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Forecasting Land Use and Land Cover Dynamics in the Municipality of Porto Seguro, Bahia

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Abstract: Uncontrolled urban growth impacts the environment and society, resulting in habitat fragmentation, loss of green areas, and increased soil impermeability. Within this context, the municipality of Porto Seguro, in Bahia, Brazil, exemplifies the complexities associated with accelerated urban growth. The aim of this study is to model land use and land cover scenarios for 2029, 2039, and 2049 in the municipality of Porto Seguro, Bahia. For this purpose, data from the MapBiomas platform were acquired. The spatial data were processed in a Geographic Information System environment, and spatial modeling was performed using the Molusce plugin, using descriptors such as correlation analysis, area variation analysis, modeling, simulation, and validation methods. The results from 1985 to 2021 showed an increase in mangroves, forest recovery, and fluctuations in other classes. However, the simulations indicated a slight decline in mangroves, forest maintenance, and expansion of non-vegetated areas and water bodies. Therefore, it is important to implement careful management to protect these valuable ecosystems and ensure their long-term preservation. The active participation of the local community and civil society is essential for the conservation and effective management of these natural resources.

Keywords: Atlantic Forest; Geoprocessing; Sustainable Development

Resumo: O crescimento urbano desordenado impacta o meio ambiente e a sociedade, resultando em fragmentação de habitats, perda de áreas verdes e aumento da impermeabilização do solo. Dentro deste contexto, insere-se o município de Porto Seguro, na Bahia, Brasil, que exemplifica as complexidades associadas ao crescimento urbano acelerado. Objetiva-se com este estudo, modelar cenários de uso e cobertura do solo para 2029, 2039 e 2049 no município de Porto Seguro, Bahia. Para isto adquiriu-se dados oriundos da plataforma MapBiomas. Os dados espaciais foram tratados em ambiente de Sistema de Informação Geográfica e, a modelagem espacial, foi realizada por meio do plugin Molusce, utilizando descritores como análise de correlação, análise de variação de área, métodos de modelagem, simulação e validação. Os resultados de 1985 a 2021 mostraram aumento do mangue, recuperação de florestas e flutuações em outras classes, contudo as simulações indicaram leve declínio no mangue, manutenção da floresta e expansão de áreas não vegetadas e corpos d'água. Portanto, é importante implementar uma gestão cuidadosa para proteger esses ecossistemas valiosos e garantir sua preservação a longo prazo. A participação ativa da comunidade local e da sociedade civil é fundamental para a conservação e gestão eficaz desses recursos naturais.

Palavras-chave: Mata Atlântica; Geoprocessamento; Desenvolvimento Sustentável.

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1. Introduction

Although urban areas occupy a relatively small portion of the earth's surface, their extent, distribution and evolution have an impact on the environment and socioeconomic dynamics (Seto et al., 2012). This impact is a result of the changes in land cover and land use associated with urban sprawl, both organized and disorderly. Increasing urbanization and the expansion of urban areas have generated global concern. The increase in population in cities causes transformations in the landscape and land use, raising questions about sustainable urban planning, environmental preservation and the quality of life of urban communities. In this context, spatial modeling in land cover and use is essential to understand urban dynamics and guide decisions for sustainable urban development.

In the urban environment, the expansion of urban areas represents a global trend that poses considerable challenges for planning and environmental sustainability. The disorderly growth of cities can cause fragmentation of natural habitat, loss of green areas and increased soil sealing, resulting in problems such as flooding and loss of biodiversity, among other several negative impacts (Alves et al., 2018). In this context, the municipality of Porto Seguro, in Bahia, Brazil, is included as an example of the complexities associated with the accelerated urban growth. Rapid urban expansion in coastal areas such as Porto Seguro can lead to environmental and social challenges (Serra Silva, 2019). With a broad history and geographical diversity, the region faces environmental challenges that require territorial management.

Porto Seguro is currently the main tourist destination in the region, attracting visitors with several interests. In addition to the main town, Porto Seguro includes other important tourist destinations, such as the districts of Arraial D'Ajuda, Trancoso and Caraíva. Green (2019) points out that to reach the district of Arraial D'Ajuda from the center of Porto Seguro, visitors can travel approximately 69 km on BA 001 or use the ferry located at the mouth of the Buranhém River. This ferry operates 24 hours a day and is a vital means of transport, reinforcing the importance of the river as a tourist destination.

The region has several natural beauties, beaches, history and culture, making it a coveted destination for tourists in search of unique experiences (Garcia et al., 2021). However, tourism growth and urban sprawl can bring challenges to the region's environmental preservation and sustainability. Candiotto (2009) points out that an adequate planning of tourism development is essential to ensure the conservation of natural resources and the quality of life of local communities.

With the economic growth promoted by tourism on the coast of Porto Seguro, there is an increase in the number of hotels and inns near the beach, resulting in notable changes in the landscape (Smith et al., 2021). Among the activities with the greatest impact on mangrove ecosystems, vegetation suppression in several areas stands out, which directly affects the dynamics of estuarine ecosystems and reduces biodiversity (Souza, 2018). Therefore, studies that assess the future projection of land use and land cover in Porto Seguro are crucial, given the tourist importance and economic development of the region, driven by real estate expansion and speculation.

The mapping of land use and occupation is a basic product for spatial environmental studies, assisting in the management and preservation of natural resources. In this sense, an initiative at the national level is the Annual Mapping Project of Brazil's Soil Coverage and Use - MapBiomas, which involves several specialists in Brazilian biomes, land uses, remote sensing, Geographic Information Systems (GIS) and computer science. In general, there were few previous initiatives on the mapping of land use and occupation in the Atlantic Forest domain with spatial and thematic details, however, the best reference is the "Atlas of forest remnants of the Atlantic Forest" produced by the "Fundação SOS Mata Atlântica" and "Instituto Nacional de Pesquisas Espaciais - INPE" (MapBiomas, 2018). The Atlas is a more consolidated initiative, and presents a concept of forest restricted to well-conserved vegetation, being more used for identification of deforestation and analysis of biodiversity conservation, while MapBiomas presents a more comprehensive forest concept, indicated for analysis of fragmentation, restoration and protection of water (Rosa, 2016), however, the Atlas presents only the data of forest remnants between 2005 and 2017, not differentiating land uses and occupations, thus MapBiomas can be a solution for thematic studies and with greater temporal resolution. Therefore, this study aims to model scenarios of use and occupation of land for 2029, 2039 and 2049 in the municipality of Porto Seguro, Bahia.

2. Methodology

2.1 Study area

The municipality of Porto Seguro is located on the Costa do Descobrimento, in the Far South region of the State of Bahia, at a distance of 720 km from the capital Salvador (Figure 1). According to the IBGE-cities demographic census (2021), the municipality has an estimated population of about 168,326 inhabitants. With an area of approximately 2,285.73

km² (IBGE, 2022), it has a diversified geography, including pristine beaches, coral reefs, tropical forests and mangroves, and is bathed by the Atlantic Ocean, which boosts tourism and fishing.

