Land use/land cover forecast and urban sprawl analysis in a Brazilian city in the Atlantic Forest Biome

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Abstract

Urban sprawl, a consequence of urban growth, profoundly impacts land use/land cover, particularly in regions like the Brazilian Atlantic Forest, as this Biome hosts most of the Brazilian population and is recognized as a global biodiversity hotspot. This study uses geospatial techniques, the Cellular Automata model, and structural landscape metrics to simulate future urban land use changes for 2050. The simulation suggests a significant increase in urban areas by 2050, changing from 32.1% in 2020 to nearly 43% by 2050, mainly encroaching upon agricultural lands. Conversely, forest fragments are projected to decline (lost 3% of areas), and the connectivity analysis highlighted the loss along the rivers, emphasizing the need for proactive conservation strategies. Preserving periurban agriculture is vital for food security and sustainable development, while innovative management of riparian ecosystems enhances urban biodiversity and citizen well-being. Sustainable urban planning and conservation efforts are imperative to mitigate the adverse effects of urban sprawl and foster resilient cities. This research provides crucial insights for decision-makers aiming to balance urban development with environmental preservation in the face of rapid urbanization.

1. Introduction

Urban sprawl is a consequence of urban growth, resulting in changes in land use and land cover, increased ecosystem fragmentation, and the loss of agricultural lands.

These changes have significant ecological, social, and health consequences, impacting the urban environment's ecosystem services and human well-being (Pereira et al., 2023). Habitat fragmentation, noise pollution, air pollution, reduced water quality, reduced vegetation cover and structure, and artificial light all degrade urban ecosystem services.

These multidimensional problems are critical in Brazilian cities within the Atlantic Forest, as this Biome hosts most of the Brazilian population and is recognized as a global biodiversity hotspot. Thus, forest protection, restoration efforts, and potential ecosystem services are also examined as key topics shaping the future of the Atlantic Forest Biome.

Although urban areas represent only a small percentage of the planet's terrestrial surface, they are predicted to grow by 1.2 million km^2 by 2030 (Seto et al., 2012).

Future scenario simulation models, such as Cellular Automata, have been extensively used to simulate the effects of urban sprawl and land use changes. By integrating Cellular Automata models with geographic information system (GIS) and remotely sensed data, it becomes feasible to monitor the current conditions and forecast future spatio-temporal land use and land cover changes. This integrated approach can facilitate the analysis of environmental protection and urban sustainability initiatives, thereby enabling informed decision-making for sustainable urban development.

In this regard, this study uses geospatial techniques, the Cellular Automata model, and structural landscape metrics to simulate future urban land use changes for 2050. It aims to assess their impact on land use and land cover in Sorocaba municipality in the Atlantic Forest Biome. This forecasting approach can inform decision-making about environmental protection and urban sustainability initiatives offering multigenerational benefits for city dwellers.

2. Material and Methods

2.1 Study area

The study area is Sorocaba municipality, a typical urban landscape in the Atlantic Forest context in southwest Brazil in the São Paulo state (Figure 1). The municipality has 450 km^2 in area and a vast urban area surrounded by a highly fragmented forest composed of small fragments of Seasonally Dry Tropical Forest.

The local population has grown from 586,625 in 2010 to 723,682 in 2022, making it the ninth largest in São Paulo state. Today, 99% of its residents live in urban areas.

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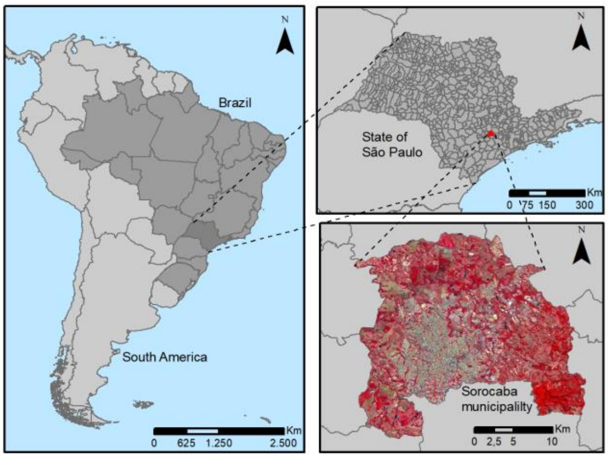

Figure 1. Sorocaba, state of São Paulo, Brazil. False-color composition R(NIR), G(Red), and B(Green) from CBERS-4 satellite image from 2021.

