Geointerações, Assú, v. 7, p. 78-95, e.05, 2023. ISSN 2526-3889.

PEIXOTO, F.S.; OLIVEIRA, J.P.; SANTOS, H.D.C. O esgotamento sanitário e a expansão urbana em Mossoró/RN. Sociedade e Território, v. 33, n. 2, p. 189-211, 2021. ISSN:2177-8396

PITTS, A. Planning and Design Strategies for Sustainability and Profit: Pragmatic sustainable design on building and urban scales. Architectural Press, 2004.

PONTA GROSSA, Prefeitura Municipal de. Projeto para Estruturação da PPP de Iluminação Pública Situação Técnico-Operacional. Ponta Grossa, 2023.

SAATY, T.L.; KATZ, J. How to make a decision: The analytic hierarchy process. European Journal of Operational Research, v. 48, n. 1, p. 9-26, 1990. https://doi.org/10.1016/0377- 2217(90)90057-I.

SANCHES, P.M.; PELLEGRINO, P.R.M.; Greening potential of derelict and vacant lotss in urban areas. Urban Forestry & Urban Greening, [S.L.], v. 19, p. 128-139, 2016. http://dx.doi.org/10.1016/j.ufug.2016.07.002.

SANTOS, E.L.B.; SOARES, L.E.S.; BRITO, V.R.; GUEDES, Z.M. Cidades sustentáveis no semiárido brasileiro: os desafios para o município de Mossoró/RN. Revista Homem, Espaço e Tempo, n. 14, v. 1, p. 9-26, 2020. ISSN: 1982-3800.

SÃO PAULO. Sistema de classificação Unidades Homogêneas de Cobertura da Terra e do Uso e Padrão da Ocupação Urbana (UHCT) e Mapeamento da Vulnerabilidade de Áreas Urbanas de Uso Residencial/comercial/serviços a Eventos Geodinâmicos do Estado de São Paulo. Instituto Geológico, Coordenadoria de Planejamento Ambiental, 2016. Secretaria do Meio Ambiente do Estado do São Paulo. Disponível em http://igeologico.sp.gov.br/ files/2016/06/Ficha_Tecnica_UHCT_2016.pdf

SILVA, M. N.; CARDOSO, A. L.; DENALDI, R. (org.) Urbanização de favelas no Brasil: trajetórias de políticas municipais. Rio de Janeiro: Letra Capital, 2022.

SILVA, A.M.B.; ESCOBAR, M.L. Análise qualiquantitativa e a contribuição socioambiental das praças da zona central de Mossoró-RN. Revista GeoUECE, n. 21, v. 12, p. 1-18, 2022. e202206, e-ISSN: 2317-028X.

SILVA, C.S.P.; GRIGIO, A.M.; PIMENTA, M.R.C. Levantamento e espacialização da criminalidade urbana do município de Mossoró-RN. Holos, [S.L.], n. 32, v. 3, p. 352-362, 2016.

STAPLES, M. Green network vacant and derelict land study for glasgow and clyde valley structure plan. Joint I. Edinburgh: RPS, 2006. https://www.gcvgreennetwork.gov.uk/

TEIXEIRA, V.M.L.; Pereira, C.S.S.; Silva, C.F. Social division of space and socio-spatial fragmentation. Mercator, [S.L.], v. 21, n. 1, p. 1-13, 2022. http://dx.doi.org/10.4215/rm2022.e21015.

VIEIRA, J.D.C. Mapeamento dos locais adequados para implantação de conjuntos habitacionais de interesse social com base no método multicritérios. 59 p. TCC (Graduação) – Curso de Engenharia Civil, Universidade Federal Rural do Semi-árido, MOSSORÓ, 2022.

ZHANG, Z.; MEEROW, S.; NEWELL, J.P.; LINDQUIST, M. Enhancing landscape connectivity through multifunctional green infrastructure corridor modeling and design. Urban Forestry and Urban Greening, v. 38, p. 305–317, 2019. https://doi.org/10.1016/j.ufug.2018.10.014

Author's Affiliation

Oliveira, N.G.D. - Federal University of Rio Grande do Norte, Macaíba (RN), Brazil.
Domingues, G.F. - Professor at the Federal University of Minas Gerais, Belo Horizonte (MG), Brazil
Marcatti, G.E. - Professor at the Federal University of São João Del-Rei, Sete Lagoas (MG), Brazil
Santos, A.R. - Professor at the Federal University of Espírito Santo, Alegre (ES), Brazil.
Vieira, F.A. - Professor at the Federal University of Rio Grande do Norte, Macaíba (RN), Brazil

Authors' Contribution

Oliveira, N.G.D. - The author contributed to the elaboration, realization and manipulation of data and writing.
Domingues, G.F. - The author contributed to the elaboration, realization and manipulation of data and writing.
Marcatti, G.E. - The author contributed to the elaboration, realization and manipulation of data and writing.
Santos, A.R. - The author contributed to the elaboration, realization and manipulation of data and writing.
Vieira, F.A. - The author contributed to the elaboration, realization and manipulation of data and writing.

Editors in Charge

Alexandra Maria Oliveira
Alexandre Queiroz Pereira