2.2 Methodological procedures

The methodology adopted in the study was organized in the following steps, as described in the flowchart (Figure 2):

1. Data Acquisition: Matrix data were obtained from the MapBiomas platform, available free of charge at the link (https://brasil.mapbiomas.org/map/colecao-7/). The database included rasters from 1985, 1991, 1997, 2003, 2009, 2013, 2015 and 2021.
2. Definition of the Study Area: Vector data were used in shapefile format of the limits. The "Reclassify by Table" tool of QGIS allowed to reclassify the rasters according to the classification of collection 7 of MapBiomas (Figure 3) for the following macros classes:
    a) Mangrove: The mangrove ecosystem, a subclass of the forest macro class, plays a crucial role in ecological balance and maintaining biodiversity in coastal areas. It is composed of several species of trees, shrubs and herbs that play distinct roles within the ecosystem.
    b) Forest: Includes Forest Formation, Savanna Formation and Wooded sandbank.
    c) Non-Forest Natural Formation: Includes Waterlogged Field and Wetland Area, Grassland, Salty Flat, Rocky Outcrop, Herbaceous sandbank, and other non-forest formations.
    d) Agriculture: Includes Pasture, Agriculture, Forestry and Mosaic of Uses.
    e) Non-vegetated area: Includes Urbanized Area, Mining and other non-vegetated areas.
    f) Bodies of water: Includes River, Lake and Ocean, as well as Aquaculture.
    g) Data Quantification: The "Report single-value raster layer" tool in QGIS was used to quantify the values of the classes in hectares and analyze the variations over the studied period.
    h) Land Use and Occupation Simulation Model: The MOLUSCE plugin was used to model land use and changes in forest cover. MOLUSCE helped analyze the potential transition and future simulation of land use and occupation.
    i) Identification and Understanding of Changes: The years 1985 and 1991 were used as input data, and 1997 as validation data, to improve modeling. This period was chosen to capture critical transitions in the analyzed classes.
    j) Hyperparameter Adjustment: Adjustments to the MOLUSCE hyperparameters were made to reflect changes in land use over time. This adjustment was crucial for obtaining more accurate results.

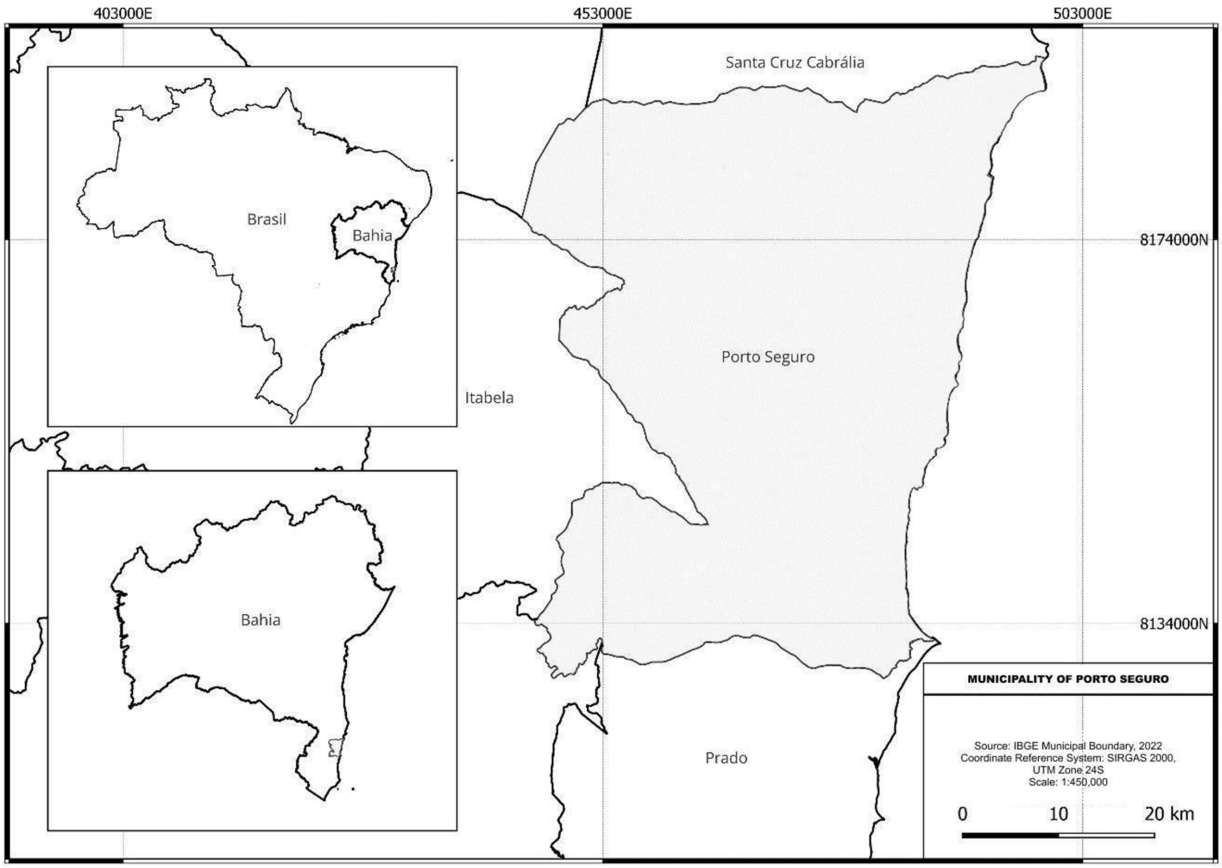

Figure 1 - Municipality of Porto Seguro, SIRGAS 2000 Reference System.
Source: IBGE, 2022. Prepared by the authors (2025).