2.2 Data set

The data used in this study includes land use and land cover maps from the MapBiomas project (https://brasil.mapbiomas.org) - accessed directly from Google Earth Engine in raster format (30-m resolution, Collection 8.0). For this study, the land use and land cover maps are classified into four classes: forest fragments, mosaic of agriculture and pasture, urban, and water.

The 12.5 m resolution ALOS PALSAR digital elevation model (DEM) data (acquisition date: 4 December 2018) was downloaded from the Alaska Satellite Facility Distributed Active Archive Center (https://asf.alaska.edu/) and used to generate the slope and altitude map.

Land surface temperature data was obtained from Ribeiro et al. (2024) in the period corresponding to the summer season (between December 2018 and March 2019). Landsat-8 images with minimum cloud cover were selected to compose a maximum value temperature composition (Landsat crossing time of 01:00 p.m. for OLI sensor), and it was normalized to a standard scale by a linear fuzzy set membership function, ranging from 0 to 255 on ArcGis software (version 11.8).

The boundaries of Protected Areas registered in the city between 2012 and 2016 were obtained from the Brazilian National Protected Areas Register (https://www.gov.br/mma/pt-br).

The macro zoning land use was obtained from the Department of the Environment of the Sorocaba Municipality, and it was divided into four class levels for land use change policies: very-high restrictions (areas for conservation), high restrictions, moderated restrictions, and minor restrictions.

The Department of the Environment of the Sorocaba Municipality provided the vector data for roads and streets, rivers and water bodies, parks and squares, and the land use zoning of Sorocaba, all based in 2014.

2.3 The model

The land use and land cover future model for 2050 was simulated in DINAMICA EGO (https://csr.ufmg.br/dinamica/). This spatially explicit simulation model combines the concepts of Markov Chain and Cellular Automata modelling. DINAMICA EGO uses historical land use and land cover maps (2010 and 2020 from MapBiomas, in this case) and selected spatial variables organized into two cartographic subsets: dynamic and static (Soares-Filho et al., 2002).

The processing steps include (Figure 2):

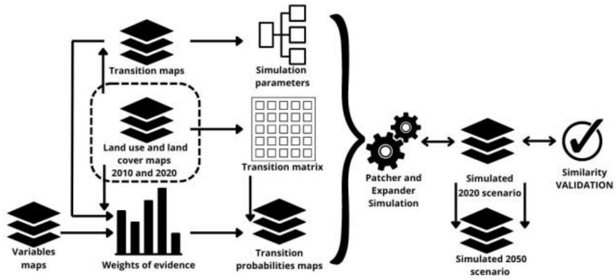

Figure 2. Steps used to develop the 2050 simulation scenario.

(i) Calculation of the annual overall transition rate by cross-tabulating classification maps extracted from MapBiomas data in 2010 and 2020;

(ii) Calculation of the local transition rate by the weight of the evidence model. Four classes of land use and land cover and a raster with eight variables (static maps) were considered: altimetry, slope, land surface temperature, distance from rivers and water bodies, distance from roads and streets, distance to Protected Areas, land use zoning map, and distance to parks and squares. The simulated landscape maps are oriented, besides historical land use and land cover maps, through spatial transition probability maps, which depict the probability of a cell at a position (x, y) to change from state i to state j, being the i and j types of land use and land cover class - Bayesian probability-based methods. The transition probability maps were developed through weights of evidence, where weights of evidence value represent the influence of each level or distance range of each variable on the local or spatial transition probabilities.

(iii) Calibration of the model to confirm the independence between each pair of spatial variables. Cramer’s coefficient (C) and joint information uncertainty (J) were used, ranging from 0 to 1, where 0 indicates independence, and 1 signifies complete correlation. When the C and J values are less than 0.5, there is no apparent correlation between the two variables.