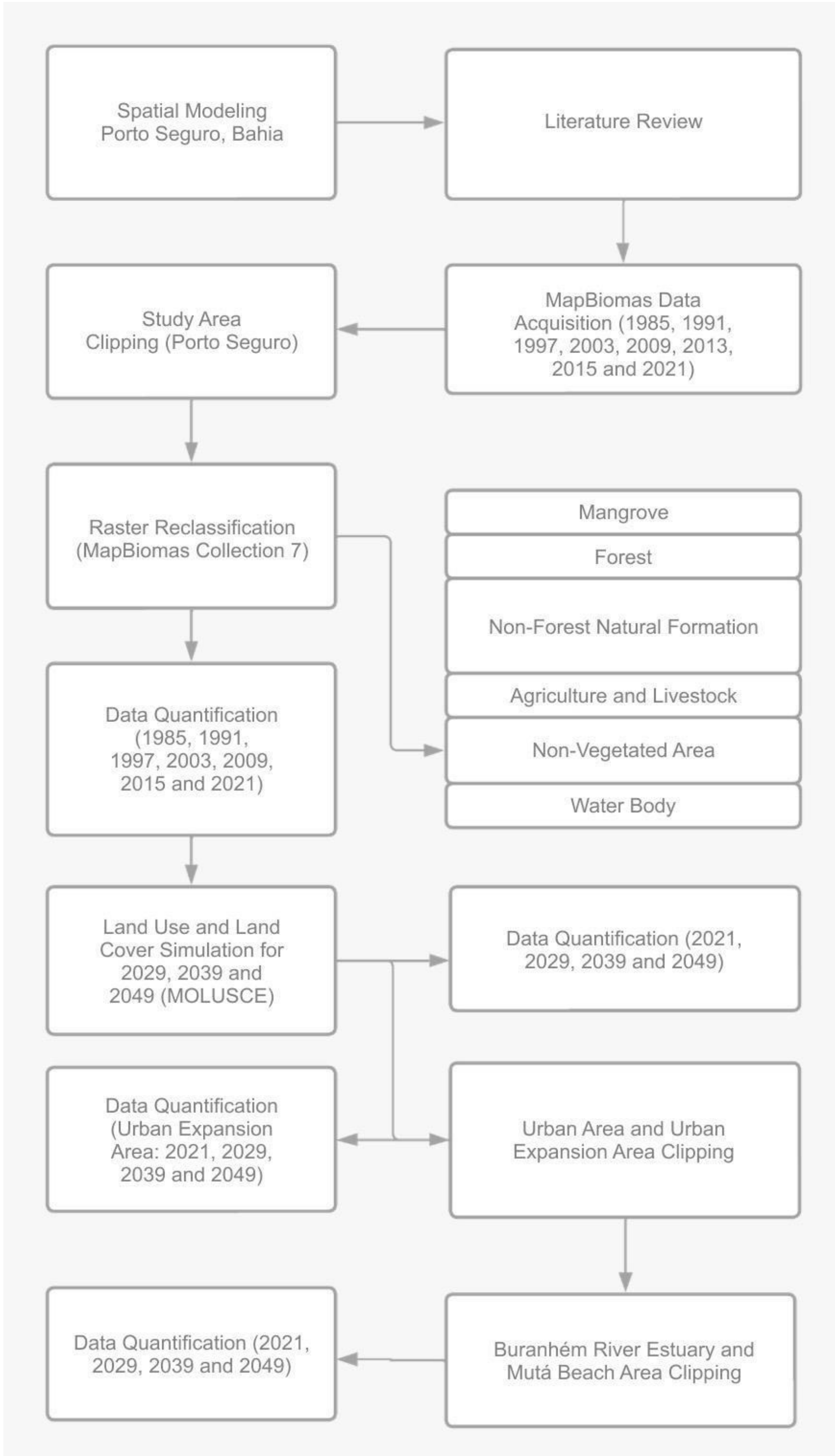

Figure 2 – Methodological Flowchart.
Source: Authors (2025).

MAPBIOMAS

Codes of the legend classes and color palette used in MapBiomas Collection 7

COLEÇÃO 7 - CLASSES	COLLECTION 7 CLASSES	NEW ID	Color number	
1. Floresta	**1. Forest**	1	#129912	
1.1 Formação Florestal	1.1. Forest Formation	3	#006400	
1.2. Formação Savânica	1.2. Savanna Formation	4	#00ff00	
1.3. Mangue	1.3. Mangrove	5	#687537	
1.4. Restinga Arborizada	1.4. Wooded Sandbank Vegetation	49	#6b9932	
2. Formação Natural não Florestal	**2. Non Forest Natural Formation**	10	#bbfcac	
2.1. Campo Alagado e Área Pantanosa	2.1. Wetland	11	#45c2a5	
2.2. Formação Campestre	2.2. Grassland	12	#b8af4f	
2.3. Apicum	2.3. Salt Flat	32	#968c46	
2.4. Afloramento Rochoso	2.4. Rocky Outcrop	29	#ff8C00	
2.5 Restinga Herbácea	2.5. Herbaceous Sandbank Vegetation	50	#66ffcc	
2.6. Outras Formações não Florestais	2.5. Other non Forest Formations	13	#bdb76b	
3. Agropecuária	**3. Farming**	14	#ffffb2	
3.1. Pastagem	3.1. Pasture	15	#ffd966	
3.2. Agricultura	3.2. Agriculture	18	#e974ed	
3.2.1. Lavoura Temporária	3.2.1. Temporary Crop	19	#d5a6bd	
3.2.1.1. Soja	3.2.1.1. Soybean	39	#c59ff4	
3.2.1.2. Cana	3.2.1.2. Sugar cane	20	#c27ba0	
3.2.1.3. Arroz (beta)	3.2.1.3. Rice	40	#982c9e	
3.2.1.4. Algodão (beta)	3.2.1.4. Cotton (beta)	62	#660066	
3.2.1.5. Outras Lavouras Temporárias	3.2.1.5. Other Temporary Crops	41	#e787f8	
3.2.2. Lavoura Perene	3.2.2. Perennial Crop	36	#f3b4f1	
3.2.2.1. Café	3.2.1.1. Coffee	46	#cca0d4	
3.2.2.2. Citrus	3.2.1.2. Citrus	47	#d082de	
3.2.1.3. Outras Lavouras Perenes	3.2.1.3. Other Perennial Crops	48	#cd49e4	
3.3. Silvicultura	3.3. Forest Plantation	9	#935132	
3.4. Mosaico de Usos	3.4. Mosaic of Uses	21	#fff3bf	
4. Área não Vegetada	**4. Non vegetated area**	22	#ea9999	
4.1. Praia, Duna e Areal	4.1. Beach, Dune and Sand Spot	23	#dd7e6b	
4.2. Área Urbanizada	4.2. Urban Area	24	#af2a2a	
4.3. Mineração	4.3. Mining	30	#8a2be2	
4.4. Outras Áreas não Vegetadas	4.4. Other non Vegetated Areas	25	#ff99ff	
5. Corpo D'água	**5. Water**	26	#0000ff	
5.1. Rio, Lago e Oceano	5.1. River, Lake and Ocean	33	#0000ff	
5.2 Aquicultura	5.2. Aquaculture	31	#29eee4	
6. Não observado	6. Non Observed	27	#D5D5E5	

Figure 3 - Classes and legend codes of MapBiomas classes (MapBiomas Project – Collection 7.0, 2023). Source: Authors (2025).

Methodologic Workflow at molusce (Figure 4):

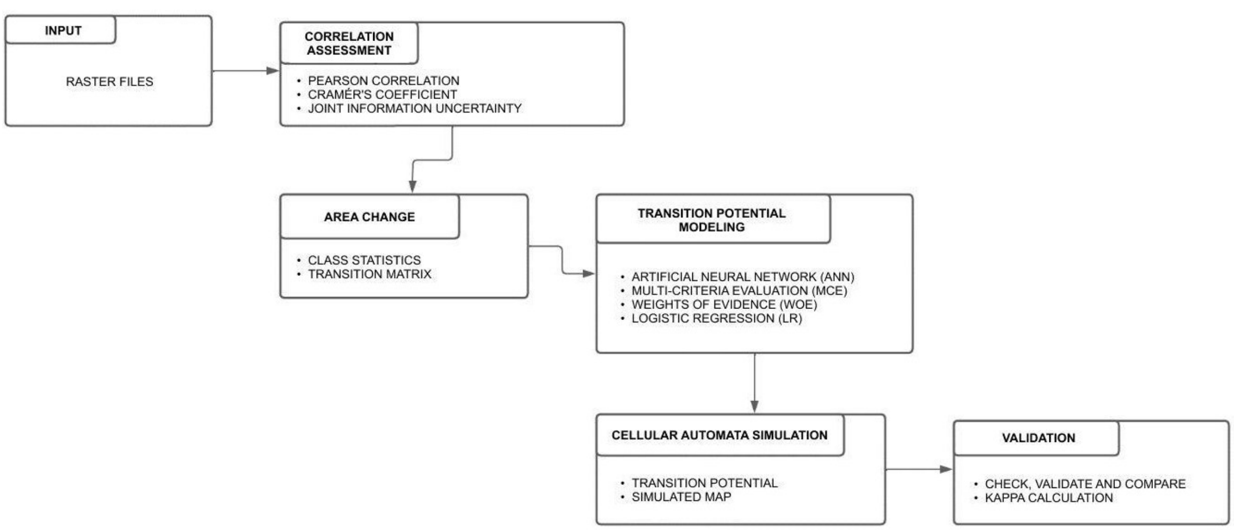

Figure 4 - Methodologic workflow at the MOLUSCE for the simulation of future scenarios of land use and land cover in the municipality of Porto Seguro – BA. Source: Authors (2025).

- Data Compilation: Classified maps from MapBiomas were reclassified to Forests, Mangrove, Non-Forest Natural Formation, Agriculture and livestock, Non-Vegetated Area and Water Body. Spatial Variables were generated from the Digital Elevation Model (DEM) and slope data (Figure 5).

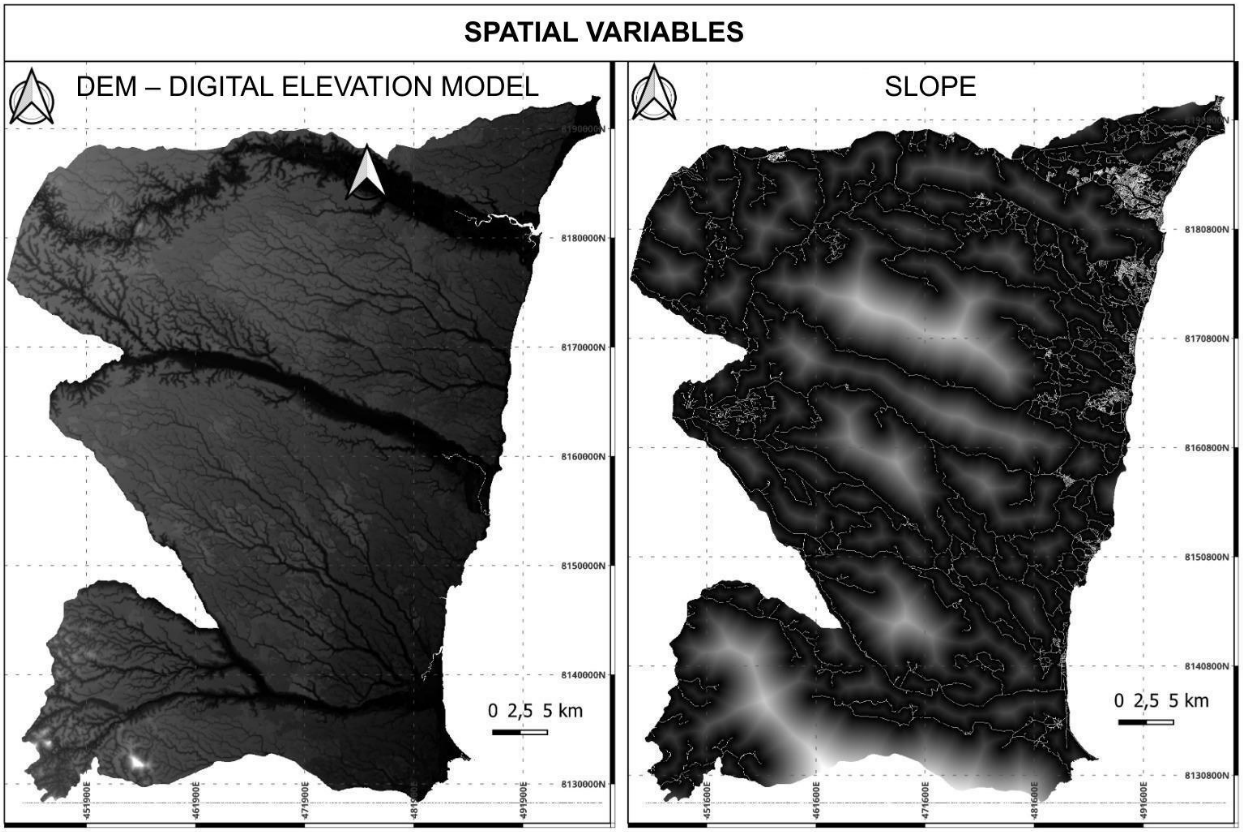

Figure 5 - Spatial input variables for MOLUSCE, Digital Elevation Model (DEM) and Slope Maps in the municipality of Porto Seguro - BA.
Source: Authors (2025).

- Correlation Analysis: three techniques were used for correlation analysis: Pearson Correlation, Cramer's Coefficient and Joint Information Uncertainty. The Pearson Correlation was chosen because it does not require previously categorical data.
- Area Variation Analysis: Classes Statistics Tables, Transition Matrices and Alterations Maps were generated. The Transition Matrices described the changes between the classes over time.
- Transition Potential Modeling: The MOLUSCE applied methods such as Artificial Neural Networks, Multi-Criteria Evaluation, Weights of Evidence and Logistic Regression for the Transition Potential Modeling.
- Hyperparameters Adjustments: Adjustments were peformed in the hyperparameters, including Neighborhood, Learning Rate, Maximum Iterations, Hidden Layers and Momentum, to optimize the simulation results.
- Learning Iteration Results: The MOLUSCE provided validation results, including Global Minimum Validation Error, Overall Accuracy Variation and Current Validation Kappa. ****

For the Buranhém River Estuary Area studied, particularly in the mangrove areas and Mutá Beach, a specific approach was applied for spatial clipping and quantification of classes and their changes. The image segmentation and the associated quantification of each class enabled an in-depth analysis of temporal and spatial variations. The municipal master plan, according to Article 26 of Municipal Law No. 1511/2019, defines the boundaries of the urban area and the urban expansion zone. These boundaries were created using QGIS based on the offset from the high tide line provided by SPU and on the Monte Pascoal National Park shapefile, obtained from the Chico Mendes Institute for Biodiversity Conservation (ICMBIO) website.

3. Results and Discussion

The town of Porto Seguro presented significant variations in its land cover classes over time, based on data collected for the years 1985, 1991, 1997, 2003, 2009, 2015 and 2021 (Figure 6). The analysed classes include Mangrove, Forest, Non-Forest Natural Formation, Agriculture and Livestock, Non-Vegetated Area and Water Body (Table 1).

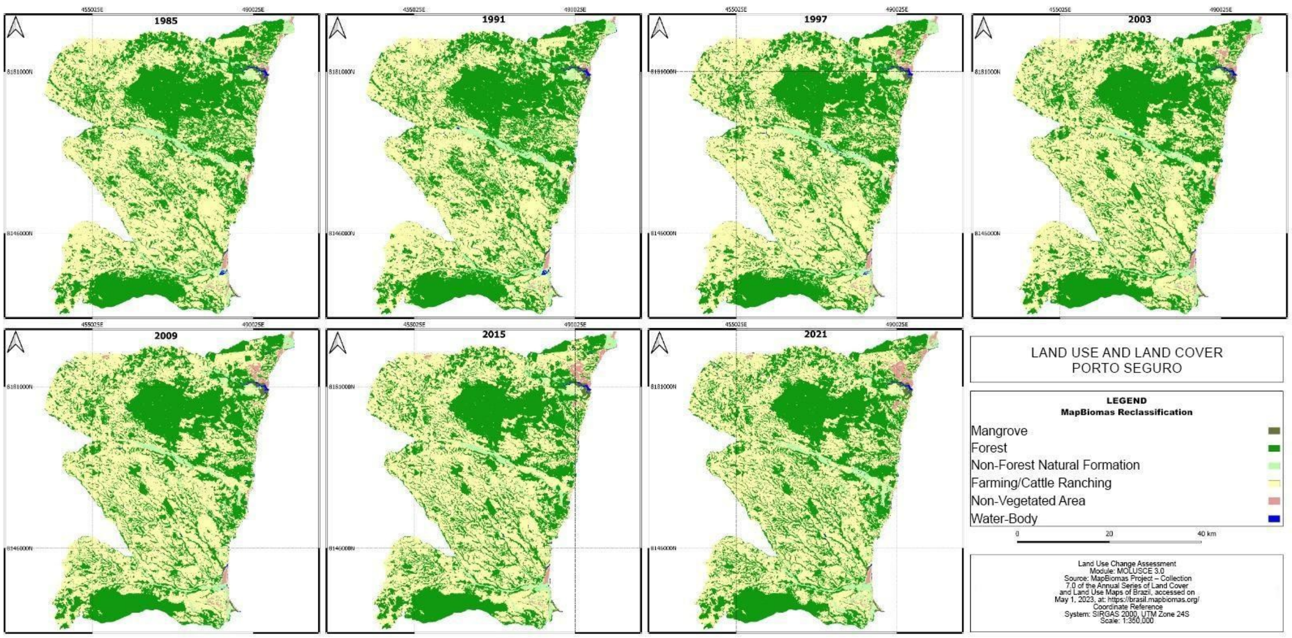

Figure 6 - Land Use and Land Cover Maps in the Town of Porto Seguro – BA, based on MAPBIOMAS for the years 1985, 1991, 1997, 2003, 2009, 2015 e 2021.
Source: Authors (2023).