(iv) Execution of the model (2010-2020) through a Cellular Automata rule transformation engine, which includes two complementary transformation functions: Expander and Patcher. The Expander function manages the expansion and contraction of existing patches, while the Patcher function controls the generation of new patches.

(v) The accuracy assessment of the simulated and actual observed changes using the interactive fuzzy comparison method. The similarity of simulated and actual land-use changes is compared, that is, between the 2020 current and the 2020 simulated value. The comparison is accomplished by scanning multiple-sized neighborhood windows - e.g., 3x3, 5x5, 11x11 cells - corresponding to the multiresolution goodness-of-fit approach.

(vi) Setting up and simulating the future urban sprawl scenario.

We applied the change detection analysis (intersect tools) in ArcGIS software to evaluate and quantify differences between land use and land cover from 2020 to 2050. This involves employing metrics at the class levels, including Total Area and Percentage of Landscape.

Additionally, connectivity analysis for 2020 and 2050 was conducted using the Probability of Connectivity (PC) index (Saura and Pascual-Hortal, 2007) in the Graphab software (https://sourcesup.renater.fr/www/graphab/en/home.html). The PC index is a global metric given by Eq. (1).

$$PC = \frac{\sum_{i=1}^{n} \cdot \sum_{j=1}^{n} \cdot a_i . a_j . p_{ij}^*}{A_L^2}$$

where p_{ij}^* is the maximum probability of movement between the parcels i and j (i.e., corresponding to the minimum cost); a_i a_j are the areas of the parcels i and j; AL is the total area of the study zone, and n is the number of parcels.

The probability p_{ij}^* is obtained by transforming the distance dij, between parcels i and j by an exponential function such that:

$$p_{ij}^* = e^{-\alpha d_{ij}}$$

where d_{ij} is the least-cost distance between i and j, and α expresses the intensity of decreasing probability of dispersion p resulting from the exponential function.

The value α was determined by p_{ij}^*=0.5 when d corresponds to the median dispersal distance (for birds). Thus, the PC metric was set up at a distance (d) of 100 m, covering 50% of the dispersal events of the focal study species (i.e., Atlantic Forest birds).

The fractions were calculated from 0 to 1, and the results were multiplied by 100 to interpret the percentage. The Natural Breaks algorithm was used to classify the Probability of Connectivity (PC) on the ArcGIS software into high, medium, and low levels.

3. Results and Discussion

The simulated land use and cover for 2020 (Figure 3) showed a 67% similarity with the actual landscape within an analysis window of size 5x5. This means that the simulation correctly identified the location of land use and land cover classes in more than half of the created pixels.

These excellent results were attributed to the variables selected for this model. The correlations between variables, the C and J values, showed that all variables are critical in explaining the phenomenon, with the "land use zoning map" and "altimetry" showing the highest correlation. We tested various Patcher values, and adopted a value of 0.17 for this model.

Therefore, after calibrating the model and achieving great performance, it was deemed viable to continue simulating scenarios, as these would provide critical predictive insights for ongoing discussions.

The simulation indicates that the urban area rates will increase from 32.1% in 2020 to nearly 43% by 2050 (Figure 4), with most of the expansion occurring in agricultural lands and pastures (Figure 5-6).

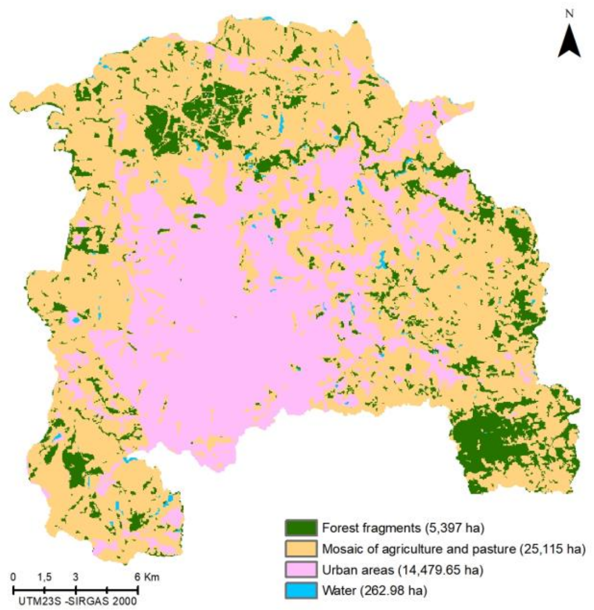

Figure 3. Land use and cover simulation for 2020 in Sorocaba, State of São Paulo, Brazil.

The municipality's boundaries are expanding into the surrounding areas, a typical pattern of suburban sprawl (Figures 4 and 5). This pattern of urban growth contrasts with the compact city model, which aims to accommodate urban development while minimizing the consumption of undeveloped land (UN-Habitat, 2021). These undeveloped areas, often mosaics of agriculture and pasture or forest fragments, are vital for providing ecosystem services to urban areas, such as flood mitigation and reducing urban heat islands. In this sense, this study can help the municipality's urban planning prioritize compact planning, discouraging the further sprawl of the already substantial urban limits.

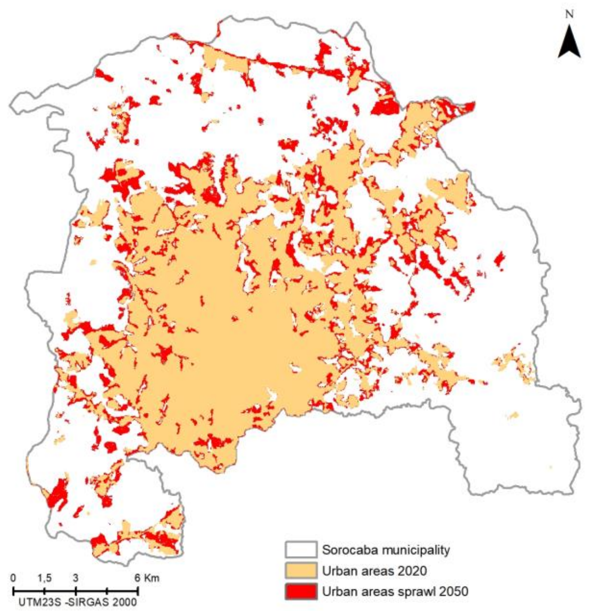

Figure 4. Urban sprawl simulated for 2050 for Sorocaba municipality, São Paulo state, Brazil.

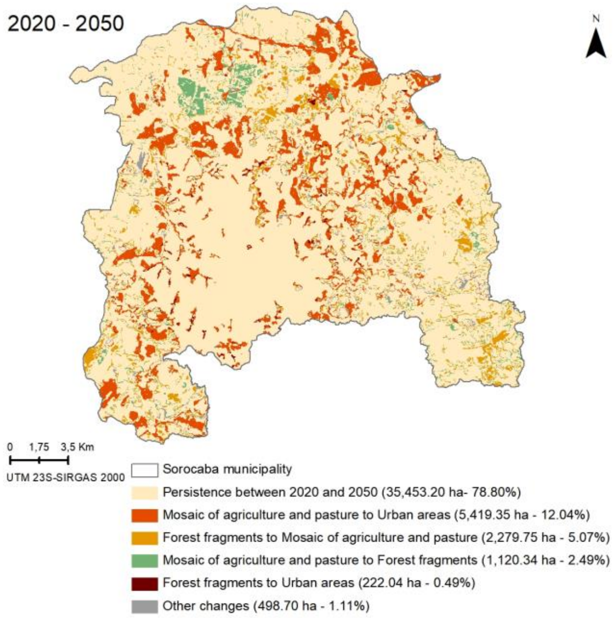

Figure 5. Change detection map between 2020 and 2050, in Sorocaba, State of São Paulo, Brazil. The 2020 map was adapted from MapBiomas.

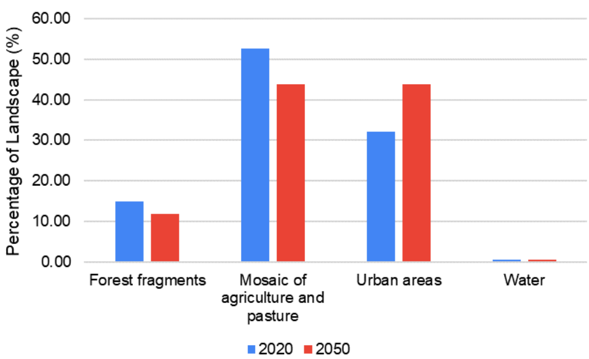

Figure 6. Land use/land cover changes between 2020 and 2050 for Sorocaba municipality, State of São Paulo, Brazil.