The study reveals an increase of 13.79% in the mangrove area extent in Porto Seguro over the analysed period. That gradual expansion is important because the mangroves play a crucial role in the local biodiversity and in the climate change mitigation. Similar research, such as that of BRAUM (2017), demonstrates the importance of mangroves in coastal protection, water purification and marine fauna and flora support. Additionally, the mangroves act as blue carbon stocks, essential for combating carbon emissions. The conservation of those ecosystems should be a priority to preserve biodiversity and contribute to the global climate balance.

Between 1985 and 1997, Porto Seguro experienced a pronounced decrease in the forest cover, with a loss of 48,337.83 hectares, mostly because of the deforestation caused by the increase in Agriculture and Livestock activities. However, from 2003 on, the forest area began to recover, reflecting conservation and reforestation efforts. Studies indicate that forest recovery brings significant benefits, such as habitat restoration, soil quality improvement and carbon sequestration. It is crucial to keep investing in forest protection and promote sustainable management practices to guarantee ecological health in the long term.

The Non-Forest Natural Formation in Porto Seguro varied over time, from the highest value recorded in 1985 (9.872,46 ha) to the lowest in 2009 (5.978,16 ha). These fluctuations show the savanna and grassland areas sensitivity to climate change, land use and human activities. The conservation of these areas is crucial to maintaining the habitat diversity and the ecosystem integrity. Strategies such as the creation of protected areas and ecological corridors are recommended to preserve these natural formations. The agriculture and livestock experienced a significant growth until 1997, with of

50,633.55 ha increase. However, from 1998 until 2021, the agriculture and livestock designated area stabilized. Agriculture and Livestock are essential for the local economy, but they should be managed in a sustainable manner to balance economic development and environmental conservation. Encouraging sustainable farming practices is fundamental to minimize negative impacts and promote a balanced development.

Table 1 - Land Use and Land Cover Quantification in the municipality of Porto Seguro – BA for the years 1985, 1991, 1997, 2003, 2009, 2015 and 2021.

Classes	1985	1991	1997	2003	2009	2015	2021
Mangrove	633.51 ha 0.28%	647.73 ha 0.28%	680.31 ha 0.29%	701.64 ha 0.30%	704.52 ha 0.30%	712.35 ha 0.30%	720.90 ha 0.30%
Forest	138,012.84 ha 61.53%	99,025.29 ha 43.17%	89,675.01 ha 37.76%	90,716.85 ha 38.27%	90,616.86 ha 38.36%	91,134.81 ha 38.42%	94,628.88 ha 39.84%
Non-Forest Natural Formation	9,872.46 ha 4.40%	7,138.98 ha 3.11%	6,505.11 ha 2.74%	6,731.37 ha 2.83%	5,978.16 ha 2.53%	6,177.24 ha 2.60%	7,697.97 ha 3.24%
Agriculture and Livestock	78,042.24 ha 34.77%	119,372.22 ha 52.00%	128,675.79 ha 54.22%	127,319.94 ha 53.66%	127,930.10 ha 54.15%	127,132.47 ha 53.59%	121,569.48 ha 51.24%
Non-Vegetated Area	1,208.61 ha 0.54%	1,419.03 ha 0.62%	1,994.67 ha 0.84%	2,210.22 ha 0.93%	2,467.35 ha 1.04%	2,649.15 ha 1.12%	3,216.87 ha 1.36%
Water Body	580.59 ha 0.26%	748.80 ha 0.33%	819.54 ha 0.34%	667.98 ha 0.28%	655.47 ha 0.28%	540.54 ha 0.23%	512.37 ha 0.22%

Source: Authors (2025).

The non-vegetated area in Porto Seguro increased 166.16% between 1985 and 2021, reflecting the urban and industrial growth. That increase may result in land sealing, local climate changes and natural habitat loss. Sustainable urban planning strategies, such as green areas establishment and ecological corridors, are necessary to mitigate these impacts. Policies which encourage a sustainable construction and the green areas preservation are essential to reduce the negative effects of the uncontrolled expansion. Water body areas in Porto Seguro presented fluctuations that reflect the climatic factors influence and the public environmental management. These areas of preservation is crucial to guarantee the water resources quality and quantity, as well as the aquatic biodiversity. The implementation of protective and monitoring actions is essential to keep the balance of aquatic ecosystems.

To improve the spatial modeling overall accuracy, data from 1985 and 1991 were used to adjust the hyperparameters in order to simulate the year 1997. That careful adjustment allowed the identification of the hyperparameters configuration, which was then applied in the simulations for the subsequent years. The results were shown by MOLUSCE, according to Table 2.

Table 2 - Learning Iteration Results (1985-1991).

Δ Overall Accuracy	-0,00137
Min Validation Overall Error	0.02996
Current Validation Kappa	0.71037

Source: Authors (2025).

The minimum validation error was -0.00137. Although a negative minimum validation error is atypical, this value may indicate potential technical issues. The overall accuracy variation was 0.02996. A low variation in the overall accuracy indicates a relatively stable model performance. The Validation Kappa's rate was 0.71037. This relatively high Kappa value proposes a good agreement between the model classifications and the true classes, suggesting an effective model generalization. Thus, the Figure 7 is demonstrating a real comparison and the simulation of 1997.

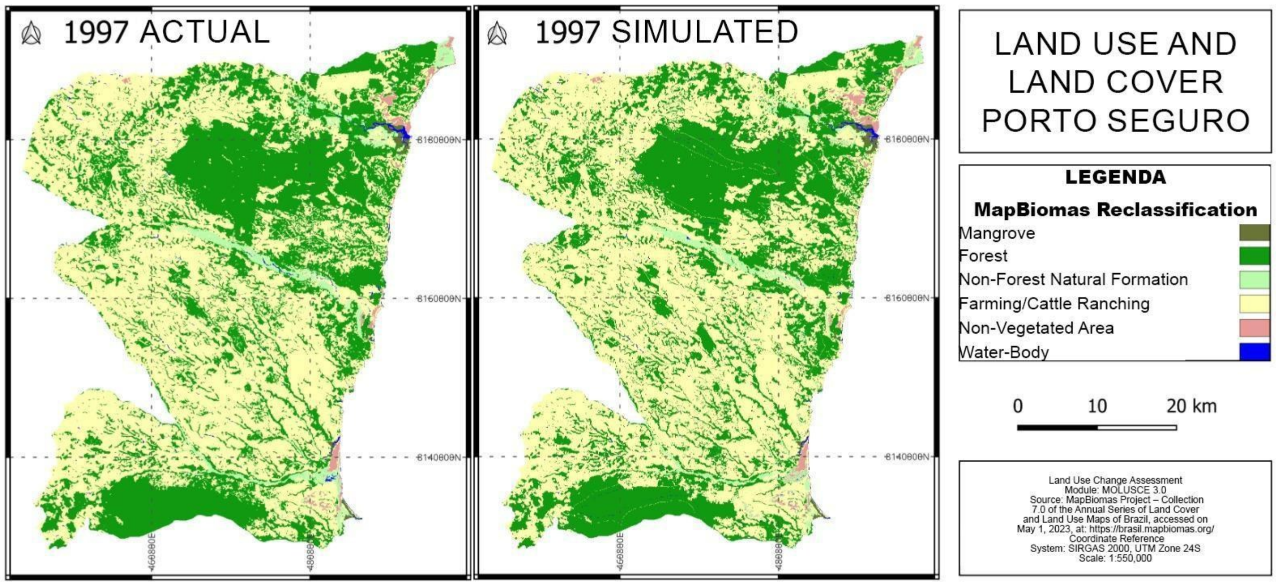

Figure 7 - Comparative of the use and land cover in 1997 between the real and simulated for the model. Elaboração: Authors (2025).

To project the future land use and land cover scenarios, the years 2029, 2039 and 2049 were chosen in alignment with the periodic review of the municipal master plan. Using data from 2013 and 2021, the simulation for 2029 was based on these intervals, and for the subsequent years, previous years' data were used. The simulation results were obtained with MOLUSCE Plugin, presenting the scenarios for the years 2029, 2039 and 2049 (Table 3 and Figure 8).

Table 3 - Data from 2021 and a scenario simulation of 2029, 2039 and 2049 for land use and land cover in the municipality of Porto Seguro – BA.

Years	**2021**		**2029**		**2039**		**2049**	
Classes	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Mangrove	720.9	0.32	679.59	0.30	677.79	0.30	675.99	0.30
Forest	94,628.88	41.44	95,077.26	41.64	97,084.71	42.52	98,100.45	42.96
Non-Forest natural formation	7,697.97	3.37	7,702.20	3.37	7,300.80	3.20	7,389.72	3.24
Agriculture	121,569.48	53.24	121,017.87	53.00	119,502.27	52.33	118,464.21	51.88
Non-Vegetated area	3,216.87	1.41	3,365.01	1.47	3,310.02	1.45	3,287.70	1.44
Body of water	512.37	0.22	504.54	0.22	470.88	0.21	428.40	0.19

Source: The authors (2025).

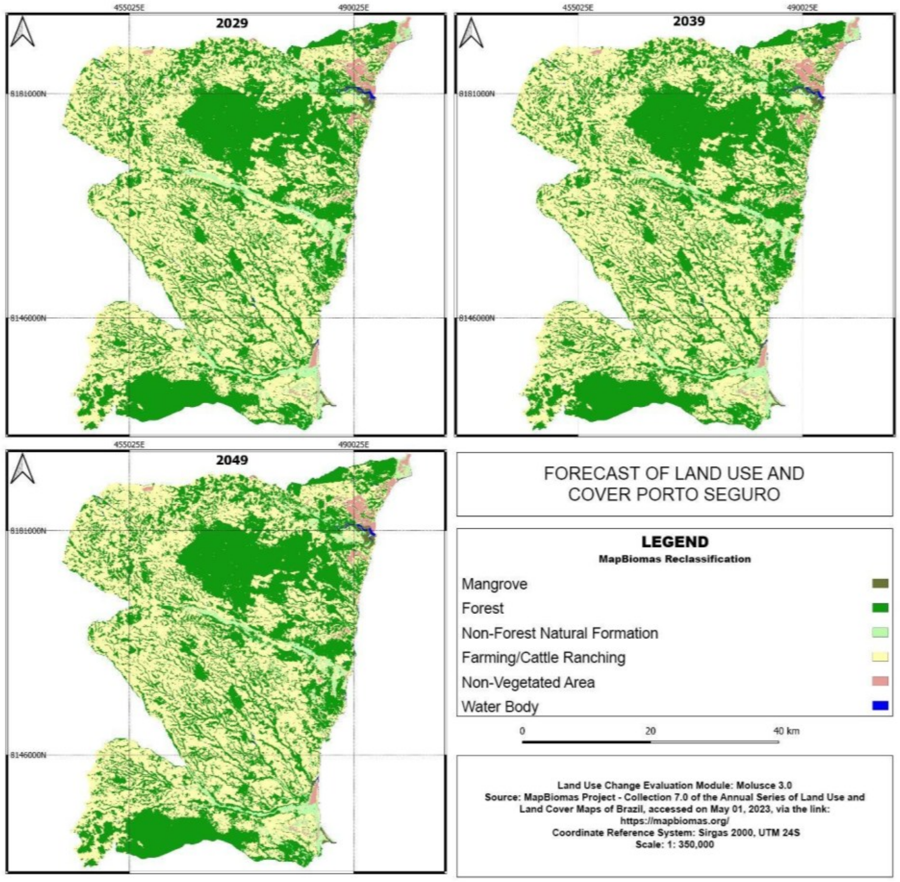

Figure 8 - Land use and land cover forecasting in the municipality of Porto Seguro for the years 2029, 2039 and 2049. Source: The authors (2025).

The results show land use and land cover change between 2021 and 2049 will be more limited (Figure 9). This suggests a stabilization in land use, possibly driven by conservation policies and urban planning. This stability reflects a period during which land use changes were less intense. An analysis of urban area and urban expansion was based on the municipal Master Plan definition, which includes urban perimeter and expansion areas (Table 4). The simulation for the years 2021, 2029, 2039 and 2049 highlighted the following trends:

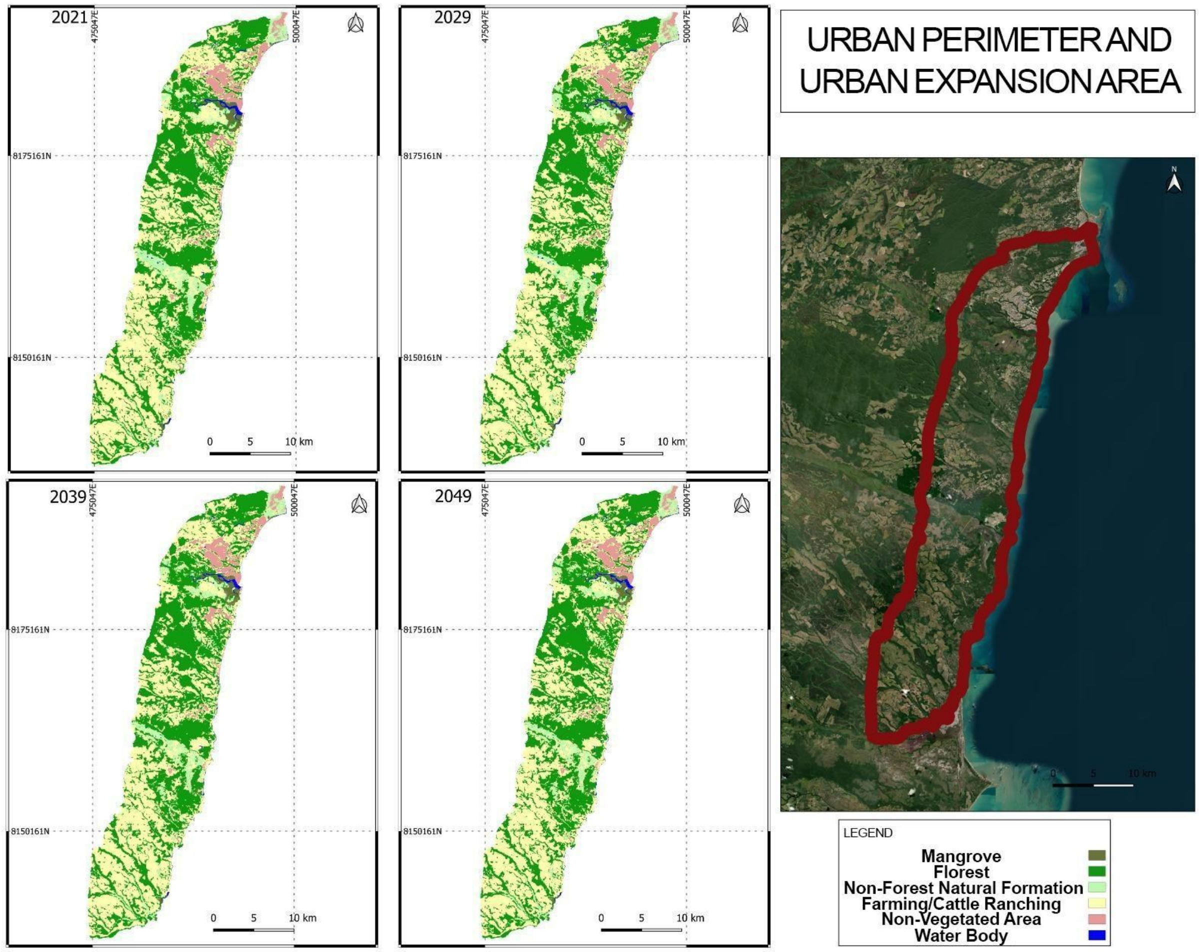

Figure 9 - Urban perimeter and urban expansion - Porto Seguro, BA.
Source: The authors (2025).

Table 4 - Quantification of data for 2021, 2029, 2039 and 2049 - (Urban area and urban expansion).

Years	**2021**		**2029**		**2039**		**2049**	
Classes	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Mangrove	601.92	1.12	567.18	1.06	565.56	1.05	564.3	1.05
Forest	21,952.44	41.00	22,233.78	41.48	22,764.06	42.42	23,023.35	42.92
Non-Forest natural formation	3,224.61	6.01	3,208.5	5.99	3,019.59	5.63	3,031.83	5.66
Agriculture and livestock	24,981.3	46.62	24,673.41	46.05	24,408.99	45.47	24,165.27	45.12
Non-Vegetated areas	2,527.2	4.72	2,606.4	4.86	2,554.65	4.77	2,535.75	4.73
Body of water	324.63	0.61	322.83	0.60	298.44	0.56	290.79	0.54

Source: The authors (2025).

The analysis revealed that both mangrove area and water bodies are projected to decrease, while forest cover is projected to increase (Figure 10). Agricultural and livestock land remained the dominant class within the urban expansion area. These trends indicate a gradual urban growth, with varying impacts on different land-use classes. A cross-comparison of the data from the Buranhém River Estuary and the urban expansion areas for 2021 and 2049 underscored substantial shifts across land cover categories. In the Buranhém River Estuary, a gradual decrease in mangrove area was observed, dropping from 483.21 ha (10.38% of the total area) in 2021, to 450.27 ha (9.68%) in 2049. This decrease may be concerning for the conservation of this vital ecosystem.In contrast, the forest area saw a considerable expansion, rising from 1,872.00 ha (40.23%) in 2021 to 1,979.46 ha (42.53%) in 2049, indicating possible reforestation and preservation efforts. The area dedicated to agriculture fluctuated, yet it continues to represent a significant portion of land use.

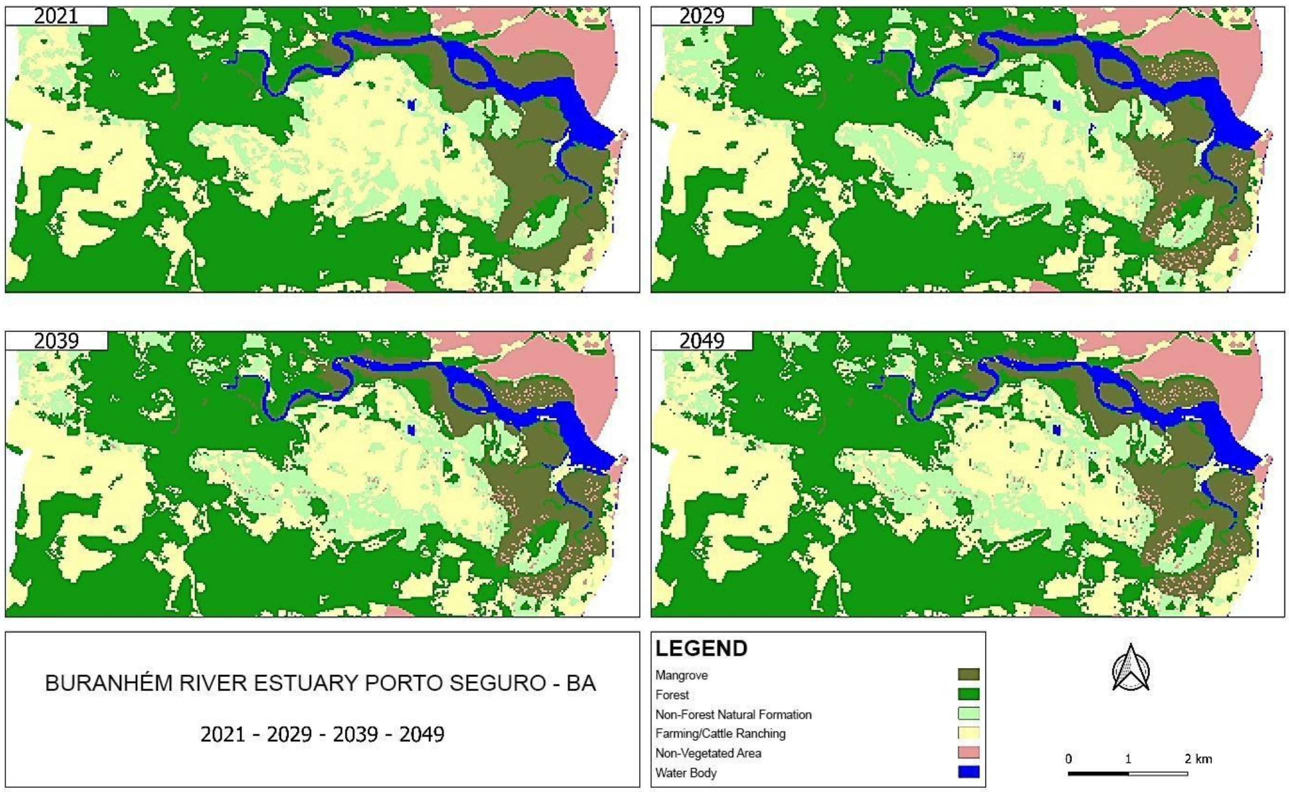

Figure 10 - The Buranhém River Estuary in Porto Seguro, Bahia, in 2021 and simulations for 2029, 2039 and 2049. Source: The authors (2025).

The expansion area exhibits a different pattern. The mangrove zone also decreased, from 601.92 ha (1.12%) in 2021 to 564.3 ha (1.05%) in 2049. However, the forest showed a consistent increase, from 21,952.44 ha (41%) in 2021 to 23,023.35 ha (42.92%) in 2049. Agriculture and livestock remained the dominant class. These trends indicate a complex dynamic between land-use classes, carrying important implications for environmental conservation and urban planning. Although the estuary is part of the urban expansion area, the data suggest subtle differences in land-use dynamics, requiring an in-depth analysis to fully understand the drivers and consequences of these changes (Table 5).