Conversely, the mosaic of agriculture and pasture is projected to decrease from 52.6% in 2020 to 44% by 2050 (Figure 5). However, this class has the most extensive persistence area (without land use and land cover changes) in the landscape, covering nearly 17,000 ha, followed by urban areas with nearly 14,000 ha. Given the encroachment of urban sprawl, protecting agricultural land in periurban areas is crucial for limiting land use and land cover conversion, ensuring continued proximity of ecosystem service and food production to city consumers (Magoni and Colucci, 2017; UN-Habitat, 2021). Moreover, agricultural land systems are relevant to 11 of the 17 Sustainable Development Goals (SDGs). For instance, periurban agricultural lands can help reduce poverty and improve water quality, while urban agriculture contributes to increasing urban livability and access to green spaces (e.g., urban gardens and green roofs), mitigating the impact of natural hazards and pollution, and ensuring food security. Therefore, proactive management of urban land expansion is critical for preserving agricultural lands and fostering equitable urban landscapes, especially in small and medium cities.

In 2020, forest fragments comprised nearly 15% of the landscape, a proportion projected to decrease to 12% by 2050 (Figure 2). Our forecast (Figure 5) indicates that 5.07% of the forest fragments would convert to a mosaic of agriculture and pasture, while another 2,49% will transition to urban areas, with these changes most noticeable in the riparian areas. In 2020, the key forest fragments essential for connectivity were concentrated along Pirajibu-Mirim river, one of the main rivers in the municipality (Figure 7). However, by 2050, the forecast shows decline in connectivity along the rivers due to the loss of forest fragments in riparian areas. This will result in concentrated connectivity in the southwest, a region with the highest altimetry and many smaller rivers, and in the north, near the Protected area known as the Corridor of Biodiversity.

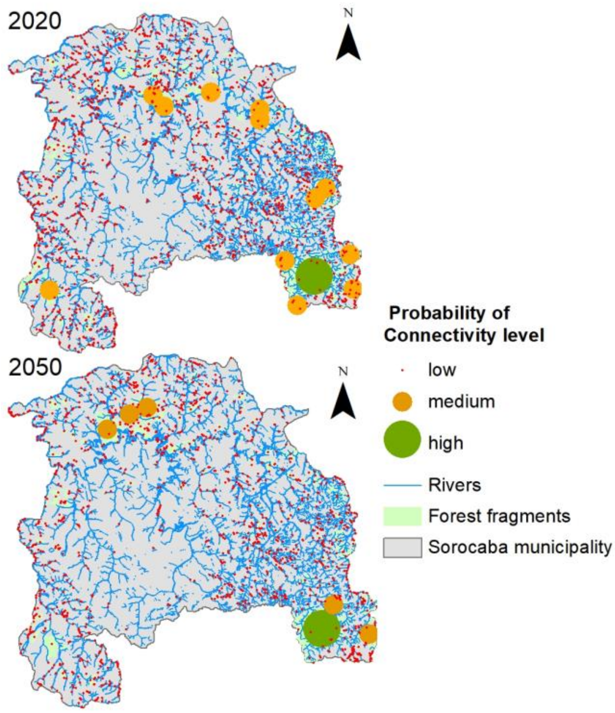

Figure 7. Essential forest fragments for Sorocaba municipality, State of São Paulo, Brazil, with highlighted nodes by Probability of connectivity index.

Riparian ecosystems in urban environments are often degraded; however, implementing innovative management practices is crucial for conserving these ecosystems’ services, which can lead to improvements in air quality, microclimate, and urban biodiversity (Veról et al., 2020). In other words, sustainable management of urban riparian areas can potentially improve the health and well-being of the citizens. Therefore, monitoring land use sprawl and changes in urban green infrastructure, including their impact on habitat connectivity, is crucial to supporting policymakers and planners in ensuring sustainable urban development and maintaining biodiversity in the Sorocaba municipality.