The study by Ribeiro et al. (2019) on urban expansion in Porto Seguro between 2004 and 2017 highlighted that urban growth occurred primarily in mangrove and Atlantic Forest areas. The lack of adequate planning and conservation policies contributed to the loss of green spaces and exacerbated environmental problems. To address these challenges,it is essential that Porto Seguro adopt sustainable development and conservation strategies, including the creation of management plans for mangroves and conservation areas, as suggested by Alongi (2015) and Dahdouh-Guebas et al. (2005). An analysis of the data from *Mutá Beach* reveals changes in land use over the years, with specific considerations for each land use class, such as Mangrove, Forest, Non-Forest Natural Formation, Agriculture and Livestock, Non-Vegetated Area and Bodies of water (Table 6).

Table 5 – Quantification of data for 2021, 2029, 2039, and 2049 – Buranhém River Estuary.

Years	**2021**		**2029**		**2039**		**2049**	
Classes	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Mangrove	483.21	10.38	452.52	9.72	451.44	9.70	450.27	9.68
Forest	1,872	40.23	1,905.57	40.95	1,957.23	42.06	1,979.46	42,53
Non-forest Natural Formation	457.65	9.83	601.65	12.93	507.51	10.91	505.44	10.86
Agriculture and Livestock	1,418.31	30.48	1,242.09	26.69	1,298.25	27.90	1,281.42	27.53
Non-vegetated Area	245.25	5.27	274.68	5.90	274.32	5.89	273.6	5.88
Body of water	177.39	3.81	177.3	3.81	165.06	3.55	163.62	3.52

Source: Authors (2025).

Table 6 - Data Quantification 2021, 2029, 2039 e 2049 -Mutá Beach.

Years	**2021**		**2029**		**2039**		**2049**	
Classes	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Mangrove	14.94	1.38	14.58	1.35	14.58	1.35	14.58	1.35
Forest	218.16	20.18	217.62	20.17	222.3	20.61	226.53	21.00
Non-forest Natural Formation	428.94	39.68	410.31	38.03	397.89	36.88	397.62	36.86
Agriculture and Livestock	86.49	8.00	85.41	7.92	115.74	10.73	112.05	10.39
Non-vegetated Area	318.24	29.44	337.68	31.30	315.09	29.21	314.82	29.18
Body of water	14.22	1.32	13.23	1.23	13.23	1.23	13.23	1.23

Source: Authors (2025)

The mangrove area remained relatively stable throughout the analyzed period, showing little variation in size (Figure 11). The stability of the forest is also notable, with minimal variations over the years. The Natural Non-Forest Formation gradually decreased, possibly due to urbanization and agricultural expansion. Agriculture and livestock farming increased, reflecting an expansion of agricultural activities in the region, while the non-vegetated area fluctuated before returning to 2021 levels. The body of water class remained constant, indicating adequate preservation of aquatic areas.

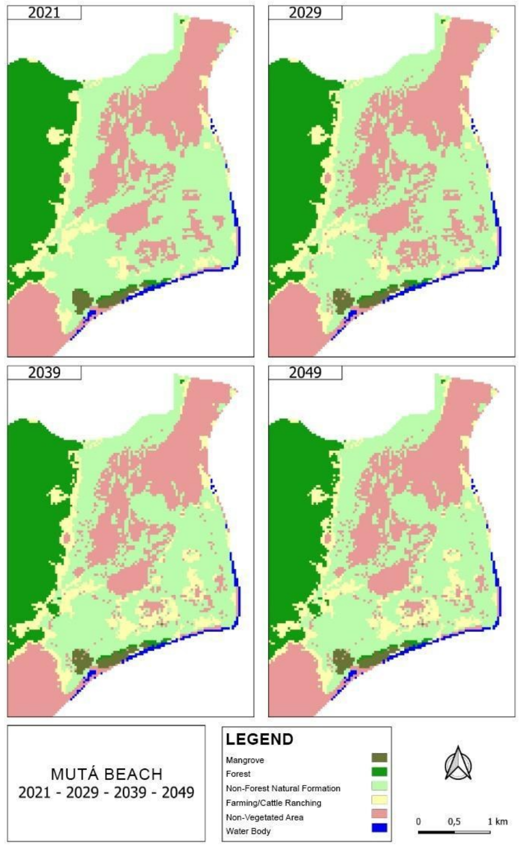

Figure 11 - Land use and land cover at Mutá Beach for the year 2021 and projections for the years 2029, 2039, and 2049.
Author: The author (2025).

An analysis of changes in land use and land cover in Porto Seguro reveals important patterns that warrant attention. The decline of mangrove ecosystems and changes in forest areas and natural formations highlight the need for conservation policies and sustainable urban planning. Monitoring agricultural expansion and protecting water resources are essential to ensuring an environmentally healthy and socially just future for the region.

This study highlights the complexity and importance of spatial modeling for understanding and predicting changes in land use and land cover in Porto Seguro. The methodology applied, which includes the use of historical data, hyperparameter adjustments, and modeling tools, provides a solid foundation for future research and policies on environmental management and urban planning. The preservation of natural ecosystems, such as mangroves and forests, is crucial for the region's environmental sustainability and balanced economic development.

4. Concluding Remarks

The analyzed data reveal that Porto Seguro has been through changes in the classes of land cover between 1985 and 2021. Initially, there has been a significant reduction in forest areas, but in the last years it was observed a recovery of the forest and mangrove area. The variations in the areas of non-forest natural formation, agriculture and livestock, non-vegetated area and water bodies reflect the complex interaction between human activities and environmental conservation over time. This information is crucial to support public policies and sustainable management practices, aiming at the preservation and environmental balance of the region.

The scenarios for the years 2029, 2039 and 2049 suggest a balance, with a small advance of the non-vegetated and agricultural and livestock areas between 2021 and 2029. However, as of 2039, variations tend to stabilize, indicating a potentially more optimistic future in terms of conservation and sustainable land use. It is important to emphasize that these forecasts can be influenced by several external factors, and a continuous commitment to environmental conservation and management is essential to ensure that these positive trends materialize.

The analysis also revealed that the disorderly urban expansion, especially through irregular settlements, has led to the reduction and fragmentation of forest areas and non-forest natural formation. This trend is worrying because these areas play critical roles in local biodiversity. Therefore, it is necessary to review and strengthen the policies of territorial planning and environmental management in Porto Seguro. The preservation of mangroves, green areas and water bodies must be a priority, and urban planning must limit the disorderly expansion of natural ecosystems.

The stability of mangrove areas in Porto Seguro, even with urban expansion, highlights construction restriction by urban zoning. Mangroves continue to play a crucial role, and their conservation is vital to maintaining the region's environmental health. Therefore, it is imperative to implement careful management to protect these valuable ecosystems and ensure their long-term preservation. The active participation of the local community and civil society is fundamental to the conservation and effective management of these natural resources.

The use of MOLUSCE in soil use and occupation modeling presented significant challenges due to the discontinuation of the plugin and its functional limitations, such as the impossibility of simulating continuous future scenarios and the difficulty to process larger rasters than the study area. These restrictions highlight the need to explore alternative and more robust tools for spatial modeling. Despite these difficulties, the research generated valuable results on the dynamics of soil use and highlighted the importance of updating and diversifying modeling methods.

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