Overall, global landscape connectivity would decline from 4.60% in 2020 to 2.87% in 2050. The connectivity analysis revealed that this decrease was primarily due to forest fragmentation and area loss, driven by urban expansion (Figure 6). Furthermore, most forest fragments are insufficient to support connectivity, indicating a fragmented landscape with low connectivity (Figure 7). We emphasize the crucial role of municipal governments in establishing urban ecological networks to foster more resilient cities. Regularly updated spatio-temporal analysis of green infrastructure, urban sprawl, and landscape connectivity analysis can offer significant ecosystem benefits to urban populations when integrated into urban planning studies.

This research on urban sprawl addresses the pressing challenge of enhancing sustainability and resilience in global urban environmental agendas, particularly in rapidly urbanizing landscapes like the Brazilian Atlantic Forest. Urban sprawl simulations are crucial for helping cities meet the Sustainable Development Goals (SDG), particularly SDG Goal 11, the New Urban Agenda (UN-Habitat, 2020) recommendations, and the United Nations campaign - Race to Resilience. These efforts aim to transform urban areas into healthy, clean, safe, and resilient to the impacts of climate change. This is especially important for developing countries such as Latin America, where cities continue to experience significant sprawl. Effective planning for these sprawls requires conserving green infrastructure and improving ecosystem services and city resilience.

Future urban expansion planning analysis offers a valuable tool for balancing future urban development and ecological conservation; however, assessing urban land sprawl is uncertain and has practical limitations.

In this regard, future research must prioritize filling knowledge gaps in the theoretical framework and practical land use applications. It should also strive to enhance modeling techniques, integrate economic and political variables into simulation models, and formulate holistic urban planning strategies explicitly focusing on sustainability and resilience.

4. Conclusion

The 2020 land use and cover simulation achieved a 67% similarity with the actual landscape, effectively identifying land use and cover classes in more than half of the pixels. This success is attributed to the carefully selected model variables. After successful calibration and performance, the model was deemed viable for further scenario simulations, offering valuable predictive insights for future planning.

The projections indicate a significant increase in urban areas by 2050. They predict that urban area rates will increase from 32.1% in 2020 to nearly 43% by 2050, with most expansion occurring in agricultural lands, pastures, and forest fragments, leading to a decrease in landscape connectivity.

In the forecast, the municipality's boundaries expanded, reaching the surrounding areas in suburban. This differs from the compact city model, which aims to minimize the use of undeveloped land, such as a mosaic of agriculture and pasture and forest fragments. Preserving these lands in periurban areas is essential, as these areas provide critical ecosystem services, including flood mitigation, temperature regulation, and food production, which are vital for sustainable urban living.

Forest fragments are projected to decrease to 12% by 2050, with some converting to agriculture, pasture, and urban areas. The loss of forest fragments, especially in riparian zones, is a concern for urban biodiversity and landscape connectivity. Implementing innovative management practices in these areas can enhance air quality, microclimate, and overall urban biodiversity, contributing to the health and well-being of residents.

The decrease in landscape connectivity from 2020 to 2050 underscores the impact of urban expansion on forest fragmentation. Municipal governments must establish urban ecological networks to create more resilient cities. Continuous monitoring and analysis of green infrastructure and urban sprawl are crucial for sustainable urban development and achieving global urban environmental goals.

This study emphasizes the importance of urban sprawl simulations in addressing the challenges of urban sustainability and resilience, particularly in rapidly urbanizing regions like the Brazilian Atlantic Forest. Such simulations can aid cities in achieving Sustainable Development Goals, adhering to the New Urban Agenda recommendations, and participating in initiatives like the United Nations' Race to Resilience campaign. This is particularly pertinent for developing countries, where managing urban sprawl is critical for conserving green infrastructure and enhancing urban resilience.

While future urban expansion planning can provide a balanced approach to development and conservation, addressing uncertainties and limitations in assessing urban sprawl is essential. Future research should focus on enhancing modeling techniques, integrating economic and political variables, and formulating holistic urban planning strategies emphasizing sustainability and resilience.

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